

CRANFIELD UNIVERSITY

CATHRYN HARVEY

INVESTIGATING THE INFESTATION: UNDERSTANDING AND
COMMUNICATING DEATHWATCH BEETLE ACTIVITY ON HMS
VICTORY

CRANFIELD DEFENSE AND SECURITY
CRANFIELD FORENSIC INSTITUTE

DOCTOR OF PHILOSOPHY

PhD

Academic Year: 2021 - 2024

Supervisor: Dr Fiona Brock

Associate Supervisors: Diana Davis ACR, Dr Jenny Kidd, Dr David
Errickson, Dr Andrew Shortland

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ABSTRACT

Despite a long history of knowledge, remarkably little is known about the Deathwatch beetle (DWB), a beetle that infests decayed wood. They have associations with folklore, as their tapping behaviour was commonly heard during the vigil before a person died. Despite this and the structural damage they cause, few investigations into DWB have been conducted, resulting in limited literature.

HMS *Victory* has a longstanding DWB infestation. Campaigns of insecticide were conducted throughout the 20th century, but the poorly understood nature of the beetle and the size and complexity of the ship has meant the population remained. With the introduction of Integrated Pest Management (IPM) into the heritage sector, the emphasis shifted to management rather than eradication. To develop effective pest management strategies, a thorough understanding of the lifecycle and behaviour is essential. The National Museum of the Royal Navy, since taking over management of the ship in 2016, has policies that dictate retaining historical material whenever possible and only replacing timbers when structurally essential. While an IPM plan has been implemented, the structural damage the DWB has the potential to cause means a greater understanding of the population on *Victory* is essential to manage the infestation.

Heritage conservation is a field not widely known to the public, as much of the work has historically taken place behind the scenes. This hidden nature is not sustainable as it contradicts the primary mission of cultural institutions, which is to transform audiences into stewards or custodians of heritage. It also has potential material impacts, as this lack of awareness at resource allocation levels has led to many funding and department cuts.

The current conservation programme is a long-term project to enable the survival of the ship with only routine maintenance for the next 50 years. This PhD contributes to this programme by (1) using micro-CT of a DWB-infested and rotten deck plank to understand more about the tunnelling behaviour of the DWB and (2) conducting investigations into potential methods of identifying areas of activity with non-invasive means. The results from both explorations will be used to (3) generate two public engagement prototypes to communicate findings from the research. The evaluation of these prototypes means the thesis also contributes unique insight into methods of disseminating complex conservation research to the public to raise awareness.

Keywords:

Heritage Conservation, National Museum of the Royal Navy, Non-invasive detection, micro-CT, public engagement, Deathwatch Beetle, Deathwatch Beetle damage

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LIST OF ABBREVIATIONS

DWB	Deathwatch Beetle
HMS	His/Her Majesty's Ship
NMRN	National Museum of the Royal Navy
PhD	Doctor of Philosophy
PHD	Portsmouth Historic Dockyard
ICON	Institute for Conservation
IPM	Integrated Pest Management
FPRL	Forest Products Research Laboratory
m, cm, mm, µm	Metre, centimetre, millimetre, micron/micrometre
Cranfield	Cranfield University
ATR-FTIR	Fourier Transform Infrared Attenuated Total Reflectance Spectroscopy
GC-MS	Gas Chromatography Mass Spectrometry
LiDAR	Light Detection and Ranging or Laser Imaging Detection and Ranging
2D	2-Dimensional
3D	3-Dimensional
BIM/HBIM	Building Information Model / Heritage Building Information Model
VIM	Victory Information Model
AEC	Architecture, engineering and construction
NDT	Non-destructive Testing
AE	Acoustic Emission
GPR	Ground Penetrating Radar
ERT	Electrical Resistivity Tomography
Micro-CT	Micro computed tomography
FTIR	Fourier-Transform Infrared Spectroscopy
XRF	X-ray Fluorescence
EDS	Energy Dispersion Spectroscopy
SEM	Scanning Electron Microscope
Vox.	Voxels
HU	Hounslow Unit
RPW	Red Palm Weevil
AI	Artificial Intelligence
TOF	Time of Flight
MC	Moisture Content

IR	Infrared
Hz/THz/ GHz	Hertz, Tetrahertz, GigaHertz
<i>Ibid.</i>	<i>Ibidem</i> , in the same place
e.g	<i>Exempli gratia</i> , for example
i.e.	<i>Id est</i> , that is
US/USA	United States of America
UK	United Kingdom
USS	United States Ship
H.L. Hunley	Horace Lawson Hunley, Confederate Submarine
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
VR	Virtual reality
AR	Augmented Reality
COVID-19	Coronavirus Disease
FAAM	Fleet Air Arm Museum
WWII	World War Two
GPS	Global Positioning Satellite
F, CF, CA, A	Fore, Centre-Fore, Centre-Aft, Aft
kV	Kilovolts
μA	Micro-Amperes
ms	milliseconds
EDXRF	Energy Dispersive X-Ray Fluorescence
LUT	Look-up Table
ROI	Region of Interest
LOWESS	Locally Weighted Scatterplot Smoothing
VOCs	Volatile Organic Compounds
ZSL	Zoological Society of London
OFD	Object to Film Distance
FOD	Focus to Object Distance
GT/GTM	Grounded Theory Method

1 INTRODUCTION

Despite a long history of knowledge of their existence and their status as a pest species of historical wooden structures, remarkably little is known about the Deathwatch Beetle (DWB). Scientific investigations into the species have been limited, and primarily took place in response to severe infestations (Baines, 1923; Fisher, 1937a; Maxwell-Lefroy, 1924). The main focus of many of the studies is eradication. The earliest studies that investigated the habits, behaviours and lifecycle lacked modern scientific rigour and were never replicated (Baines, 1914, 1923; Fisher, 1937b, 1938, 1940b, 1941; Kimmins, 1933; Maxwell-Lefroy, 1924). For example, it was initially thought that the beetles were unable to fly, but studies in the late 1990s, conducted as part of English Heritage's Woodcare project, proved that they did in fact fly provided the temperature was above 17°C (Belmain, 1998). Many of the early observations, especially those made by Ronald Fisher, like the supposed inability to fly, were accepted by other researchers without question (Hickin, 1975). As the Woodcare project made clear with the observations about DWB flight, the findings from early studies must be considered with a degree of wariness. The Woodcare project was the last significant period of study into the DWB (Belmain et al., 2002), and technology has improved drastically since then.

HMS *Victory*, Admiral Nelson's flagship in the Battle of Trafalgar (1805), has been infested with DWB since at least 1932 (first record of infestation) (Bugler, 1966: 87). Many eradication treatments were tried throughout the 20th century, none of which were successful (Davis, 2020: 5). The National Museum of the Royal Navy (NMRN) took over the management and care of the vessel in 2016 and introduced the current system of management and monitoring used in heritage conservation (Child & Pinniger, 1994; *Victory IPM Strategy*, 2023; McCormack, 2016; Pinniger, 1995; Pinniger & Winsor, 2011). Although successful methods of general pest eradication exist, the size, scale and location of *Victory* prevent their implementation (*Ibid.*). A better understanding of the species is required to be able to effectively address the infestation within the

existing parameters of the ship (Davis, 2021). The museum began a partnership with Cranfield University to further understanding of the DWB as part of a large-scale conservation project to ensure *Victory*'s survival with only routine maintenance for the next 50 years. This original PhD research will significantly contribute to the research for this project.

One of the biggest challenges facing the NMRN conservation team is locating areas of active infestation, particularly areas of larval activity, as it is this lifecycle stage that causes the damage that compromises the structural integrity of the timber (Davis, 2021). The current system of pest monitoring is passive and relies on the more mobile adults walking across sticky blunder traps. By the time the adults emerge, the damage has already been done (*Victory IPM Strategy*, 2023). A method that enables detection of larvae in the timber would be extremely beneficial in the management of the infestation as it would enable more targeted interventive treatments such as pesticide application or microwave irradiation (Davis, 2021). In order to follow the conservation principle of minimal intervention and not damage the historical timbers, the method must be non-invasive.

The live conservation and restoration project being undertaken on *Victory* by NMRN (*Victory Live!*) is being conducted in a way that involves and engages the public throughout the process to increase public understanding and interest in the work (*Victory Live*, 2022). Heritage conservation is not a field that is well-known to the general public, as the work has historically taken place behind-the-scenes. There is a pervasive assumption that heritage, when in a designated space, simply exists, and does not require further care (Koutromanou, 2015: 6). This is not the case, but if people do not see the work, they cannot be expected to understand it and its importance, resulting in a world of diminishing budgets and resources allocated to conservation, which impacts the survival of and access to heritage collections (Hardaker, 2024; Koutromanou, 2015; *Economic Value of the Heritage Sector*, 2023). Public engagement with conservation has been identified as an important requirement of the profession, particularly within the past 20 years (Brooks, 2008; Koutromanou, 2015; McClure, 2013; Marçal,

2019; Williams, 2013b). It even featured as one of the key themes of the Institute of Conservation (ICON) 2024 conference, entitled *Conservation for Change*. However, existing methods of engagement are predominantly short term and rely on conservators giving up their already limited time (Koutromanou, 2015; Williams, 2013b).

In this thesis, DWB tunnelling behaviour in wood from HMS *Victory* is rigorously investigated to enhance understanding of the species. It also explores non-invasive methods to detect areas of active infestation, providing valuable insights for the conservation team in their efforts to preserve the ship. Lastly, this thesis reports how data from these investigations was used to underpin two conservation-themed digital public engagement prototypes that were user tested with visitors. These contribute unique insights into the value of public engagement with heritage conservation.

1.1 Aims and objectives

1.1.1 Aim

The main aim of this project is to better understand DWB behaviour on HMS *Victory* to inform conservation decisions and to test methods of communicating research findings to the public so the museum can raise awareness of this conservation issue. There are three main components to this aim:

1. Deathwatch beetle tunnelling: what features within the wood are the beetles following? Are there distinguishable trends? Can these trends be used to quantify damage and predict areas of risk?
2. Non-invasive detection: can active infestation be detected, measured and/or monitored with non-invasive methods?
3. Public engagement with conservation: how can complex conservation research be communicated to the public?

1.1.2 Objectives

To achieve the aim described above, objectives have been identified for each component, all of which contribute to the achievement of the main aim.

1.1.2.1 Deathwatch Beetle Tunnelling

The goal for this section is to identify any trends within the wood caused by the DWB tunnelling. This will be achieved by answering the following questions:

- Are there any discernible trends?
 - What characteristics of wood structure attract DWB? Do the tunnels follow particular features of wood i.e. early vs. late wood, in line with or against wood fibres? Are they going towards external surfaces?
- Is there a correlation between surface damage and internal damage as proposed by Brock et al., 2024?
- Is it possible to determine areas of fungal decay and whether the DWB prefer those areas?
- What can the *in situ* locations of beetles and larvae reveal about the tunnelling behaviours?

1.1.2.2 Non-Invasive detection

To enable conservation efforts to be more targeted at areas of active infestation, a method of detection that will not damage the historic timbers is required. The work in this section will identify suitable non-invasive methods for further inquiry and will lay the foundational groundwork for future investigations.

- Identify suitable methods that may be appropriate for use on *Victory*.
- Are these methods worth investigating further? Are they suitable for use on HMS *Victory*?

1.1.2.3 Public Engagement Objectives

Sharing conservation research with those outside of the community is integral to the survival of the discipline and can have significant impacts on funding opportunities. It is increasingly being considered an essential part of conservation research. Work to achieve this will:

- Examine existing methods to raise public awareness of specific conservation issues.

- Develop 2 public engagement prototypes based on the data generated from investigations into tunnelling behaviour and non-invasive detection.
- Gather and analyse public reaction to the prototypes by presenting them to visitors on the ship to inform further development.

1.2 Thesis structure

Each chapter of this thesis is an individual building block that can be read individually but will narratively build on each other to provide a more thorough understanding of the research.

Chapter 2 will provide the background and context information for understanding the project. It will cover a brief history of HMS *Victory*, provide an overview of DWB and the current knowledge, introduce hard- and soft-wood structure and Integrated Pest Management (IPM). Some key terminology and concepts will also be covered.

The following chapter will examine and critique the literature for the topics of investigation to evaluate the state of knowledge prior to this research. The first section will cover the research into DWB and will be followed by non-invasive methods used in cultural heritage and insect detection. The final section will examine the literature on public engagement with conservation.

Chapter 4 is the first of the investigative chapters. This chapter covers the research and investigations undertaken to examine the DWB tunnelling behaviour. The next chapter presents the methodology and findings of the investigations into non-invasive detection methods for areas of active infestation. The final investigative chapter demonstrates how the data generated in chapters 4 and 5 was developed into prototype public engagement experiences that were user tested with museum visitors. Each chapter will rigorously examine and discuss the results, before discussing how the research can be taken further in future

The final chapter will tie chapters 4-6 together with the overall conclusions of the research, its importance, and what it has contributed to the understanding of

DWB, HMS *Victory*, and public engagement with conservation. Supplementary information that is referred to in the text can be found in the appendices.

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2 BACKGROUND

This chapter will cover the necessary background and context to provide the foundational knowledge to understand the project. A brief history of HMS *Victory* will be followed by a description of Deathwatch beetles, their anatomy and lifecycle, basic wood anatomy, and Integrated Pest Management (IPM). The topics covered in this chapter will be referred to regularly throughout the thesis.

2.1 Key concepts and terms

Below are some key words that will be regularly used throughout this thesis. Further key terminology in each section will be introduced as they appear in each chapter, and a more comprehensive glossary can be found in Appendix B.

Naval terminology is used to refer to locations and directions on the ship by NMRN and in this thesis:

- Port: left
- Starboard: right
- Aft: towards the stern of the ship
- Stern: the back of the ship
- Fore: towards the prow/bow
- Bow: the fore-most part of the ship
- Bowsprit: a spar (pole for rigging) projecting at an angle though the bow to which the forestays (standing parts of rigging) are attached. The base is attached to the ship at the fore end of the middle gun deck (see below).
- Knees: Oak timbers grown to shape to which ends of beams are secured to the sides of the ship. Can be cast (at an angle), hanging (vertical) or lodging (horizontal).
- Keel: Extends longitudinally from stern to sternpost. Considered backbone of ship and foundation for the frames. Usually made of Elm.

The decks of the ship are as follows, and can be seen in [Fig. 1](#):

- Poop deck: the highest and aft-most deck
- Quarter Deck: deck that extends from main mast to stern.
- Upper Gun Deck (UGD): first of the three gun decks (house the guns). Below the quarter deck.
- Middle Gun Deck (MGD): second gun deck, between the upper and lower gun decks.
- Lower Gun Deck (LGD): final gun deck. Below the middle gun deck and above the orlop deck
- Orlop Deck: lowest deck above the hold, below the waterline
- Hold: Space below the orlop, used for storage of ballast and stores

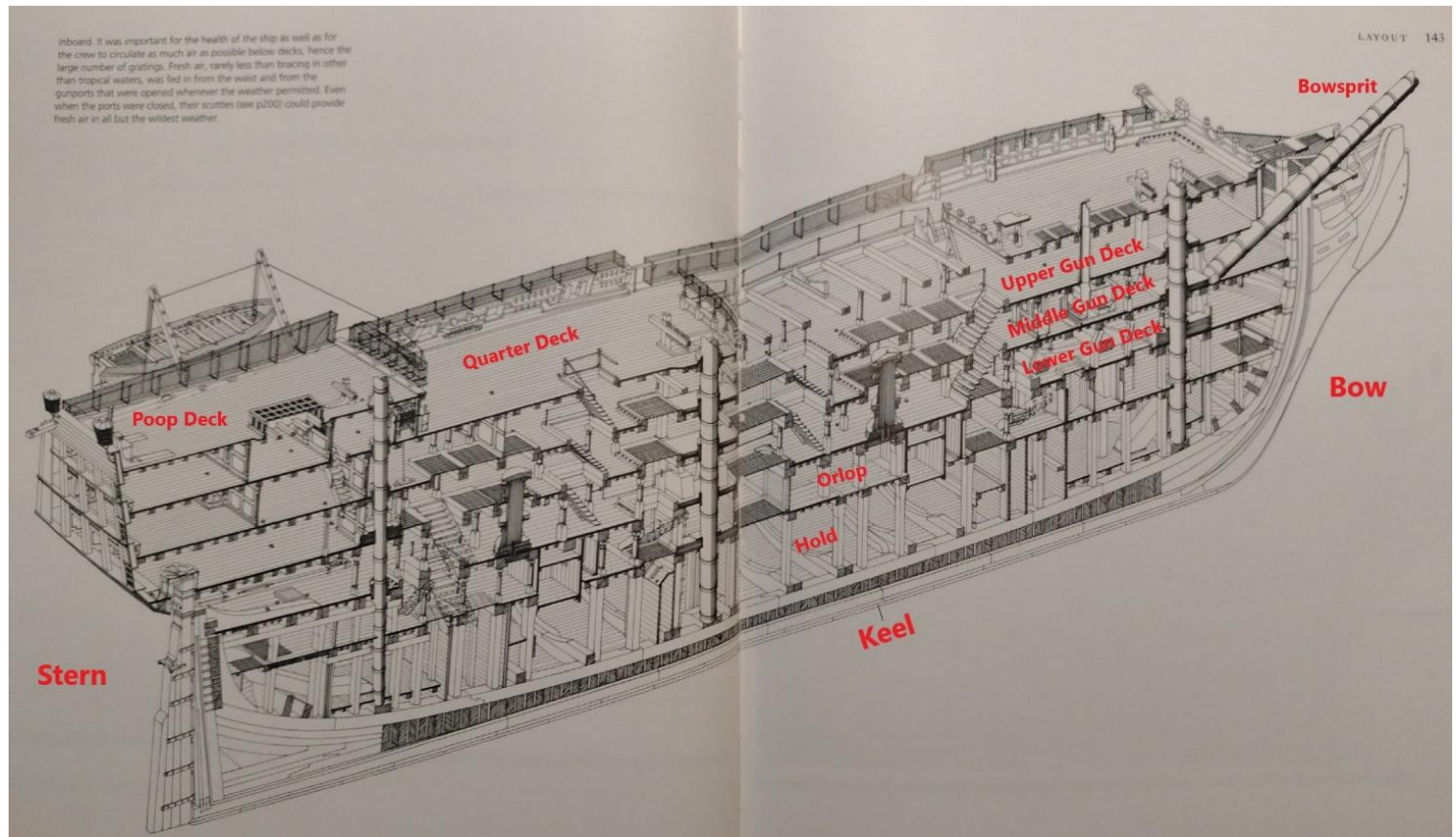


Figure 1: Longitudinal cross section of HMS Victory. Diagram from McGowan 1999, labels by author

2.2 HMS *Victory*

The history of HMS *Victory* ([Fig. 2](#)) is long and varied. It has filled several books and has been the topic of many theses and dissertations (Ballantyne & Eastland, 2005; Bugler, 1966; Westbury, 2019). This section will cover the highlights of her history that make her a national treasure and those points of significance relevant to the DWB and *Victory* story.

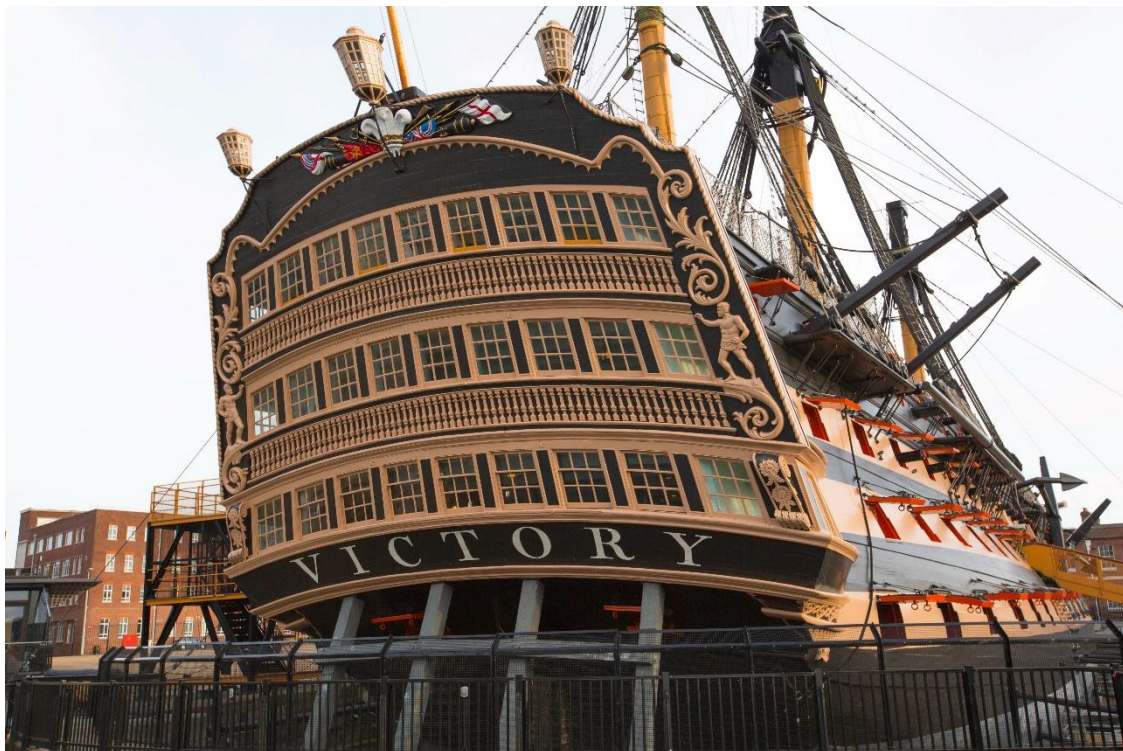


Figure 2: HMS *Victory* viewed from the stern end of the dry dock. Image © The National Museum of the Royal Navy

2.2.1 Construction

HMS *Victory* was built as a 104-gun, first rate ship of the line, and is the oldest commissioned warship in the world (Bugler, 1966: 1-11). Building commenced in Chatham Dockyard in 1759, using English oak for the planking and elm for the keel (*Ibid.*). The European timber used to build the rest of the ship, having primarily come from existing stockpiles, was more than usually well-seasoned (Ballantyne & Eastland, 2005: 38). Over 2500 oak and elm trees were used in its construction (*Ibid.*). However, the Seven Years War for which it was commissioned ended before its construction was completed, and it

consequently was not launched until 1765 (Bugler, 1966: 7). This gap prior to launch meant that, unlike many ships of the time, the timber was given 3 years (rather than the usual couple of months) to season (more details in [section 2.4](#)), helping her subsequent longevity (McGowan, 1999: 11).

2.2.2 Action

HMS *Victory* spent the years immediately following its launch “in ordinary” (not officially in service) on the River Medway (Ballantyne & Eastland, 2005: 40). It was finally commissioned in 1778, in the midst of the American War of Independence (*HMS Victory*, 2022), and officially began its life of service. It saw action off Ushant (1778) as part of the American Revolutionary War, then saw several battles during the French Revolution, most notably at the Battle of St. Vincent (1787), during which it was nearly wrecked (Ballantyne & Eastland, 2005: 44-57).

It must be noted at this stage that ships during this period were not designed to last long periods of time. All wooden ships begin to deteriorate after launch (McGowan 1999: 14), so regular repairs were commonplace, as were substantial repairs after action. They were expected to last approximately 18-20 years (*Ibid.*). In 1797, already past its expected lifespan, *Victory* was declared unfit for service and became a designated hospital ship, and the decision was made to have it refitted as a prison ship (*HMS Victory*, 2022). However, this alteration would have been irreversible, and the loss of HMS *Impregnable* in 1799 (another first-rate ship) saw that decision reversed (*Ibid.*). *Victory* subsequently underwent a costly refit between 1800 and 1803 to bring it up to current naval standards (*HMS Victory*, 2022; McGowan, 1999: 20). Although ships were regularly repaired or refitted throughout their lifespan, particularly after action or damage while at sea, refits of such a scale and expense were rare, especially given its age at the time (McGowan, 1999: 22).

HMS *Victory* is most famous for being Admiral Nelson's flagship in the Battle of Trafalgar (1805) ([Fig. 3](#)) (Adkins, 2005). *Victory* sustained substantial damage as a result of the action at Trafalgar: losing its mizzen topmast, studding sails, the hull riddled with holes, and more (McGowan, 1999: 22-25). Urgent repairs were carried out in Gibraltar, but upon its return to Britain, it underwent more extensive repairs (*Ibid.*). The triumph of the battle and the hero-cult of Nelson (the reverence of the man in the decades and centuries following his death- see Westbury's 2019 thesis for a comprehensive analysis) secured the ship's everlasting fame, and it became a symbol for Britain's naval prowess (Westbury, 2019). Not only is it exceptional because of the action it saw, but *Victory* was already 40 years old by the time of Trafalgar, well past its expected lifespan, and it continued to serve in the years to come (McGowan, 1999: 22).



Figure 3: The Battle of Trafalgar, 21 October 1805 by J.M.W. Turner. HMS *Victory* is the central ship. Although heavily stylised, the damaged sails and leaning masts hint at the extensive damage the ship sustained during the battle. Image © National Maritime Museum, Greenwich, London. Greenwich Hospital Collection

2.2.3 Later life

2.2.3.1 19th century

With the advent of the Industrial Revolution and steam technology, wooden sailing ships became largely obsolete. Its revered status meant that the Royal Navy was reluctant to break it up. In 1812, it was relegated again to ordinary in Portsmouth Harbour, marking the end of its active fighting life (Ballantyne & Eastland, 2005: 183). Although it experienced occasional periods of being recommissioned as a flagship, it never left Portsmouth Harbour again (Victory Conservation Management Plan, 2016).

Another expensive and large-scale refit in 1814-15 saw the most drastic change to its appearance (Bugler, 1966: 32). Its square bulkhead was replaced with a round bow to keep it up-to-date with naval requirements, which it had to maintain as a naval patrol ship (McGowan, 1999: 27). After this large structural change, it only saw minor repairs until 1857, when it had another sizeable repair. During this work, it was permanently moored in Portsmouth Harbour ([Fig. 4](#)) (*Ibid.*). The ship sprang a major leak in 1887, and was docked for repairs, during which its lower masts were replaced with the hollow ferrous-metal masts from HMS *Shah* (*Ibid.*).



Figure 4: HMS *Victory* afloat in Portsmouth Harbour taken between c.1890-1900. When compared to both modern and historic images, you can see evidence of structural changes, highlighting the changing nature and regular repairs of wooden ships. Image from Library of Congress (2024)

In 1903, it was accidentally rammed by HMS *Neptune*, causing damage to the orlop deck, and prompting urgent repairs (Victory Conservation Management Plan, 2016). It was berthed in dry dock and repairs made (*Ibid.*). It became increasingly clear after the ramming incident that preserving the ship would not be possible while keeping it afloat in the harbour. Although it was used as a training school by the Royal Navy and the Scouts, by 1920, it was at risk of foundering at its moorings and more drastic measures were required to ensure its preservation (McGowan, 1999: 30).

2.2.3.2 Dry docking and restoration to Trafalgar condition

In 1922, it was permanently dry docked in Berth 2 of Portsmouth Historic Dockyard (Bugler, 1966: 37), where it remains to this day. The decision was made to restore it as closely as possible to its Trafalgar condition by the Board of Admiralty and the Society for Nautical Research, but there was contention over funding (McGowan, 1999: 30-31). The Board of Admiralty was willing to fund any repairs necessary to maintain the ship but would not provide the funds for restoration (i.e. removing the rounded bow) (*Ibid.*). The Society for Nautical Research launched an appeal, *Save the Victory!*, to raise the funds (Westbury, 2019: 27), with the plan to begin work once the fund had reached £50,000 (McGowan, 1999: 33). The campaign raised £30,000, and with a £50,000 donation from Sir James Caird, a Dundee ship owner, to make up the difference, work began in 1923 and was completed in 1928 (*Ibid.*). In addition to removing the round bow, changes made during the late Georgian and Victorian periods were removed, such as an octagonal skylight, the deckhouse, raised bulwarks, fire-engine pump, and partition changes ([Fig. 5](#)) (Victory Conservation Management Plan, 2016).



Figure 5: The Nelson Touch' by W.L. Wylie c.1925. Painting the workers undertaking 'The Great Repair'. Image from Society for Nautical Research (2024)

2.2.3.3 Remainder of the 20th century

Following the restoration to its Trafalgar condition, little work beyond maintenance was carried out during the 1930s (McGowan, 1999: 40). However, it was during this time that freshwater, instead of seawater, was used for daily scrubbing of the decks (*Ibid.*). The introduction of further moisture without salt as a mild inhibitor to timbers already exposed to the elements greatly encouraged fungal decay and rot (*Ibid.*).

It was in 1932 that Deathwatch beetles (DWB) were first reported on the ship (Victory Conservation Management Plan, 2016). In 1937, 1496 beetles were captured (*HMS Victory Deathwatch Beetle Collection Records, 1932-1938*), showing a widespread and intense infestation. It is uncertain whether the beetles were noticed on the ship prior to this point after dry-docking, but the issue was clearly substantial enough in 1932 to warrant reporting. There are no records as to whether there were any DWB on the ship prior to *Victory's* drydocking, when the wood was kept in more saline conditions. The lack of research or reported evidence of infestations while on the sea means that it is impossible to determine. It is difficult to determine the date of much of the historical damage that exists on the ship as the infestation has been there for so long.

The damage caused by the rot and the DWB, in addition to damage to the dry dock, hold, orlop and keel caused by bombs during WWII, prompted another large-scale repair between 1955 and 1964 (McGowan, 1999: 40-1).

There were no more large-scale repairs in the subsequent decades, but regular repairs to maintain the structural integrity of the ship continued to take place (Victory Conservation Management Plan, 2016). More replacement work took place in the 1980s, replacing much of the outer hull planks with teak and iroko (McGowan, 1999: 50). It was during this period that concerns of retention of historical fabric became more prominent (Victory Conservation Management Plan, 2016).

Deathwatch beetles continued to be a major source of concern, and a great deal of work went into trying to eradicate the infestation (*Ibid.*). Fumigation of the entire ship was carried out three times in the 1950s, which saw a subsequent decline in the number of beetles collected (McGowan, 1999: 100). But numbers rose again in the late 1960s to the early 1970s, and an annual spray treatment of the insecticide permethrin was implemented in addition to an insecticidal smoke (McGowan, 1999: 100). Even though the chemicals used had been successful in killing the beetles during laboratory tests, the fumigant and spray failed to fully penetrate the sizeable timbers on the ship. Due to the cryptid nature of the beetles, the majority of the infestation would not have been exposed to the chemicals at all. Numbers continued to increase. Although the battle waged against the beetles, active collection ceased in the 1980s with the replacement work (although there had also been a brief cessation during WWII), as the belief was that the beetles would not infest the new teak and iroko timbers (Victory Conservation Management Plan, 2016). A system of passive blunder traps was introduced around 2005, but the system was not managed by anyone with conservation training, so was ineffective (Davis pers. comm., 2024).

2.2.4 The National Museum of the Royal Navy

The National Museum of the Royal Navy (NMRN) took over ownership from the Royal Navy in 2012, but the ship continued being maintained by BAE Systems,

an independent contractor with no specialist heritage conservation knowledge. The museum started preserving and maintaining the ship directly in 2016 (Victory Conservation Management Plan, 2016). It is now a key feature of the Portsmouth Historic Dockyard experience.

Victory is currently undergoing large-scale conservation work, which began in 2021, where the goal is to ensure its survival with only routine maintenance for the next 50 years ([Fig. 6](#)) (*Victory Live*, 2022). This project is taking a multi-faceted approach. Not only will it replace much of the outer planking and rotten timber with oak, but a great deal of research into the more endemic problems *Victory* faces have been funded in an effort to address these issues more effectively (Davis, 2021). This thesis is part of that research aspect, focusing on the DWB activity on the ship.

This concludes the brief overview of the history of *Victory*, from the laying down of its keel in 1759 to the present day. As demonstrated, it has undergone a tremendous number of refits and repairs throughout its lifetime. Refits and repairs are in keeping with the working nature of ships, and *Victory* is still a commissioned warship. It must be noted that most of the repairs are on the outer edges of the ship which are more exposed to the elements. The closer to the midline, the older the timbers. *Victory* still retains much of its original keel. The NMRN has a conservation management plan based on retaining and preserving as much of the original material as possible, but compromises must be made to ensure the structural integrity and survival of the ship.



Figure 6: Aerial view of HMS *Victory* undergoing the current conservation programme (2023). Image © The National Museum of the Royal Navy

2.3 Deathwatch Beetles

Deathwatch beetles (*Xestobium rufovillosum* de Geer) are famed for their folkloric associations with dying and death, for which they appear in many literary works, like those below. The tapping for which they are best known was most commonly heard during the quiet death vigil over a person's sickbed, causing the tapping sound to be thought of as a herald of approaching death (Allen, 1698; *Deathwatch Beetle*, 2021).

“Next the ghastly ticking of a death-watch in the wall at the bed's head made Tom shudder—it meant that somebody's days were numbered” *The Adventures of Tom Sawyer* (Mark Twain, 1876; Ch. 9 pg. 1)

“Beset with plainful gusts, within ye hear
No sound so loud as when on curtain'd bier
The death-watch tick is stifled.”
From *Endymion* (John Keats, 1818; Book 4 verse 34)

“And then from all over the dresser came a chorus of little tapplings, all sounding together, and answering one another, like watch-beetles in an old worm-eaten window-shutter—
Tip tap, tip tap, tip tap tip!”
The Tailor of Gloucester (Beatrix Potter, 1903; pg. 34)

“The deathwatch beetle
earned its name
not from its ugliness
or our terror
of insects
but simply because of the sound
it makes, ticking.”
From *The Deathwatch Beetle* (Linda Pastan, 1998)

However, despite knowledge of their existence for centuries as a result of their infamous tapping, remarkably little scientific investigation has gone into the DWB (see [Chapter 3](#)). As demonstrated in [Section 2.1](#), there is a long-standing infestation of DWB on *Victory*. This section will focus on basic facts about the beetles, particularly their distribution, anatomy, and lifecycle. However, it must be noted that given the minimal amount of scientific research into the DWB, few of these facts can be considered definitive.

2.3.1 Distribution

Deathwatch beetles are found in temperate forests, being particularly prevalent in Europe and Asia, but also noted on the East Coast of the United States (Bouchard, 2014; Fisher, 1937b: 603; Hickin, 1975). However, it is believed that they are not native to North America, and instead have been introduced (Leng et al., 1920: 358; Robinson, 2005; *UK Beetle Recording*, 2023). They are also found in New Caledonia in the Pacific, but that appears to be an outlier and is likely to be the result of contaminated furniture transported to the island (*Ibid.*). Their limited geographical range suggests that they prefer more temperate climates.

2.3.2 Ecological Niche

DWB are saproxylic organisms, meaning they rely on dead or decaying wood for part of their lifecycle (García et al., 2018; Gimmel & Ferro, 2018; Lassauce et al., 2011). These organisms, of which fungi and beetles constitute the most in terms of number of species, aid in degradation (*Ibid.*). When trees die or begin to decay, ecological succession of species dictates that different elements of decay are carried out by different species (Nieto & Alexander, 2018), of which DWB form a part. They serve to help cull weak trees, allowing for new growth, and decomposers of trees in forest systems allow for nutrient recycling (García et al., 2018; Nieto & Alexander, 2018). DWB have an apparent preference for decaying hardwood, specifically willow and oak, but have been noted to attack elm, beech, hornbeam, sycamore, hawthorn, chestnut, alder, walnut and some softwoods like pine on occasion (Alston, 1922; Fisher, 1937b; Menendez, 1990).

They have become considered economic pests in the timber industry and a major pest in historic buildings as infestations cause structural damage and loss of historical fabric. Their prevalence in historic buildings may be due to a loss of habitat, as forested areas within the UK and Europe are continually decreasing and are heavily managed (Nieto & Alexander, 2018).

DWB do have natural predators and parasites, the most notable being the *Korynetes caeruleus* beetle (which had been present on HMS *Victory* until the insecticide campaigns were conducted) (McGowan, 1999: 100-102) and the parasitic *Pyemotes* species mites (Menendez, 1990: 42).

2.3.3 Beetle Anatomy

DWB are small, wood-boring members of the *Coleoptera* family. They range between 5-9mm in length, with the females typically larger than the males, and are reddish-brown with yellow hair (called setae) giving them a mottled or spotted appearance (*Death Watch Beetle Identification Guide*, 2021). The setae attract wood dust, further camouflaging the beetle, and making them challenging to spot on degraded wood surfaces.

Their body is made up of three main parts: the head, thorax, and abdomen (Fisher, 1940a). The head is normally hidden by the thorax but is more apparent from the underside or side ([Fig. 7-9](#)). Their wings are hidden under the elytra (hardened forewings) (*Ibid.*).



Figure 7: Dorsal view of a Deathwatch Beetle. Image © Malcolm Storey, www.bioimages.org.uk



Figure 8: Lateral view of a Deathwatch Beetle. The head is usually tucked within the thorax and may not always be visible when viewed dorsally. Image © Malcolm Storey, www.bioimages.org.uk



Figure 9: Ventral view of a DWB. Image © Malcolm Storey, www.bioimages.org.uk

2.3.4 Lifecycle

Studies investigating the DWB lifecycle have observed it to range between 1-13 years (Belmain, 1998), the length of time varying with environmental conditions. DWB metamorphosis follows the same pattern as many other beetles, but the length of time for each of the initial stages and the number of larval instars (stages) is uncertain (Belmain et al., 2001). Adults only appear to live for 6-10 weeks, with females living longer than the males (Fisher, 1937b). [Figure 10](#) provides a useful summary of the metamorphic cycle (Birch & Menendez, 1991).

The adults usually begin to emerge in late spring, with peak emergence in May/June, but they do continue to emerge throughout the summer (Belmain, 1998) (and climate change is likely to impact this seasonality). By late summer, most of the adults have emerged, laid eggs, and died. On the ship, adults have been found as early as February (*HMS Victory: Integrated Pest Management Strategy*, 2018), with most adults dead by mid-July (pers. obs.).

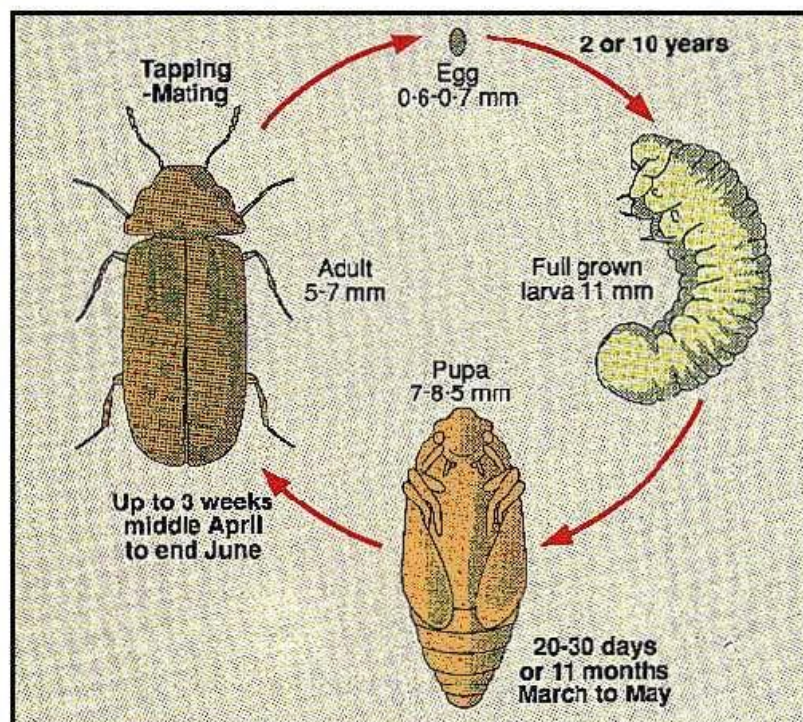


Figure 10: Lifecycle of the Deathwatch beetle. The length of time and months allocated to each stage of the cycle are approximations. From Birch & Menendez, 1991.

2.3.4.1 Eggs

When a female is ready to oviposit (lay eggs), she searches for suitable crevices or cracks for her eggs. Eggs are deposited singly, in pairs or in small clutches (Hickin, 1975). A cement-like substance adheres eggs together and to the wood (*Ibid.*). The number of eggs a female lays varies considerably (29-201), but tends to be between 40-60 (Fisher 1938; Hickin 1975). Eggs are pearly-white and lemon-shaped, approximately 0.6-0.7mm in length and their greatest width approximately 0.4-0.5mm (Fisher 1938). When conditions are suitable, the larvae will emerge from the eggs, although what conditions are considered suitable has not been scientifically concluded.

2.3.4.2 Larvae

Once it emerges from the egg, the larva walks over the surface of the wood in the area from which it emerged before starting to tunnel (Hickin, 1975). This surface may or may not be an external one. It is the larval stage that causes the majority of the damage to wood, as their ingestion of the wood creates the tunnels, also called galleries. The spinules and setae (bristle-like structure) on their body in conjunction with hydrostatic pressure allow them the purchase they need to bite the wood with their jaws (Fisher 1937; Hickin 1975). The wood is then ingested and digested before coming out as the distinctive, ovoid frass (excrement) ([Fig. 11](#)) (*Ibid.*).

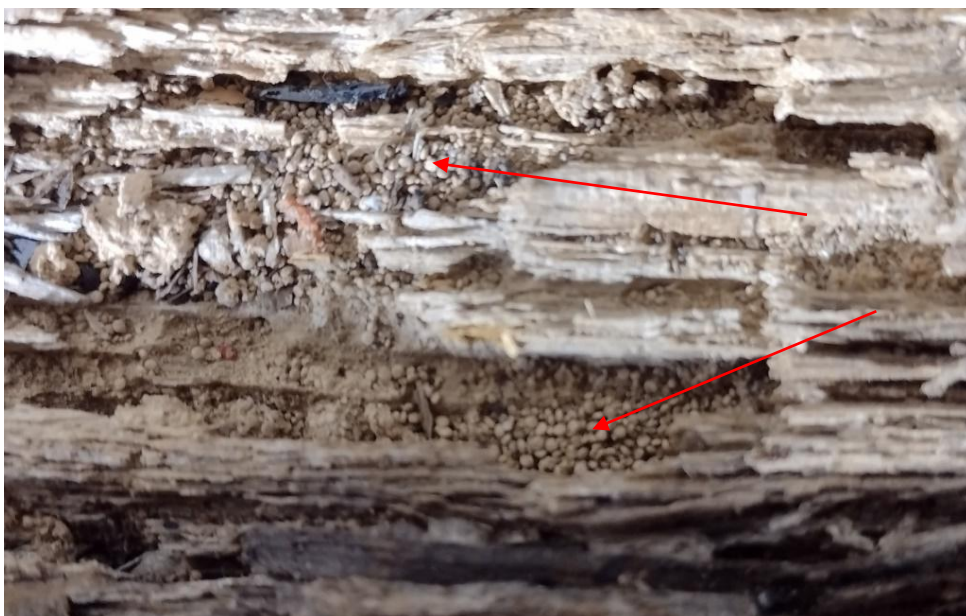


Figure 11: Deathwatch beetle frass on decayed wood

Fully grown larvae ([Fig. 12](#)) are creamy white in colour and are fleshy, soft, and usually held in a hook-shaped position, with the thoracic region swollen (Fisher 1937). They have six small legs that help with movement and can be up to 11mm in length (*Ibid.*).



Figure 12: Deathwatch Beetle larvae. From *Victory IPM*, 2023

2.3.4.3 Pupation

Once the larva is fully grown (can take between 1-13 years), it creates a pupation chamber and pupates (Hickin, 1975). The cuticle of the pupa is thin and soft, and there is flexibility in the abdomen (*Ibid.*). The eyes progressively darken throughout this stage, starting as a milky white before becoming dark brown. The pupation stage is the only stage of the lifecycle where the beetles can easily be sexed ([Fig. 13](#)) (Fisher 1937). The pupae can range between 7-8.5mm in length, and 2.5-3.5mm wide, with the female pupae generally being larger (*Ibid.*). It is uncertain how long this stage can take, with estimates varying between 3-4 weeks and 11 months (Belmain, 1998; Birch & Menendez, 1991). Whether a wintering or hibernation period is necessary for development is also unclear, as there is debate as to what time of year pupation occurs and what triggers it (Belmain, 1998). Larval development and pupation are notoriously difficult to observe in woodboring beetles (*Ibid.*).

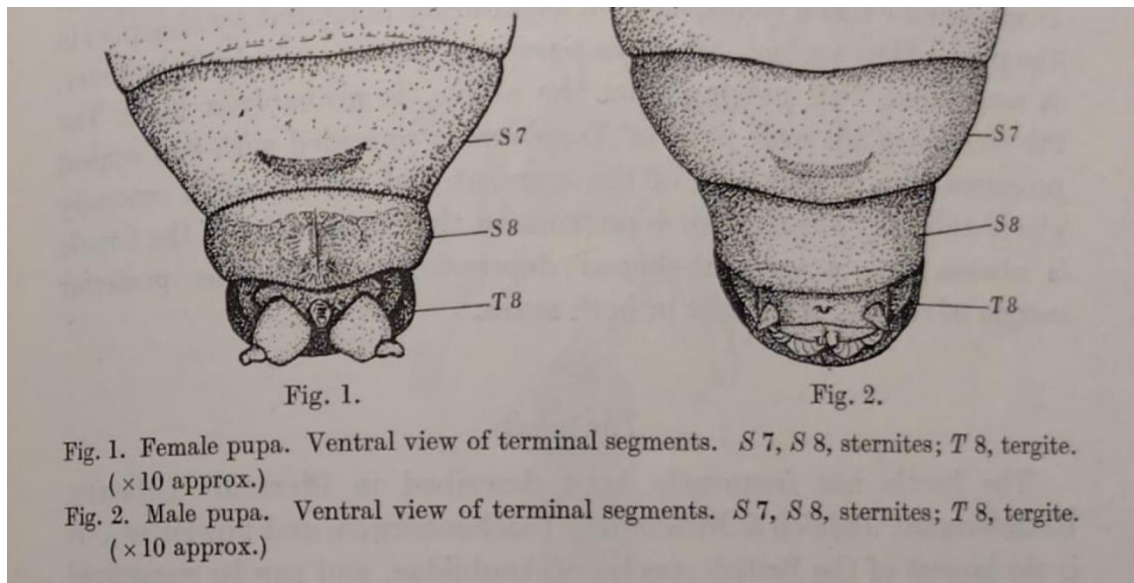


Figure 13: Comparative diagrams of male and female pupa, demonstrating the sexual dimorphism. From Fisher 1937: 605.

Eventually, the adult beetle emerges from the pupation chamber, using their jaws to create the distinctive round exit (or flight) holes 3-6mm in diameter, though they do not ingest the wood (Fisher 1937; Hickin 1975). If there is anything immediately adjacent to the timber from which they are emerging, they will chew through that as well. They have been observed to chew through lead roofing tiles on occasions where the roofing timbers are infested (Belmain, 1998; Kimmins, 1933).

2.3.4.4 Adulthood and mating

Upon emergence from the pupation chamber ([Fig. 14](#)), the adult beetle's main prerogative is to find a mate and reproduce (Hickin, 1975). In order to find a mate, the beetle tucks its head more tightly into its thorax ([Fig. 15](#)) and hits its head 4-11 times on the substrate at a frequency of approximately 10-11Hz (Goulson et al., 1994; White et al., 1993). Once it has heard a response, it moves in the direction of the noise, regularly stopping to tap and listen again to orient itself (Goulson et al., 1994). Both males and females tap at the same rate and frequency, however the males are usually the ones to initiate the tapping, to which the females will reply, responding more often to those with a higher number of taps, and creating a tapping duet (White et al., 1993). As the initiators, the males move and tap more than the females, who largely remain

stationary (*ibid.*). As this behaviour is easy to observe, this is the one aspect of the DWB that has been studied in great detail. This tapping behaviour is what the beetles are most famous for, and it is likely that knowledge of the noise and the associated folklore predates the knowledge of the beetle.



Figure 14: Adult Deathwatch beetle emerging from wood. Image © Daniel Radix 2004

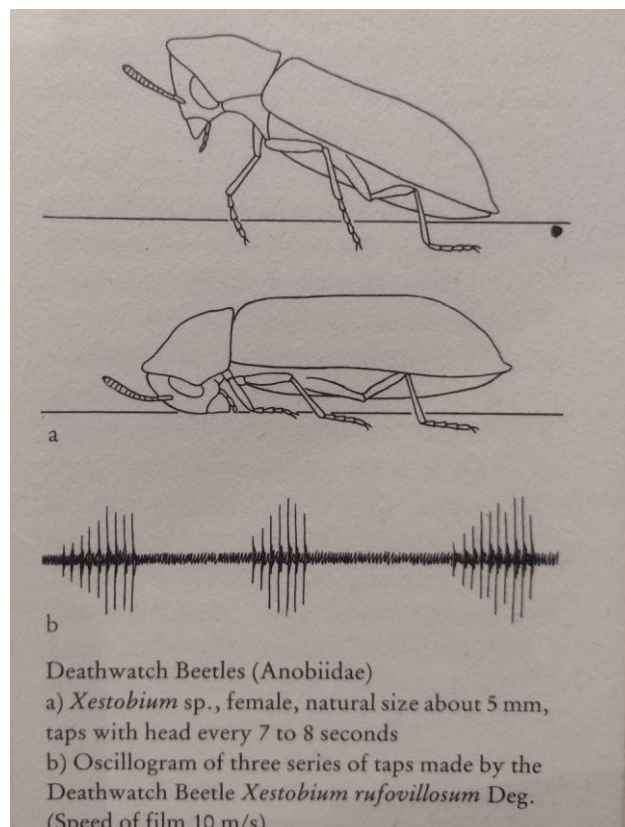


Figure 15: Diagram of Deathwatch beetle tapping and oscillogram showing frequency and level of taps. From Klausnitzer 1983; 115

Once the beetles meet, the male mounts the female and when coition has been established, it falls backwards and rests on its back, tightly tucking its legs and antennae (Fisher 1938). The female, with the male still attached ([Fig. 16-17](#)), is able to move around freely (*Ibid.*).



Figure 16: Mating DWB, where the female drags the male on his back once coition is established. Image © Daniel Radix 2004



Figure 17: Beetle coition in progress. Photo courtesy Brooke Oakley

Adults have never been observed to feed. The sole objective of their existence appears to be to find a mate and begin the cycle again. Females have been observed to live up to 10 weeks after mating, and the males 6-8 weeks (Fisher 1938). This difference is likely due to the need for oviposition, as it may take some time for the female to deposit all her eggs.

2.4 Wood Structure and Anatomy

As this project is investigating the tunnelling activity of the DWB, an understanding of the structure and anatomy of wood is necessary and will regularly be referred to throughout.

Wood, the material that makes up the stem and branches beneath the bark of a tree, is composed of three structural polymers: cellulose (40-50%), lignin (20-40%) and hemicellulose (20-30%) (McCaig & Ridout, 2012; Unger et al., 2001). Cellulose is arranged into microfibrils, which are responsible for the tensile and bending strength of the wood (*Ibid.*). It is also hydrophilic (*Ibid.*). Lignin holds the

microfibrils in position within cell walls, giving the cells compressive strength (*Ibid.*). It also lines water transportation systems throughout the tree due to its hydrophobic nature. Hemicellulose forms the interface between the lignin and cellulose polymers, cross-linking the fibrils, and giving the tree flexibility (*Ibid.*).

The wood is surrounded by bark, with a microscopic layer of cells between called the cambium ([Fig. 18](#)) (Dinwoodie, 1989; Meier, 2023c). This layer is responsible for the horizontal growth of the tree by forming new wood cells to perform a variety of functions (*Ibid.*). These active cells make up the sapwood, through which water is conducted in the form of sap from the roots to the leaves (*Ibid.*). Sclerenchyma cells containing the lignin form the vascular tissue, but the majority of the new cells are parenchyma cells, which are thin-walled undifferentiated cells that can perform a variety of different functions (Dinwoodie, 1989; Meier, 2023b; Petruzello & The Editors of Encyclopaedia Britannica, 2018). Some cells, formed into rays, run perpendicular to the rest of the wood fibres, and serve to channel nutrients between the cambium, sapwood and pith (Dinwoodie, 1989; Meier, 2023b).

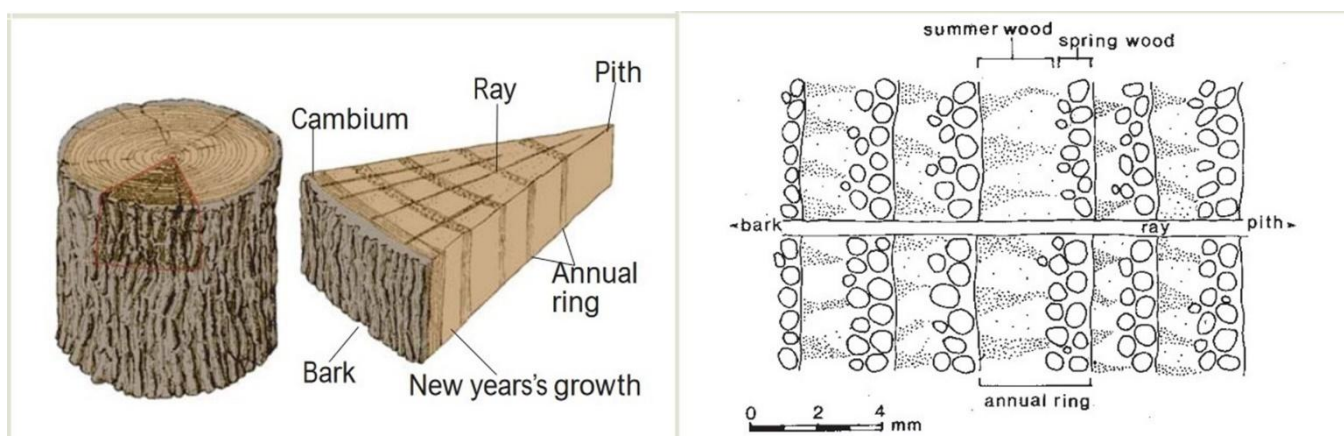


Figure 18(a) and (b): (a- left) Macro- and (b- right) microscopic structure of oak wood. Diagrams from *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*, 2004: 8 originally drawn by J Dobie

The size of the sapwood is proportional to the size of the leafy crown to balance water conduction (less energy efficient) with the needs of the leaves and the size will remain constant as the cambium continually adds to it (McCaig & Ridout, 2012). As the tree grows, the innermost core, or pith, of the wood is no longer needed to conduct water. The cells then die and much of the nutrients

they contain are re-absorbed (Dinwoodie, 1989; Meier, 2023c). The deposition of metabolic processes (extractives), i.e. resins, takes place as well (Dinwoodie, 1989; McCaig & Ridout, 2012). These dead cells form the heartwood. Heartwood is much more resilient than sapwood after cutting as the empty vessels of the dried sapwood contain oxygen (necessary for decay) (*Ibid.*).

Wood and its timber is divided into hardwoods and softwoods (Dinwoodie, 1989; Meier, 2023c). The names were originally based on their working properties, but now are attributed to the type of tree from which they originate and how they conduct water (McCaig & Ridout, 2012). The following section will provide an essential overview of the types of wood, their basic structure and anatomy that will be referred to throughout the thesis.

2.4.1 Features and characteristics of hard- and softwoods

2.4.1.1 Hardwoods

Hardwood comes from angiosperms; trees that are broad-leafed and flower bearing (Dinwoodie, 1989; McCaig & Ridout, 2012; Meier, 2023c). The majority are deciduous, and comprise of such trees as oak, beech, teak, and walnut (*Ibid.*). There are three main categories of hardwoods based on the arrangement of vessels ([Fig. 19](#)): ring-porous, diffuse-porous and semi-ring-porous (Hather, 2000; Meier, 2023b; Wheeler et al., 1989). Ring-porous, where the large earlywood vessels form rings that correspond to annual growing seasons, are common in temperate climates (*Ibid.*). Diffuse-porous, where there is no distinction between pore arrangement in early to late wood, are more common, but not limited to, tropical zones, where the growing season is throughout the year (*Ibid.*). Finally, semi-ring-porous has features of both - it does not have clear rows, but the vessels decrease from the early to latewood (*Ibid.*).



Figure 19: Different porosity types found in hardwoods. Image from Meier 2023b

As oak is the predominantly DWB infested timber on *Victory*, and the most common wood in cases of DWB infestation (based on reports and investigations thus far), its properties will be discussed. Oak is a ring-porous hardwood with columns of water conducting cells throughout the trunk and fibrils in between for strength (Dinwoodie, 1989; Meier, 2023a). Wider vessels are laid down in spring to maximise water conduction, with smaller vessels in autumn and winter, thereby forming the characteristic rings (McCaig & Ridout, 2012). Interestingly, the number of sapwood rings in oak regardless of age is relatively consistent (*Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates*, 2004). Oak has both uniseriate (1 cell wide) and multiseriate (multiple cells wide) rays (Wheeler et al., 1989). Once the oak (except for red oaks) is of sufficient size for the formation of heartwood, tyloses (foam-like structures that block large vessels) are formed in the transition between the sap and the heartwood (*Ibid.*). These tyloses make the oak heartwood extremely hardy and inhibit decay (Gale & Cutler, 2000; Meier, 2023b).

This durability makes oak (class 2 on durability scale) one of the ideal woods for shipbuilding and construction (*BS EN 350-2*, 1994; McGowan, 1999). To achieve this peak durability, a period of seasoning is required. Seasoning is the

process of drying out the wood to reduce the moisture content of the timber, making it less susceptible to shifting and major dimensional changes (Edmondson, 2019, 2020; *What Is Seasoning of Timber?*, 2016). It can be achieved through the more traditional air-drying or the accelerated kiln-drying (*Ibid.*). When air-dried, the process can take years to fully complete for oak, particularly in damper climates (*Ibid.*). During shipbuilding, the frames are first laid out, before a further period of seasoning was done to allow the timbers to settle into their curved states (Christopher, 2014; McGowan, 1999). Typically, ships in the 18th century were given up to 12 months to season in frames (*His Majesty's Navy*, 1771; Christopher, 2014). *Victory's* original frames, however, were given 3 years to season as the war for which it was commissioned ended during construction and was followed by a brief period of peace (Christopher, 2014; McGowan, 1999). It is this extra drying time that is suspected to have been responsible for the survival of *Victory* beyond the usual and expected lifespan for the wooden ships of the time period, enabling its survival to the Napoleonic Wars that forever secured its fame (McGowan, 1999).

2.4.1.2 Softwoods

Softwood comes from gymnosperms, or coniferous trees, most of which are evergreen (McCaig & Ridout, 2012). Pines, spruces, and firs are some of the most well-known softwoods. Although DWB appear to mostly infest decayed hardwoods, they have still been observed in softwoods (Alston, 1922; Fisher, 1937b). There is a pine beam in the lower hold that is actively infested on *Victory* (pers. obs.). Although no softwood was analysed during the course of this project, a basic overview of softwoods will be given to provide context and contrast to the properties of hardwoods.

Although formation of the sapwood and heartwood is the same, softwoods are structurally different (Meier, 2023c). Water conduction and strength are both provided by closed-ended cells called tracheids, which are connected via valves that open and close, thereby preventing bubbles in the sap (McCaig & Ridout, 2012). This indirect system makes the tree more resilient to harsher environments, which is why many are more associated with colder climates

(*Ibid.*). Strength increases through lignification and thickening of the cell walls (*Ibid.*). Early wood (produced in the spring in temperate climates) has thinner cell walls to maximise conduction of water, whereas the late-wood (produced in late summer in temperate climates) has thicker walls to promote strength, but is less able to conduct water (McCaig & Ridout, 2012; Meier, 2023c). In some species of softwoods, the early wood is lighter in colour than the darker late-wood, creating annual growth rings (Meier, 2023d). The presence of intercellular canals or resin canals is also a distinction between soft and hardwoods, and is a feature unique to conifers (Meier, 2023d; Richter et al., 2004). These tubular ducts conduct secondary products like sap or resin along the length of the tree (*Ibid.*).

2.5 Integrated Pest Management (IPM) in museums

2.5.1 What is IPM?

Integrated pest management (IPM) is a method of pest control, originally developed for agricultural use, that does not rely on the regular use of pesticides (Lima et al., 2020; Pinniger & Winsor, 2011; Querner, 2015). It does this by taking a holistic view to reduce the risk of pest infestation by using knowledge of biology and lifecycle of pests to prevent the conditions in which they thrive from occurring (*Ibid.*). IPM began to be adapted for museum and heritage use in the 1980s (*Ibid.*), although it took time for it to become more widespread. Although more interventive treatments for dealing with infestations exist, these can be costly and present a danger to human health. Preventing infestations in the first place or changing the environment to prevent conditions in which pest species thrive are safer and more effective solutions.

Each museum and heritage site will tailor their IPM policy to their individual needs, but common methods included in policies may involve (Pinniger & Winsor, 2011; Querner, 2015):

- Good housekeeping and keeping things clean.
- Keeping environmental conditions below thresholds - temperature ranges, ventilation, and airflow.

- Quarantining new objects and infested objects to prevent spread.
- Monitoring to catch infestations in early stages, though the use of strategically placed blunder traps.

2.5.2 Application to HMS *Victory*

NMRN introduced IPM to *Victory* and the other historic vessels in their care when they took over maintenance in 2016 (Davis, 2020; *Victory IPM Strategy*, 2023). However, historic vessels like *Victory* present unique challenges to the implementation of IPM strategies, as they are often exposed to the elements and cannot easily be subjected to climate controls.

Although dry-docked, *Victory* is still a commissioned ship, and is occupied 24/7 by the Royal Navy for offices and events, in addition to its status as a visitor attraction, which drew nearly 200,000 visitors in 2023 (Britton, 2024). This presents a challenge between the needs of the ship from a conservation standpoint and its status as a commissioned ship and visitor attraction (McCormack, 2016).

In an ideal situation, the best way to ensure the survival of *Victory* would be to enclose it in a custom building where the environment could be rigorously controlled, similar to the *Mary Rose*. However, this is not realistic or feasible. While enclosing the ship may solve some problems, it may create others, like shrinkage and movement, that would be irreversible. The historic site and berth upon which *Victory* is situated, including the skyline, form a part of the intrinsic value of the ship (Victory Conservation Management Plan, 2016) and are protected themselves as sites of historical import (*Ibid.*). The cost of such a structure is also prohibitively expensive. Although the current conservation work is not cheap, it makes use of the available resources, expertise, and structures already in place, and the goal is to limit the amount of interventive work required in future.

The current IPM strategy implemented at the museum is aimed at all the pests present on the ship, of which the DWB is the most prevalent. It lays out the team with the responsibility for implementing the policy and their roles and

actions to be carried out. The following paragraphs provide a brief summary of the current (2023) strategy.

Surveys of active pest species present are regularly carried out by the shipkeepers and conservators (*Victory IPM Strategy*, 2023). Although DWB remain the main concern, other wood decaying pests, such as wood weevils, longhorn beetle and millipedes have been found in the past along with other pests such as woodboring wasps, booklice, silverfish, and moths (*Ibid.*). These surveys are performed using blunder traps, which are monitored monthly for DWB numbers and visually inspected for other species (*Ibid.*). The traps have to be placed strategically around the ship, while also ensuring they are not visually obtrusive or accessible to visitors, who may pick up and move them, decreasing efficacy and impacting data (Pinniger & Winsor, 2011). Traps are placed against floor-to-wall angles and in corners wherever possible (as these areas are more attractive to insects), and replaced when the adhesive fails or the number of insect bodies becomes attractive to scavengers (*Victory IPM Strategy*, 2023).

The daily cleaning regime of vacuuming and dusting was updated to better reflect conservation aims in October 2016 by adding a supplement of a rolling, long-term and targeted deep cleaning in areas of the ship off the visitor routes and in neglected areas (*HMS Victory IPM Strategy*, 2018).

Environmental conditions of temperature and humidity, heavily impacted by the external weather, are continuously monitored throughout the ship through the use of data loggers (*Victory IPM Strategy*, 2023). The data collected thus far shows that the conditions on the ship are not ideal - the Relative Humidity (RH) fluctuates greatly and remains consistently high during the winter months (*Ibid.*), with an overall average around 70% RH. Even in drier months when the temperature is warmer (RH and humidity are usually directly inversely proportional to each other), humidity remains high, suggesting other factors such as leaks and water ingress, visitors, and timber saturation (*Ibid.*). Water ingress is a particular concern - during a rainstorm, the author assisted with bucket placement around the bowsprit to mitigate significant water ingress. The covered scaffolding built for the current conservation programme may aid in

minimising the amount of water ingress for the duration it remains erected. The replanking as part of the conservation work should also help in reducing points of water ingress. A high RH and moisture content in timber is ideal for fungal and pest species to thrive, and the need to reduce humidity on the ship has been highlighted as a major concern and challenge (*Ibid.*). Portable heaters and dehumidifiers have been placed in strategic areas throughout the ship (*Ibid.*). In enclosed spaces such as the Orlop Bread Room, there has been a notable positive effect from such measures, with a ~10% average reduction in RH (*Ibid.*).

Successful remedial treatments for pest infestations (see [Table 1](#)), typically used on objects, do exist, and several are used by NMRN (* in table) on objects and small, easily enclosed areas of the ship (*HMS Victory IPM Strategy*, 2018; *Victory Conservation Management Plan*, 2016). Unfortunately, the size and scale of the ship means that these methods cannot be applied more widely. The strategy outlines why some measures are not applicable on the ship (i.e. fumigated pesticides are a serious health risk to staff and visitors), and what methods are available and may be used for smaller-scale items (*HMS Victory IPM Strategy*, 2018).

Table 1: Remedial Pest Treatments

Treatment	Description
Freezing (low temperature) *	Reducing the temperature to -30°C for at least 3 days or -18°C for at least 7 days will kill all stages of the insect lifecycle.
Pesticides/insecticide *	There is a huge range of options available, varying greatly in toxicity and application method. Historic pesticides were extremely hazardous to human health. Constrain, a conservation-approved water soluble-, permethrin-based repellent and insecticide and a boron solution are used by the museum and applied locally
Modified Atmospheric Processes (i.e. nitrogen or carbon dioxide)	Enclosing an object in a tightly sealed chamber at ≥24°C and ~50% RH with barriers impermeable to oxygen and flooding the chamber with a minimum of 60% CO ₂ or 99% Nitrogen for ≥3 weeks. A similar effect of Nitrogen can be achieved through the use of oxygen scavengers in the chamber (iron compounds that react with oxygen and remove it from the air). These methods will kill insects through oxygen deprivation (Oxygen levels <900ppm).
Humidity regulated heat treatment (heat/elevated temperature) *	Heating an object above 45°C will kill any insect. The process involves heating a humidity-controlled chamber to 52°C for at least 24 hours. This method was used to treat the capstan.

References: *HMS Victory: Integrated Pest Management Strategy*, 2018; Landsberger et al., 2019; Pinniger & Winsor, 2011; Strang, 1992

Further preventative measures, to reduce chances of new pest introduction and infestation spread, in addition to the cleaning routine and long-term improvement of environmental conditions (already discussed) include:

- Removal of food sources - replacing at-risk materials with synthetic replacements.
- Exclusion of food sources - checking foliage (used for events) for pests, removing food waste, shop consumables kept sealed and packaged, and all refuse (including food and foliage) removed and disposed off the ship.
- Use of repellent spray to deter moth and woodworm - Constrain used as a repellent to reduce spread of infestations to new areas.

Quarantining items and materials for repairs before they are introduced to the ship or stores prevents infestations being spread. However, no suitable quarantine space for objects had been identified at the time (2023), and inspection of existing stores found presence of pests including DWB (*HMS Victory: Integrated Pest Management Strategy*, 2018; *Victory IPM Strategy*, 2023). Materials for repair, particularly wood, have to be inspected and pre-treated against insect and fungal attack and the use of sapwood should be avoided wherever possible (*Ibid.*). The IPM strategy is currently being adapted for use in the workshop bays and timber stores.

The museum has also outlined a research strategy and is proactively funding research to address the main issues facing *Victory's* conservation, namely fungal growth and associated timber decay and secondary attack by woodboring insects, most notably DWB (Davis, 2021). Learning about DWB preferences and behaviours within the wood will enable conservators to identify areas of risk more effectively. The information gleaned from these projects can then be used to develop more tailored IPM methods for *Victory* in the existing surroundings and environment.

2.5.3 IPM and Deathwatch beetles

The premise of IPM is using the knowledge of the biology and lifecycle of the insects to minimise the conditions they need to thrive. However, so little is known about the DWB beyond that which is outlined in [Section 2.2](#), little of which can be considered definitive (more details in [Chapter 3](#)), that it is challenging to plan the most effective IPM measures. Although the methods laid out in the NMRN IPM strategy will provide a degree of management of the infestation, the challenges faced by the ship can limit their effectiveness, and the scale and endemic nature of the infestation requires something more substantial and specific. By understanding more about the DWB, more effective methods tailored to *Victory* can be designed and implemented.

Although parallels to other species in the Ptinidae (formerly Anobiidae) family can be made (i.e. *Anobium punctatum*, common furniture beetles) in terms of lifecycle and habitat (i.e. environmental conditions) and regularly have been, the limited research into DWB means that the accuracy of those assumptions are questionable. The order Coleoptera (beetles) is the largest on Earth, and contains approximately 400,000 species, with more added on a regular basis (Bouchard, 2014; Chapman, 2013). There is extraordinary variety within family groups and between species, and great care must be taken in assuming what must be true for one species is true for another. For example, *A. punctatum* females secrete a pheromone, which has been used to develop more effective traps, whereas DWB do not (or at least one has not been found) (Birch & White, 1988; Pinniger et al., 2003). *A. punctatum* also has a much shorter lifespan, is smaller, and exclusively attack seasoned sapwood (*Ibid.*). There may very well be a unique characteristic of the DWB yet to be discovered that can greatly aid in the development of eradication methods.

The research within this thesis will reveal information about the tunnelling preferences and serve as the foundational groundwork for further investigation into the habits and behaviours of the beetle and non-invasive methods of detection, aiding in conservation efforts for HMS *Victory*.

3 LITERATURE REVIEW

This chapter examines the existing literature to establish the research base prior to the contributions of this thesis. First, the history of research into the DWB will be presented. Next, the non-invasive investigative methods common to cultural heritage research and insect detection that are used in this thesis will be examined. Finally, the state of research into public engagement with conservation along with a review of common methods of engagement will be explored.

3.1 Deathwatch Beetles: A history of research

The goal for this section of the literature review is to critically examine the limited literature on DWB, demonstrating how the research has progressed over time and explaining why so little is known about the DWB.

3.1.1 Pre-20th Century

The first verifiable written account of the DWB is a short sentence in John Wilkin's *An Essay towards a Real Character and a Philosophical Language* (1668):

“Of exanguious animals, the death watch, either that of a long slender body, frequent about houses, making a noise like the minute of a watch, by striking the bottom of his breast against his belly; or that of a more short round figure, living in the fields, being either wholly red or sometimes spotted with black shorter coverings.” (Wilkins 1668; 127)

The only identifiable DWB element, other than the name, is the tapping behaviour, but there are other beetles that tap also dubbed ‘Death watch’ beetles in the past (Menendez, 1990). While this passage clearly indicates knowledge of the DWB, it cannot be certain that Wilkin's description is of a *Xestobium rufovillosum*. However, the way of writing implies prior knowledge on behalf of the reader, suggesting they were well known.

Four years later, in the 1672 edition of Sir Thomas Browne's *Vulgar Errors* (Browne, 1672), there is another passage that improves little in the way of

physical description, but again describes the tapping, and clearly describes the terror many felt upon hearing the noise:

“Few ears have escaped the noise of the Dead-watch, that is, the little clickling sound heard often in many rooms, somewhat resembling that of a Watch; and this is conceived to be of an evil omen or prediction of some persons death: wherein notwithstanding there is nothing of rational presage or just cause of terrour unto melancholy and meticulous heads. For this noise is made by a little sheath-winged gray Insect found often in Wainscot, Benches, and Wood-work, in the summer. We have taken many thereof, and kept them in thin boxes, wherein I have heard and seen them work and knock with a little *proboscis* or trunk against the side of the box, like *Apicus Martius*, or Woodpecker against a tree. It worketh best in warm weather, and for the most part, giveth not over under nine or eleven stroaks at a time. He that could extinguish the terrifying apprehensions hereof, might preven the passions of the hear, and many cold sweats in Grandmothers and Nurses, who in the sickness of children, are so startled with these noises.” (pg. 109)

Startingly, he does not appear to take much stock of the folkloric associations with death himself, and even collects several to observe. Interestingly, his observation of 9 to 11 strokes or taps and preference for warmer weather, is consistent with later studies (Goulson et al., 1994; White et al., 1993).

Benjamin Allen, writing in 1698, also challenges the folkloric associations. Clearly the association with death was well established in the 17th century.

“This small Beetle which'makes a Ticking or distind Beating, resembling the Noise of a Watch, being rarely heard, and not known, has obtain'd the Name of a Death-Watch, which yet I have known to be heard by many, where no mortality follow'd ; and particularly by my self, who have taken Two of the fame, Seven Years since, without any Death following that.” pg. 376

However, he goes on to give a physical description of the beetles he captured, which clearly describes *Xestobium rufovillosum*:

“This Beetle I found a Copper Body, it resembled dry Dirt in Colour. I found another, some Years before on a rotten Post; and made the Noise like a Watch, by beating its Head on the Subject that it finds fit for Sound, this found in *August*, 1695. Had another answer’d it in the same Room, and after a Minute’s distinct Beating, would forbear for the other to answer; which the other single one would not; though that would make some Breaks now and then. The part it beats with is, the extream Edge of the Face, which I may call the Upper-Lip, the Mouth being protected by this Bony Part, and lying underneath, out of view.” Pg. 376-7

The description continues for several pages, but what is interesting about this passage is Allen’s location of a beetle on a rotten post, and the tapping duet between two beetles. He even includes an image ([Fig. 20](#)) in his account, drawn with the aid of a microscope (Allen, 1698).



Figure 20: Allen's depiction of a Deathwatch Beetle, drawn with the aid of a microscope. From Allen 1698

Although one could consider these descriptions as preliminary scientific investigations, details beyond the easily observed physical description, collection location, temperature and tapping behaviour are lacking.

Two German references from the 19th century (as cited by Belmain, 1998; Fisher, 1937b) that make note of the exploitation of decayed hardwoods by the DWB. However, these could not be verified further, and they are unlikely to have added additional information beyond that already stated.

It can be concluded that prior to the 20th century, people were aware of the DWB, but primarily of the noises they make. There are no in-depth investigations into their lifecycle, further behaviour, and habitats. However, the widespread folkloric beliefs surrounding the tapping behaviour suggests that infestations were sufficiently common in dwellings to give rise to these superstitions.

3.1.2 20th Century

3.1.2.1 Beginning of the century

A large-scale infestation in Westminster Hall, first noticed in 1909, proved to be the catalyst for prompting investigation into DWB (Wood, 1999). Referred to at the time as *Xestobium tessellatum* (the previous scientific name for DWB), reports about the work indicated that they were the worst cause of decay to the Norman vaulted timber roof (Baines, 1914). The damage was so bad ([Fig. 21-22](#)), that four of the thirteen trusses were in danger of collapse (*Ibid.*). Cavities within the timbers were large enough in places to fit an adult human (*Ibid.*) It was noted at the time that “the life-history of the insect has apparently not been completely worked out” (Baines 1914: 11).

The investigations into the beetles as a result of this infestation focused on methods of eradication (Baines, 1914). However, several interesting observations were made during the course of the investigations, and it is these that this section will focus on. Larvae and beetles were collected from the roof, and introduced to wood samples, upon which a wide variety of chemicals were tested (*Ibid.*). The first observation took place shortly after several larvae, which

were placed in a test-tube with a decayed section of wood, ate through the cork securing the tube:

“...the speed with which it attacked the cork was almost incredible. It would probably take longer for the larvae to progress through hard oak than through soft cork, but it is obvious from the observations kept on these insects that their energy in attack is quite astonishing” (Baines, 1914; 11).

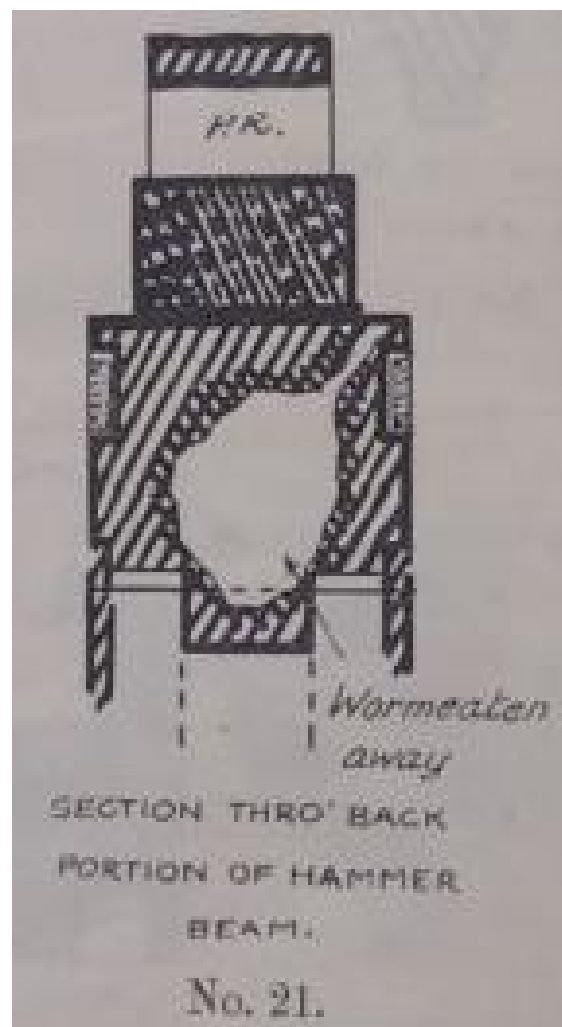


Figure 21: Diagram showing cross-section of Westminster Hall timber at risk of collapse due to the Deathwatch Beetle damage. Diagram from Baines, 1914: 64

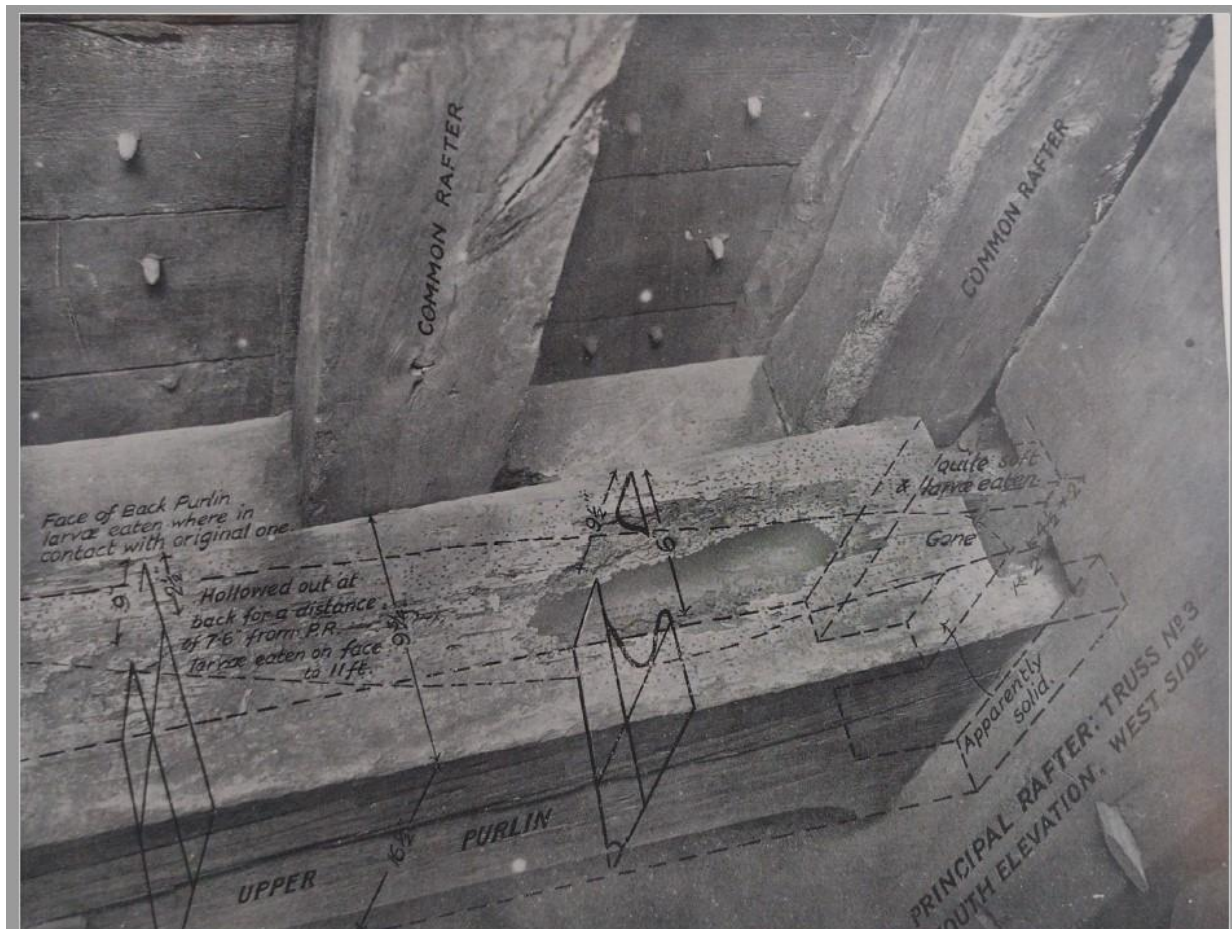


Figure 22: Annotated image of a Westminster Hall beam showing extensive Deathwatch Beetle decay. Image from Baines 1914

Harold Maxwell-Lefroy largely began the investigations into the DWB and would have been one of the leading contributors but for his untimely death. He died in 1925 as a result of chemical ingestion while developing pesticides for use on houseflies (American Entomological Society & Academy of Natural Sciences of Philadelphia. Entomological Section, 1925). Nevertheless, he made some key contributions and observations to the understanding of the DWB. He was assisted by Douglas Kimmins, who wrote of the work with Maxwell-Lefroy in 1933, over a decade after the work had taken place, and produced no other papers on DWB.

Although Maxwell-Lefroy's focus was the eradication of the beetles with chemical pesticides, his 1914 report on the work done on Westminster Hall material noted there "are large gaps in our knowledge of this beetle" (Maxwell-

Lefroy, 1919: 2) and that understanding the natural behaviour of the beetle is the best means of understanding and dealing with an infestation (*Ibid.*: 13), one of the key principles upon which IPM is based. The acknowledgement that an in-depth understanding of the species would aid eradication efforts was a relatively unique perspective when compared with the other work conducted at the time by Dr James Dobie (Government Laboratory) and Dr Emil Westergaard (Professor of Mycology, Herriott-Watt College), who, based on their reports, never attempted to further understand the DWB beyond the basic lifecycle (Baines, 1914; *DWB Infestation Westminster Hall*, 1914).

There are several notable observations Maxwell-Lefroy makes in his 1919 report. What is most noteworthy about these is his understanding of the beetles, despite limited live material to observe, and how forward-thinking many of the comments are. The first interesting remark is the fact that “it can fly but appears to do so chiefly at night and somewhat reluctantly, though when once on the wing it may possibly travel considerable distances, especially on warm still nights” (Maxwell-Lefroy, 1919: 2). The topic of DWB flight becomes a point of contention in later studies, so it is important to note that in the first scientific investigations they were seen to fly. He also notes the relation of season and temperature to occurrence of life stages and that heating buildings may have an effect on emergence (*Ibid.*: 7). He observes that the larvae largely feed “along grain in the soft summer-wood; unless compelled to, the larvae rarely burrow across the grain, but in very badly attacked wood, the tunnels cross and the wood is like a sponge, tunnels alternating with the harder wood layers between” (pg. 8). He also theorises that the beetles may not emerge out of the extremely decayed wood and instead remain within the decayed portions inside (*Ibid.*: 8). The grain is the pattern formed by the longitudinal fibres (Dinwoodie, 1989: 29). Finally, he notes the existence of natural predators and their potential use as a method of control (*Ibid.*: 30). This is unexpected, particularly coming from an entomologist whose primary focus was the development of pesticides and insecticides. The use of predatory and parasitic species as a means of biological control of pest infestations in heritage spaces is something that has only become more commonplace in the last ten years, particularly in Europe

(Biebl, 2022; Querner & Biebl, 2011). However, there is a caveat to consider: although he acknowledges that his observations are limited by the amount of live material, details on how the observation were made are lacking in the report.

This lack of methodology and detail continues in a later paper (Maxwell-Lefroy, 1924: 261), where he makes a number of claims as to their lifecycle and behaviour but fails to mention how the information was garnered.

Given his thanks of HM Office of Works for providing a tree from Richmond Park (Maxwell-Lefroy, 1924: 267) and his reference to live beetles in the 1914 report, one would assume that he or Kimmins observes the beetles, but he does not explicitly state this. Although some of the claims made were later confirmed by other studies (i.e. beetles do not burrow, usually perish by midsummer), other statements, particularly those regarding the timings of lifecycle stages, appear to be conjecture (Maxwell-Lefroy, 1924). Although there is some acknowledgement of this in his use of 'probably', how he came to determine his stated time estimates is never mentioned, nor is any information about the methodology or where he may have gathered this information.

Much like the earlier report, there are notable observations he makes that are extremely forward thinking for his time. He stresses the need for ventilation in buildings by noting the differences in the extent of infestation between two infested buildings, only one of which had ventilation (Maxwell-Lefroy, 1924: 266). He had not yet realised the connection between DWB and fungi as the reason for need for ventilation, but the importance he gives to non-toxic methods, contrary to many of his colleagues and his own expertise, is commendable.

But again, his other observations are lacking in clear evidence. For example, he mentions the presence of yeasts in larvae and the adults, with the possibility of the adult depositing the organism on the egg that then transfers to the larvae (Maxwell-Lefroy, 1924: 262), but no details are given on how this organism was identified.

Although Kimmins reveals some further details about the gathering of live insects and investigations made during the intervening period between Maxwell-Lefroy's works (1919-1924) in his 1933 paper, stating that beetles were collected from the floor of Knapton Church (Norfolk) (Kimmins, 1933: 133), the time between the observations and writing of the paper, even with meticulous notes, is a factor that must be considered.

There are several observations that Kimmins mentions that never appear in Maxwell-Lefroy's papers. Both mention the fact that beetles and larvae will emerge through material other than oak if it is adjacent to an infested area (Kimmins, 1933: 133; Maxwell-Lefroy, 1924: 262), but only Kimmins mentions damage to historic books as a result of an infested bookcase. This is mentioned in one other paper (Gahan, 1920), and in *Enquire Within Upon Everything* (118th and 124th editions), a how-to book. It could be that Kimmins was referring to the same instance as Gahan, as his work was published later. Damage to books has been acknowledged by others as a possibility, but not until relatively recently was this actually observed taking place (Karbowska-Berent et al., 2020). Gahan's (1920) work was conducted independently from the Westminster Hall investigations, although he does reference the damage to the roof (Gahan, 1920: 6). His work, found in a pamphlet for public sale, more generally investigates furniture beetles (Anobiidae) and is more of an instruction on how to manage an infestation at home. He does include a brief account of the anatomy and lifecycle of each of the main beetles, but there are no distinctive observations from that of Maxwell-Lefroy and Kimmins' work, and given he was working at the same time and mentions Westminster Hall, it is likely that he consulted them.

Kimmins also mentions that the larvae can move both forwards and backwards within the tunnels, but can also turn around to face the other direction (Kimmins, 1933: 135-36). Interestingly, this is never mentioned by anyone else in the literature. Kimmins also contradicts himself and Maxwell-Lefroy's earlier statements with regards to flight, saying that they primarily use their wings for

righting themselves after falling, but then goes onto say that Maxwell-Lefroy observed them flying.

With regards to the wider knowledge of the DWB, there Maxwell-Lefroy makes an interesting comment in his 1924 paper: "... so much is common knowledge on this point that I need not stress it..." (Maxwell-Lefroy, 1924: 271). Frustratingly, he fails to elaborate further on what the common knowledge related to the damage caused by DWB and the care of timber buildings is. But books such as *Enquire Within Upon Everything* (118th and 124th editions) include the DWB along with treatment for its eradication amongst their pages (*Enquire within upon Everything*, n.d; 1969). The beetles were clearly widespread enough to merit inclusion, which alongside statements like Maxwell-Lefroy's, and Wilkin's (1668) way of writing, imply preexisting knowledge in the respective audiences, and a relatively widespread awareness of DWB.

The final thing to note from the work on DWB of Maxwell-Lefroy and Kimmins is the call for collaboration between different disciplines to all contribute towards finding an effective solution (Maxwell-Lefroy, 1924: 260). This thesis will go on to demonstrate the importance of collaboration for this project and more widely within conservation.

The work of Dobbie and Westergaard did not contribute any knowledge towards the understanding of the DWB. However, their work on chemical treatments, alongside that of Maxwell-Lefroy's, demonstrated that there are plenty of chemicals that will kill the beetles and larvae, but the challenge lies in the delivery of the chemicals through the wood to the insects, which remains a problem to this day. Wood is an anisotropic material, meaning it has different properties in different directions (Chen et al., 2020; Dinwoodie, 1989; *The Structure and Mechanical Behaviour of Wood*, 2008). Chemical treatments, whether they be liquid, gaseous or other dispersal method, will penetrate well along the grain, travelling through the wood vessels in the same way that water would have been conducted through the tree while it was alive (Dinwoodie, 1989; Maxwell-Lefroy, 1919). Liquids will not penetrate across the grain, as there are few, if any, vessels perpendicular to the longitudinal vessels (*Ibid.*). It

is therefore impossible to ensure that all the timber is treated. There will always be untreated areas for the DWB to develop.

The work resulting from the Westminster Hall infestation can be considered the first forays into investigations of DWB lifecycle, habits and behaviour, and there were some interesting observations made, particularly by Maxwell-Lefroy and Kimmins, who contributed the most knowledge. But the frustrating lack of clear methodology, lack of detailed evidence from which conclusions were formed, and contradicting statements limits the reliability of these observations. Maxwell-Lefroy's unfortunate death also meant that the investigations were cut short, and those that continued researching focused on eradication and did not consider the wider biology of the DWB worth considering. The biggest contribution made by Maxwell-Lefroy and Kimmins was the acknowledgement and emphasis on the importance of knowing the lifecycle and behaviour is essential to more effectively address infestations. The Westminster Hall project provided the first recorded evidence of the structural damage they can cause.

What is important about this period of study is that it is the first large-scale scientific investigations into the DWB, although the focus was on their eradication. The investigations demonstrated that there were plenty of chemicals that could kill the beetles and larvae, but the challenge lay in delivering the chemicals through the wood. However, the infestation in the timber roof of Westminster Hall proved to be the impetus for further study into the beetles, and Maxwell-Lefroy and Kimmins' work provided the foundation for the next period of study.

3.1.2.2 1930s-1980s

The Forest Products Research Laboratory (FPRL) at Princes Risborough was founded in 1927, with the goal of promoting the most economical use of timber by wood-using companies (Commonwealth Forestry Review 1971). During its first few years of operation, investigations on anatomy, chemical, physical and mechanical properties and the processes of biological attack of wood were performed (*Ibid.*). This included the DWB.

While the FPRL was being set-up, a general bulletin, titled *Beetles Injurious to Timber* was published by the Forestry Commission, and meant to form part of a series (the rest of which were to be published by FPRL) (Munro, 1928). Munro, like Gahan, was writing for a public audience and more generally about wood-boring beetles, their anatomy and the damage they can cause. He was Maxwell-Lefroy's successor at Imperial College, and more directly acknowledges the work of Baines and Maxwell-Lefroy on Westminster Hall, suggesting that his information was derived from theirs.

The work on DWB at FPRL was almost entirely conducted by Ronald Fisher, who wrote the 4-part *Studies of the Biology of the Deathwatch Beetle*, considered the seminal work on the topic. His investigations build and expand on Maxwell-Lefroy and Kimmins work. In his examinations of the pre-existing literature in the first of the four parts, Fisher (1937b) highlights the lack of knowledge of the beetle, despite widespread general knowledge of their existence. He then goes on to examine the general distribution and habitat of the beetle and gives anatomical descriptions of the beetle at each lifecycle stage, focusing on the adult beetle. His work corroborates earlier findings, but his diagrams and detail of the reproductive organs from dissections are the first such examinations. His brief description of the alimentary canal (digestive tract) notes that in all the dissections performed, there was never any food material present (Fisher, 1937b: 611). The anatomy and tapping behaviour are the two aspects of DWB biology that have been most studied.

The second part examines habits of adults with particular reference to oviposition, and it is from this point that concerns about the series begin. In addition to examining the existing literature and his own observations for lifecycle stages in external and internal environments, he examined the effect of different relative humidities and temperature on oviposition. It is from this paper from which the supposition that they do not fly comes from. He states that the beetles are capable of flight and using their wings to break a fall or regain balance, but that they do not intentionally fly (Fisher, 1938: 161). Despite

Maxwell-Lefroy's evidence to the contrary (1919), this continues to be the prevailing view until Belmain's (1998) work.

In his investigations into oviposition, his methodology is vague at best. While allowance must be made for the time of writing, the experiments were never repeated. His use of sulphuric acid as a means of controlling the humidity and temperature for biological specimens (Fisher, 1938: 163) is also questionable. Sulphuric acid is highly corrosive, and long-term exposure to low concentrations via inhalation can cause harmful health effects (PubChem, 2024). It is also as an insecticide component (*Ibid.*) As it is unclear whether the beetles were exposed to the sulphuric acid, and what concentrations were used due to the lack of methodology, it does bring the results into question, as the sulphuric acid may have affected the beetles.

Parts three and four attempt to investigate the role of fungal decay of timber on the rate of development of the larvae and beetles. It is in part three that the first published mention of the DWB infestation in HMS *Victory* appears (Fisher, 1940b: 547). However, lack of a clear methodology remains an issue, and sulphuric acid continues to be used. As the investigations were meant to reveal information regarding larval development, the lack of detailed methodology raises the question of how the larvae were observed. Belmain (1998) was able to obtain more details from a member of Fisher's research team, Ernie Harris, who revealed that these experiments relied on larvae extracted from a population in willow trees that were transferred to wood blocks, usually oak, with artificial holes (1998: 39). Maintaining a suitable supply of beetles was apparently difficult (*Ibid.*). Additionally, the long larval development time meant that many experiments were abandoned before completion (*Ibid.*), bringing the results and conclusions Fisher presents with seemingly little evidence further into question. Although Fisher presented a possible relationship between the DWB larval development and high humidity, infestations have still been known to occur and thrive at lower humidities (Belmain, 1998: 39).

Fisher's *Studies* are still key works in the DWB literature and are the first larger-scale, more in-depth studies. However, with the issues highlighted above and

the limits of technology at the time, it is perhaps best that these are considered preliminary experiments, like that of Maxwell-Lefroy (1919, 1924) and Kimmins (1933), rather than the definitive work.

In addition to the *Studies*, Fisher worked with a number of other members of the FPRL research team investigating other aspects of DWB biology. He and Parkin (1930), building on the work of Campbell (1929), also mention the presence of yeast in DWB, but like Maxwell-Lefroy, there are no details of how the yeast was isolated and identified. Work was even done to examine the use of X-rays as a means of detecting larvae (Fisher & Tasker, 1940) (this will be discussed further in [Section 3.2.2](#)), as well as a means of eradication (Bletchly & Fisher, 1957).

The work conducted by Parkin and Campbell into the wood chemistry associated with woodboring beetle infestations (Campbell, 1929, 1941; Campbell & Bryant, 1940), and the anatomy and digestive enzymes of DWB larvae (Parkin, 1933; 1940) are more substantial with regards to their methodology, lending their results greater strength. Campbell's (1929) work examining the frass suggested that the DWB attack the carbohydrates in wood. However, this is refuted in his later work, where it is concluded that the fungal attack benefits the insect through the reduction of mechanical strength of the wood, supposedly making it easier for the larvae to ingest (Campbell & Bryant, 1940: 1411), and by increasing access to nitrogen (Campbell, 1941: 1205). However, it is acknowledged that the techniques used were not sensitive enough to detect the presence or absence of fungal material in the frass. They were entirely reliant on changes in weight of the wood to determine fungal decay (*Ibid.*).

Parkin's (1933; 1940) work focused on woodboring larvae. His anatomical diagrams are detailed and clear ([Fig. 23](#)) but would benefit from high-resolution images (like those of the adults in Fig. 7-9), as more subtle nuances, such as colour, are not captured in the diagrams. These images would enable easier to-life comparisons. His work on the digestive enzymes is fascinating and contains a detailed methodology (Parkin, 1940: 368-9). He was able to detect the

presence of a number of different enzymes (i.e. amylase, maltase, cellulase, hemicellulase A and B) in DWB larvae (Parkin, 1940: 376). He groups the woodboring larvae he tests into three groups, depending on which digestive enzymes are present (*Ibid.*). DWB larvae fall into the 3rd category, as the digestive enzymes present suggest that they are able to utilise cell contents and carbohydrates of the cell wall, including cellulose (*Ibid.*). However, the technology available at the time, and the fact that few of Campbell's or Parkin's experiments have yet to be repeated means that the results cannot be considered conclusive. It is certainly an area of investigation worth pursuing and investigating further to see if similar results could be obtained, particularly with the technology now available.

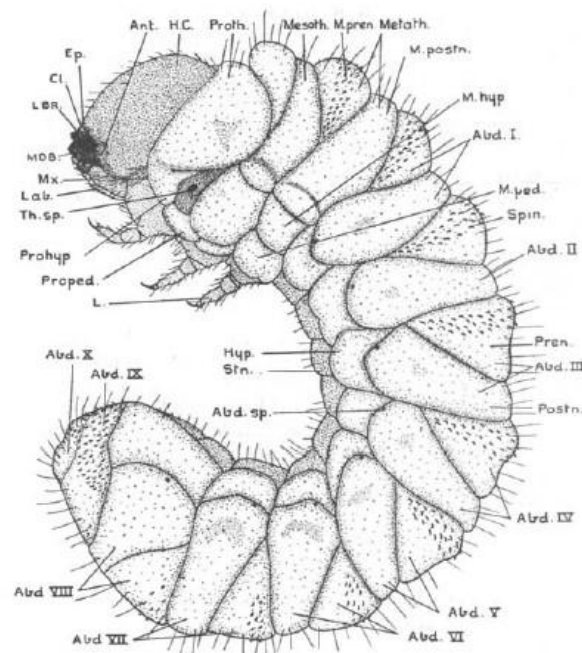


Fig. 1. *Xestobium rufovillosum*, De G. : larva, lateral view (x 15).
For explanation of lettering to figs. 1-15 see p. 68.

Figure 23: Parkin's (1933) diagram of a DWB larvae
(pg. 40)

These are the most notable works regarding DWB produced by the FPRL. The few other investigations into DWB focused on their eradication, examining the use of permethrin and gamma radiation to treat infestations (Bletchly, 1961; Bletchly & Fisher, 1957; Coleman, 1977). There was an investigation into differences between the sexes in adult DWB by Harris (1959), which previously

could only be distinguished via dissection. He noted slight differences in the adults on the final sternite, and this was used as a sexing method until the 1990s. However, the small sample size and extremely brief publication (appeared as a bulletin) raises the question of reliability of the method.

Another brief publication with small sample size was Baker's (1965) investigations on Anobiid flight. He observed that DWB had a wingbeat frequency of 70/85 cycles per second and that they were able to sustain flight for up to 10 minutes, provided the temperature was between 17-30°C (Baker, 1965). As his method involved heating a hotplate beneath the beetles (*Ibid.*), it raises the possibility that the beetles were simply trying to avoid the hot plate, which, with the small sample size and scarcity of presented information, brings the results under question.

Fisher regularly contributed to the few studies on Deathwatch and other woodboring beetles, and he was regularly consulted by the Royal Navy for treatment advice for HMS *Victory* until his death in 1958 (Bletchly, 1959). His recommendation of fumigation with permethrin, was carried out on a regular basis (*Ibid.*). Upon his death, Bletchley took over as Head of Entomology at FPRL, but most investigations into DWB ceased, apart from the few previously mentioned and the odd section in wider Anobiidae studies.

FPRL ceased to be governmentally funded in 1958 (Brazier, 1997; *BRE History*, 2022), but continued until 1972 through various administrative and governmental changes, until it merged with the Fire Research Station to become the Building Research Establishment (BRE) (*Ibid.*). Although the work done by the FPRL greatly contributed to the knowledge of the DWB, the lack of scientific rigour and details in many of the studies, and the contradictions and inconsistencies found throughout greatly diminishes the confidence in the conclusions made. The only conclusion that can be certain is the same as that found by Maxwell-Lefroy (1924): there are plenty of means (i.e. insecticides, radiation) of killing the beetles, but the challenge of fully penetrating the timber to deliver the method to the beetles remains.

As one of the main periods of DWB investigation, the work conducted during this period forms one of the largest contributions to the literature, and much of it remains fundamental to our understanding of the species. Fisher (1937b; 1938; 1940b; 1941) was the first to note the links between fungal decay and DWB attack and hypothesizes that stopping fungal decay should prevent DWB infestations. Parkin and Campbell's work revealed valuable insights to the understanding of DWB larvae and their ingestion of wood. However, the lack of clear methodology in many of the studies, limits of technology at the time, and contradictory statements undermine many of the findings. Much of the work may even be considered anecdotal (Belmain, 1998: 17). It may be more useful to consider the studies from this period as extensive preliminary investigations that can be built upon, rather than definitive work.

3.1.2.3 Early 1990s

There was a noticeable lack of investigations into DWB following the work of the FPRL until the early 1990s, when there were several studies conducted. Crucially, modern standards of scientific investigations were implemented, and a number of the studies were repeated, bringing greater certainty to the conclusions.

The first of these was a doctoral thesis, examining the life history evolution of the DWB from an ecological perspective (Menendez, 1990). Life history is the age, size and stage specific patterns of development, growth, maturation, reproduction, survival and lifespan of a species (Fabian & Flatt, 2012). Menendez is rightly critical of much of the early work on DWB, commenting that much of it is contradictory (1990: 1). Although he acknowledges the problems in Fisher's (1937b; 1938; 1940b; 1941) work, he still refers to it as the definitive work. Despite this, his examinations of previous literature are thorough, and he was even able to examine European (mostly Russian and Polish) papers on *Xestobium*, where it is noted that they were known to infest larch (*Salix* spp. – a softwood) and preferentially infest buildings with higher humidities (Menendez, 1990: 8-9). It is also interestingly noted in a Polish paper that DWB are able to inhabit wood invaded by fungi and wood without any clear external evidence of

fungal decay (Dominik, 1966 as cited by Menendez, 1990: 8-9). Menendez (1990) also makes reference to a German papers that states that adult DWB have been observed swarming in southern Sweden (Palm, 1959 as cited by Menendez, 1990: 29) and the fact that adult beetles have been collected from flowers in central Europe (Freude et al, 1969 as cited by Menendez, 1990: 31). It is worth noting that these observations come from single papers only and are never mentioned by other researchers, so the veracity of the observations cannot be certain.

Menendez's (1990) own work made use of the historical data, as well data collected from 'wild' (from trees) and 'domestic' (from buildings) DWB, and notes that given the wide range of possible wood hosts mentioned in the literature, it is more likely that wood condition is the most important factor, rather than wood type, that dictates wood suitability for infestation (pg. 16). His use of the historic data raises concerns. Although much of the work simply presents the historical data, thereby providing a useful summary, the concerns previously highlighted surrounding the collection of that data does undermine some of his findings.

In his rearing and sustaining of a DWB population, Menendez (1990) adapted a diet from Cymorek (1965), who developed the medium for *Anobium punctatum* as a means of controlling the nutritional content and speeding up the development process. Not only does this raise concerns about making assumptions of similarities between species, but rearing on artificial medium eventually led to degenerative symptoms within 3 generations of *A. punctatum* (Cymorek, 1975). It is unclear how many generations of Menendez fed on this adapted diet and whether any degenerative effects were noted.

As the thesis is from an ecological perspective, and focuses on population dynamics and wider biological contexts, it discusses predatory and parasitic species of DWB that could be used as a means of controlling infestations. *Pyemotes* spp. mites and *Korynetes* beetles are mentioned as possible biological control measures (Menendez, 1990: 42). The mites are likely to be limited in their use due to the health hazards they may present to humans and

pets (*Ibid.*), but they, along with a variety of unknown microbial pathogens, do cause DWB significant deaths, as Menendez unfortunately discovered in his initial DWB rearing stocks (whether this impacted results is unclear) (Menendez, 1990: A3). *Korynetes* beetles have no health concerns attached, and the advantage of predatory species is that they will eventually die out on their own once their food supply has gone (*Ibid.*: 209). Their presence has previously been noted on *Victory* (Fisher, 1940; Davis pers. comm., 2022), minimising worries over the introduction of new species. The only issue is rearing a suitable population for constant introductions to DWB infestations (Menendez, 1990: 209).

Surprisingly, Menendez's (1990) work was not widely published. Only one paper resulted, greatly limiting the impact of the work. The lack of subsequent publishable material also brings into question the validity of the results and conclusions. Like the earlier studies, Menendez's (1990) work has never been directly repeated, and was limited to the technology available and accessible at the time. With DNA and genomic techniques, it may be possible to understand the unique aspects of the DWB, population dynamics, their relationship to fungi, and their relationship to other woodborers.

The rest of the studies from this period were from a group of researchers based in Oxford. The studies produced four papers, primarily focusing on the tapping behaviour of the DWB. Although it was suspected that the tapping was involved with mating behaviour prior to this point, these investigations were the first to prove the hypothesis. Birch and Keenlyside (1991b) provided the first experimental analysis on the tapping behaviour of DWB, demonstrating that the tapping is performed by both sexes in bouts of 4-11 taps with a maximum frequency of 11Hz. Males tend to initiate the bouts, with the females responding, creating a kind of duet (Birch & Keenlyside, 1991b: 259), with the communication likely to be substrate-borne rather than airborne (*Ibid.*; White et al., 1993). The female beetles rarely moved between tapping bouts, whereas the males do move, repeatedly stopping to initiate tapping, and reorienting themselves based on the response (Goulson et al., 1994; White et al., 1993).

Many of the researchers involved in this study were among those who had discovered the pheromone for *A. punctatum*, noting that *A. punctatum* uses pheromones for distant mate location, yet taps when at a close range (Birch & White, 1988; White et al., 1993). The same pheromone has been noted in other species that do not tap, suggesting the tapping may serve as a species identification (*Ibid.*). But they were unable to find evidence for a DWB pheromone. They suggest that common anobiid ancestors may have used both pheromones and substrate-based vibrations, but that DWB have evolved to solely make use of vibrational communication, a relatively unique characteristic (White et al., 1993: 560). Vibrational communication works well over short distances on the same substrate, but poorly over long distances and between different substrates (*Ibid.*). They put forward two possible explanations. The first is due to the observation that DWB largely remain on the same piece of wood for several generations, therefore they only need to find mates over short distances (*Ibid.*). Alternatively, the DWB use other cues (i.e. environmental or host wood) to locate and gather on a suitable substrate before tapping to find a mate, rendering pheromones redundant (*Ibid.*).

Another key contribution from this period is a more reliable method of sexing the beetles that does not involve dissection. Goulson *et al* (1993) found that gently squeezing the beetles extruded the genitalia sufficiently for sex to be determined. A combination of this and Harris's (1959) method are used from this point onward. In this same paper, they observe that female DWB only mate once, with a preference for heavier males, often rejecting the first male to locate them (Goulson et al., 1993: 540). Once they have mated, the females will cease to respond to initiated tapping (*Ibid.*). Males supposedly donate ~13.5% of their body weight to the female during copulation, the majority of which occurs during the first mating (males mate multiple times), although they do acknowledge this is likely to be an underestimate (Goulson et al., 1993: 546). They suggest that this may be a contributing factor to the observation that mated females live longest, mated males shortest, with unmated females and unmated males falling between (*Ibid.*). With a robust methodology, awareness of inherent issues (i.e. beetles collected from buildings may have already mated before

collection) and experimental limits, this series of studies provided a reliable foundation for the next period of study.

This period marks the starting point of more reliable investigations into DWB biology with modern standards of scientific research being applied, and the beginning of the second stage of substantial investigations into DWB. The focus is on the biology of the beetles, deepening the understanding of the species, but there is little discussion on how this may be applied to infestation in historic buildings. However, it is during this period that IPM is being introduced to museum and heritage spaces (see [Ch 2 Section 2.4](#)), which influences future investigations.

Menendez (1990) provides a useful summary of the pre-existing literature, including obscure sources and re-evaluates the historic data alongside his own. While the re-evaluation and summation of historic data is useful, its use, considering the concerns raised previously surrounding the collection of that data, is something to consider. The minimal number of publications resulting from this work is also something to be acknowledged. His work contributes insights into population dynamics of DWB in wild and domestic populations, and he makes the case for using natural predators, such as the *Korynetes* beetle, as a means of managing infestations.

The other studies from this period greatly enhanced understanding of the mating behaviours of the DWB, and provided a more reliable method of sexing the beetles (Goulson et al., 1993). They provide the first scientific evidence into the tapping as mating behaviour for both sexes, with details on the frequency, rhythm, and orientation to substrate vibrations (Birch & Keenlyside, 1991; Goulson et al., 1994; White et al., 1993). Females preferentially select larger males, and mate only once, whereas males may mate multiple times, although their body weight contributions decrease with each mating (Goulson et al., 1993). They put forward several explanations for the behaviours observed but acknowledge that further investigations were required to fully understand these unique characteristics.

Although not directly relevant, it is worth noting that this was also the first period where a woman's name (Chantelle Jay) appears on the list of contributors for a paper. Diversity of viewpoints is something that will be discussed as part of the investigations into public engagement with conservation, as it is a significant factor in driving novelty and innovation. While this is unlikely to have influenced any results, it is something that should be acknowledged.

3.1.2.4 Mid- to late 1990s

The English Heritage Woodcare Project was a collaboration between English Heritage, and the European Commission (Fidler, 2001). The aim was to address the degradation of many major English cathedrals. Much like the collaboration between NMRN and Cranfield University, the technical research for this project was intended to address the identified issues, one of which was DWB infestations. The publications were also tailored to be easy-to-read and digestible, making it easier for all those involved in building conservation to read (*Ibid.*). To date, this is the largest contribution of work to knowledge of the DWB, and the vast majority of the confirmed knowledge comes from these investigations. There were a number of different people involved in the project from all over Europe and the UK. The largest contributor was Steven Belmain, whose doctoral research was funded by the Woodcare project.

The overall aim of Belmain's (1998) research was to investigate aspects of DWB biology that could lead to "further understanding of this insect as a pest of historical buildings with a view to discovering potential new control methods in buildings conservation programmes" (pg. 14). He focused on four areas of research: (1) life-cycle parameters of DWB from a laboratory culture observed almost daily compared to beetles trapped from buildings, (2) habitat diversity with the view of examining environmentally sound methods of population control through trapping and biological methods, (3) oviposition preference behaviour of host selection, and (4) investigations into orientation and dispersal mechanisms (*Ibid.*).

He was able to determine that the development of DWB from egg to adult can take anywhere between 1-13 years, with a mean of 5-8 years using a pre-

established culture from Germany (Belmain, 1998: 38). His findings on adult longevity concurred with those of Goulson *et al.*'s (1993) findings, with mated females living the longest (Belmain, 1998: 43; Belmain et al., 2001: 11). He also provided more concrete evidence towards a loose relationship between temperature, and pupation and emergence (Belmain, 1998: 45). In his investigations on habitat diversity, he examined four DWB-infested buildings and used traps to assess the species dwelling internally, as well as external immigrants (*Ibid.*: 75). His literature review expands Menendez's (1990) list of organisms that could be used as biological controls to include other beetles, mites, and spiders for the adult beetles, but notes that only beetles and spiders were found in the examined buildings (*Ibid.*: 51). He does acknowledge that microscopic species (i.e. mites) were not investigated and do warrant further study (*Ibid.*: 80). However, he proposes that multiple levels of predators for different lifecycle stages (i.e. *Korynetes* for larvae and spiders for adults) may be more effective, although investigations into efficacy would be required (*Ibid.*: 79-80).

The presence of DWB on sticky traps hung in the buildings only accessible to flying insects and multiple observations of DWB flight, provided clear evidence for flight, but also evidence for spread of infestations via adult travel (*Ibid.*). However, it was only when the ambient temperature was above 17°C that DWB were caught on the flight traps, thus establishing the flight threshold temperature for DWB, corroborating Baker's (1965) findings. Previously, it had been thought that infestations could only occur as a result of the introduction of infested timber (Fisher, 1940a). The establishment of the flight threshold proved that infestation from flying adults was also a possible cause. By laying out traps of different colours, Belmain (1998) found that DWB were more attracted to bright or white objects. He theorises that this could be due to the fact that white is a common fungal body colour, or that they provide a stronger contrast with the surrounding timber (Belmain, 1998: 76; Belmain et al., 2000).

The DWB in the oviposition experiments showed a marked preference for older wood when given the choice between wood of different ages (Belmain, 1998:

108; Belmain et al., 1998). Belmain's (1998) findings also supported the previous reports of oviposition in cracks and crevices (Kimmins, 1933; Maxwell-Lefroy, 1924), with beetles re-entering the wood to oviposit. There does appear to be an error in the measurement units given at this point with regards to the egg width and cracks. Microns are the units given, which is inconsistent with all other reports of egg sizes (mean of 0.5mm) (Menendez, 1990: 39) and seems too small for wood cracks (gives 1-10µm as mean crack size). Although there is substantial variation, earlywood oak vessels are ~0.23mm (230 µm) (Tulik, 2014). It is not possible that cracks large enough for oviposition are smaller than a wood vessel. This is possibly a typo, and it is likely meant to be millimetres. Exposing the beetles to a series of extract treated discs revealed that selection of oviposition material occurs partially through chemoreception, and that there was greater attraction towards fungal extracts (Belmain, 1998: 111; Belmain et al., 2002). Beetle frass was found to be repellent to ovipositing females. However, the frass was derived from the fungally decayed modern oak used in the culture, and no frass from historic wood was tested, this volatile test feels incomplete and less conclusive (Belmain, 1998: 118).

The examinations into chemo-orientation revealed valuable insights to DWB behaviour beyond the testing parameters. There were noticeable differences between male and female participation, with further differences between beetle ages (Belmain, 1998: 153). As the experimental design was geared towards the potential role of stimuli associated with oviposition, they may show different chemo-orientation behaviour under different parameters, but they may also be more driven by local search tactics based on their desire to mate (*Ibid.*). Both male and female beetles were initially attracted to light, but as they aged and approached oviposition age (observed to be ~10-15 days after emergence), the females were more attracted to darker areas (*Ibid.*: 156). The initial attraction to light and increased activity in brighter environments during experiments prompted Belmain (1998) to suggest that beetles are more active during the day in trees or in buildings where the light penetrates (*Ibid.*). This contradicts the previous nocturnal activity suppositions of Fisher (1937b; 1938; 1940b; 1941), Kimmins (1933) and Maxwell-Lefroy (1924).

The results of chemo-orientation examinations provided the first concrete evidence of a preferential attraction to fungally decayed or decaying wood but highlights that those volatiles that produced a lesser response should be considered less attractive rather than repellent (*Ibid.*). Belmain (1998) does acknowledge that it was not possible to test all possible volatile sources, as many plants change volatile profile as a result of fungal or insect attack and calls for further research into the specific compounds within the volatiles that the DWB are attracted to (pg. 155).

Belmain (1998), like Parkin (1940), also examined larval digestive enzymes, using a more up to date (for the time) methodology and was able to determine the activity rate of each enzyme from each gut section (Belmain, 1998: 196). He confirms Parkin's (1940) findings of enzymes that allow for the digestion of cellulose, hemicellulose and starches (*Ibid.*: 197). Strangely, this experiment is included in the appendices of the thesis, rather than the main body. While it is less substantial than the other experimental chapters and would not have fit as neatly in the thesis narrative, it is still a valuable and useful contribution to the understanding of DWB. However, the lack of references to the experiment in the main text and inclusion in the appendices suggests a lack of confidence in the experiment and subsequent results.

The other papers from the Woodcare project contribute to the wider understanding of DWB, often challenging and reassessing the earlier work and assumptions. Ridout (2001b) re-examines the Westminster Hall case study, providing a more expansive overview of the eradication treatments, and shows that the infestation persisted despite decades of pesticide treatment, but that the drying of the timber decreased the population size. Coleman (2001) explains why chemical treatments largely fail, but that combining them with a more holistic approach of environmental control and strategic trapping would make them far more effective. Investigations into fungal decay provided valuable information on the understanding of *Donkioporia expansa*, a species of fungus commonly associated with DWB attack (Moore & Fuller, 2001), as well as the effect of fungal decay on wood and methods of detection before decay is

visible to the naked eye (Esser et al., 2001). Esser et al (2001) was able to demonstrate that significant chemical changes occurred in wood with insignificant (<3%) amounts of fungal activity (pg. 86). Ridout & Ridout (2001) used a protein or amino acid assay to re-evaluate Campbell's (1941) theory of nitrogen concentration, and found that fungi does not concentrate nitrogen in wood. There were even investigations into non-invasive methods of timber detection (Demaus, 2001) and acoustic detection of larvae (van Staaldunen et al., 2001). These will be discussed in [Section 3.2.2](#).

Most of the confirmed knowledge and understanding of the DWB comes from the English Heritage Woodcare project. It was a key collaborative study that addressed an identified problem and tailored the research to specifically address the issue, demonstrating the value of such work. The studies conducted disproved many of the earlier observations through reassessment of information and employment of new technologies for new methods, although the same caveats mentioned previously with regards to historic data still apply. Replicable methods and clarity of results promote more confidence in the findings in spite of the flagged concerns. However, with the exceptions of those papers reassessing old findings, the contributors themselves acknowledge that replication of the unique experiments is required, as is further investigation into the many topics raised.

The work of Maxwell-Lefroy, Kimmins, Fisher, Campbell, Parkin and others are integral contributions to the DWB literature. However, their contributions are largely anecdotal, due to the lack of scientific rigour and replicability of methods. Many observations and statements from their studies are contradictory and were often disproven during later research. It is only from the 1990s onwards where there is more confidence in the conclusions, and most of the confirmed knowledge of the DWB comes from this period. However, few of these experiments have been repeated, and there was acknowledgement of further work required. While DWB may initially appear to be a straightforward species, the literature demonstrates that their biology is far more intricate and complex than expected, and there are many aspects yet to be explored. With the

technological and scientific advances that have taken place since the Woodcare project, there may be further tools and methods available to enhance understanding of the DWB.

3.1.3 21st Century

While the Woodcare project publications do spill over into the first few years of the 21st century, the majority of the work was conducted in the 1990s. There was no specific further work on DWB unless in reference to IPM or timber treatments until 2017, when the partnership between NMRN and Cranfield was established to address the endemic issues facing *Victory*.

The first study to come out of this collaboration was Southwell's (2017) master's project. Samples of wood from *Victory* with unknown location provenance and evidence of beetle damage were imaged with digital photography and scanned with micro-CT (Brock et al., 2024; Southwell, 2017). They found a positive correlation between the tunnel percentage of the outer surface and the tunnel volume (Brock et al., 2024: 93). As it was a pioneering study with a focus on investigating structural integrity of DWB-damaged timber, there were some issues. The number of samples was small – only 15 samples from one larger piece of timber were scanned (Southwell, 2017: i). Two different methods of segmentation (see [4.2.5](#)) were used, but both methods struggled to distinguish the frass-filled tunnels from the surrounding wood (Brock et al., 2024: 90). Only 4 of the 6 sides of the cuboid samples were imaged, thereby not including 2 sides in the determinations of tunnel surface area. The labelling of samples was also unclear, making it difficult to determine where in the original timber they were located (Brock pers. comm., 2021). As the preliminary work for which this thesis was initially based, the issues raised were useful to guide this research.

Another master's project focused on the use of nanoparticles as fungal inhibitors (Jefferys, 2021). Fungal decay, a structural threat to timber itself, is thought to be a key precursor to DWB infestation. In theory, if the fungal decay is prevented, the DWB infestation will eventually die out. As part of the project, Jefferys (2021) did some preliminary work with DWB, introducing live beetles to a choice chamber with archival oak and new oak, both infected with *L.*

sulphureus (species of fungi). Within 30 minutes of the introduction of the beetles, they had all moved to the archival side and remained there for the rest of the day (2021: 46-7). After 24 hours, one explored the chamber further, but the beetles largely remained clustered on or around the archival wood (*Ibid.*). This is broadly consistent with Belmain's (1998) findings. He theorises that the slight preference decrease could be due to the attractant diffused more evenly through the chamber over time (Jefferys, 2021: 46-7). However, as this work was undertaken during the pandemic, the beetles, of unknown age, had to be posted to Jefferys, and only 3 survived the journey to participate in the experiment (*Ibid.*).

Beetle supply continued to be an issue for other projects. Nair (2023), building on Belmain's (1998) volatile work, examined volatiles from archival, modern and freshly cut oak, Douglas fir, European redwood and Iroko, comparing the differences between fungally degraded and non-degraded samples. Additionally, she tested DWB infested samples. Ultimately, the aim was to use the results of the volatile analysis to create a series of choice chambers to determine beetle preferences. However, unforeseen circumstances delayed the project beyond the beetle emergence period, and that element of the research remains for future. The wood samples were analysed with Fourier Transform Infrared Attenuated Total Reflectance Spectroscopy (ATR-FTIR) and the volatiles with Thermal Desorption Gas Chromatography Mass Spectroscopy (GC-MS) (Nair, 2023). The ATR-FTIR spectra showed that the beetle-attacked wood was generally less absorbent than the archival oak, with a noticeably lower peak at the 1700cm^{-1} wavelength, suggesting changes to the lignin and breakage of the lignin and hemicellulose structure (*Ibid.*: 50). The volatile analysis demonstrated a significant increase in the value of terpenes limonene and α -pinene in the beetle-infested wood, and a decrease in aldehyde component emission (*Ibid.*: 62). Although good results were obtained from this study, the presentation, analysis and interpretation would benefit from the review of a wood volatile specialist.

Beyond the NMRN and Cranfield collaboration, there has been little work into DWB. Creemers (2015) did some work on woodboring beetle activity at low temperatures and included the DWB in the species tested (more details in [section 3.2.2](#)). He found that DWB are active until 1°C, though their activity drastically decreases below 10°C (*Ibid.*: 578). But this study appears to be the only one containing any investigation on DWB. There are several databases, such as What's eating my collection? (Thompson Webb, 2024) and others (*NBN Atlas*, 2024; *Xestobium Rufovillosum* (De Geer, 1774), 2024; *UK Beetle Recording*, 2023), that track and map occurrences of species, by collecting evidence of infestations and activity. But these are dependent on the reports of contributors and offer sparse details, limiting the impact of the data. There have been some recent investigations into the use of *K. caeruleas* as a means of biological control of woodborers (Baar et al., 2022; Haustein et al., 2019), but this research appears to be ongoing, and will likely result in more publications in future.

The partnership between Cranfield and NMRN has led to several pioneering studies investigating different aspects of the DWB infestation on HMS *Victory*, one of which served as the instigator for this research. Like many of the earlier studies, these were initial investigations, and further work and investigation were called for by the researchers. However, they demonstrate how modern scientific techniques can be used to improve understanding of DWB infestations by examining the problem more broadly. Until the partnership with Cranfield and NMRN began (2016), there had been no investigations into DWB for over fifteen years.

What this history of research has demonstrated, and is continued with the NMRN/Cranfield collaboration, is that much of the work is instigated by severe infestations, prompting collaborative investigations from different disciplines. However, upon completion of the investigations (usually when funding ceases), the researchers move on, and the work is never continued. As the current period of investigation continues, this is something that should be considered and planned against.

While there is a long history of knowledge of the DWB, remarkably little is truly known about them. There are less than 200 papers published on DWB since the first record in 1668. When compared to investigations into the better known *A. punctatum* (Common Furniture Beetle) or more famous species like monarch butterflies (*Danaus plexippus*), the amount of literature on DWB is miniscule. Few researchers (Belmain, 1998; Menendez, 1990) have attempted to unite all existing knowledge in their contributions, but the lack of literature hampers investigations.

Much of the early work, now nearly a century old, focused on eradication rather than understanding the beetles themselves and is somewhat repetitive and inconsistent. Much knowledge is assumed, and the lack of clear methodology undermines the conclusions made, rendering most of the findings anecdotal. The more scientifically sound later studies contribute greatly to the understanding, but the lack of consistent investigation means that many of the experiments were never replicated. It has now been 25 years since the last major period of investigation took place. Technology has improved tremendously since then, and the most recent work has demonstrated its potential. Although the challenges of a long lifecycle and hidden lifecycle stages do hinder investigations to a degree, their status as a structural pest of historic structures should have instigated more research. It was not until the adoption of IPM practices in heritage spaces that the research shifted more towards understanding the species rather than eradication. Effective methods of dealing with pest infestations do exist ([Ch 2 Section 2.4](#)), but these are not applicable to HMS *Victory* due to the size, scale and location of the ship. Wider research into DWB is therefore key to effectively develop suitable management and treatment methods for situations like *Victory*.

Based on the literature review, there are few facts about DWB on which there is certainty as these are the few studies that have been replicated. Much is known about the anatomy of beetle and larvae, and they are known to follow the 'standard' beetle metamorphic cycle. Larvae are able to digest the major components of wood based on the enzymes present in their digestive tract. The

adults fly provided the temperature is above 17°C and are initially attracted to light following emergence. Activity for both adults and larvae appears to be linked to temperature. They are considered saproxylic organisms as they have a relationship with fungally decayed wood. The exact nature of this relationship is unknown. The list of what is unknown about the DWB is significantly longer, although there have been attempts to address some aspects and possible theories put forward. The number of larval instars and the duration of each stage of the lifecycle are still unclear. Although adults have demonstrated a preference for fungally decayed wood, whether there is a preference for a specific fungal species is unknown, as are larval preferences.

Maxwell-Lefroy, in his address to the Royal Society of Arts in 1924, states that the beetle needs someone to dedicate their life to their study, in order to consolidate all existing knowledge and perform necessary research into them to fully understand them (Maxwell-Lefroy, 1924: 7). Although some individuals, like Fisher, came close, it is not a practical thing to ask of one person. A more collaborative approach with a central repository is required. Although the English Heritage Woodcare project came close to this concept, much of the work and data is inaccessible to most. The partnership between Cranfield and NMRN has the opportunity to fill this gap and the potential to serve as the impetus for the next generation of research into DWB and perhaps answer some of the long-held questions about this interesting species. This thesis will contribute knowledge to the field by investigating the tunnelling behaviour of the DWB.

3.2 Non-invasive methods in cultural heritage and insect detection

This section is a more technical review and will focus on two areas: (1) it will examine non-invasive methods used in the recording, analysis and examination of cultural heritage and (2) non-invasive methods of insect detection. As the methods used in examining cultural heritage are well established, this section of the review will be less of a critical review. Instead, it will provide a brief overview

of common methods, their use in cultural heritage, how they work, and their limitations.

Although it has been acknowledged that early detection of insect infestations is key to preventing wide-scale, long-lasting damage, it is only in the past few decades that investigations into non-invasive methods of detection of insects have become more prevalent. Some methods are used for both cultural heritage and insect detection purposes. This section will examine the most prevalent methods used for insect detection, emphasising those used in this thesis, and those in common with cultural heritage research will be reviewed in the context of insect detection.

3.2.1 Non-invasive methods in cultural heritage

It is not possible to review all the non-invasive methods used in cultural heritage (Leucci, 2019). Instead, only those used in this thesis will be assessed. The methods under review can be sorted into two categories: recording and monitoring methods, and analytical techniques.

3.2.1.1 Recording and monitoring methods

The traditional methods of hand drawings and surveys to record and monitor cultural heritage still have their uses, but the slow, painstaking nature of recording using these methods means that they have been phased out and are now rarely used.

Photography captures images by recording light via an image sensor (digital) or through a light-sensitive material (chemical) (Verhoeven, 2016: 129-163). Although its use is now almost entirely digitally based, the speed with which images can be captured established it early as an excellent means of recording and monitoring for cultural heritage (Kuzminsky & Gardiner, 2012: 2746; Verhoeven, 2016: 127). Digital photographs can provide snapshots to show objects or sites at particular times and places, and images taken over time can demonstrate how they change, thereby providing a means of recording and monitoring (Silva & Oliveira, 2024). The rapid development of the field, equipment, and technology involved has meant that the equipment is readily

available, easy to use and affordable, making it a key tool for conservators and conservation scientists, as well as anyone with a role or interest in cultural heritage. There are still a few limitations that must be accounted for. Photography can only record surfaces and images are only two-dimensional (2D), which when imaging three-dimensional (3D) objects or sites, can present problems of distortion and missing areas (Verhoeven, 2016: 163). Transparent and reflective surfaces are also tricky to photograph (Balado et al., 2025). However, the 2-dimensional nature can be worked around by taking multiple images from different angles (Verhoeven, 2016: 163), and photography remains a quick, easy method for recording and monitoring cultural heritage.

Photogrammetry builds on from digital photography, as it uses high-definition digital photographic images to map and create 3D models (Balado et al., 2025; Bhatti et al., 2021). This is particularly useful tool for surveying, mapping of sites, and creating 3D models for public dissemination (Knott, 2017). Like standard photography, it does only record surfaces, but overcomes photography's issue of 2D presentation of 3D objects (Verhoeven, 2016: 163). Although the photographic element of the method is readily available and accessible, the software required to stitch the images together can be expensive, but is often relatively user-friendly (Balado et al., 2025: 9).

LiDAR (Light Detection and Ranging) is another non-invasive method used to record and monitor cultural heritage. It uses lasers (can be ultraviolet, visible or near-infrared light) to determine the range or distance of a surface from the emitter based on the time it takes for the light to reflect back to the detector (Balado et al., 2025: 2). This can be done in a fixed direction, or in multiple directions, the latter of which is more commonly referred to as 3D laser scanning (*Ibid.*). The software generates a point cloud of all the data points, which can then be used to generate a map or 3D model (Niu et al., 2024; Zhang et al., 2024). Point clouds are a set of points in space representing an object's surface (Lynn, 2021). The greater the number of points, the higher the resolution and detail, but the longer processing takes. Although it is only a surface-based method (see previous caveats), the use of lasers to detect subtle

changes in surface range means that hidden features are often revealed (Zhang et al., 2024). Changing the wavelength of the laser used also enables the scanner to penetrate things such as tree cover, a useful feature for cultural heritage sites in forested areas (Leucci, 2019: 21).

LiDAR equipment for surveying is often specialised and expensive, as is the software to process the point clouds and generate models, and all require training to effectively use (Balado et al., 2025: 7). 3D laser scanners (handheld or mounted) are generally easier to operate, and the software is more user friendly, albeit it can be expensive (*Ibid.*). The scanners themselves vary in price, but the cheaper models often lack the resolution required to record sufficient detail for intricate and detailed objects (*Ibid.*: 4). Transparent or reflective surfaces are almost impossible to laser scan unless covered with a matting agent, which is not possible with cultural heritage (Amir & Thörnberg, 2017; Aubreton et al., 2013).

Photogrammetry and LiDAR can be used in conjunction with the other to increase accuracy (Bhatti et al., 2021), and the resulting data can be overlayed to aid with interpretation. Both laser scanning and photogrammetry can be used to track changes in set intervals by taking regular surveys extremely quickly (*Ibid.*). In addition to equipment and software costs, the major drawback to both photogrammetry and LiDAR is the enormous data output (Broadman & Bryan, 2018: 41; Zhang et al., 2024: 12). Datasets require storage, and digital storage and file formats come with their own host of issues, such as obsolescence and environmental costs (Quattrini et al., 2017: 130), all of which need to be planned for and accommodated. That being said, the speed, accuracy, and level of detail, along with the generation of 3D models for research, accessibility, and public outreach are considered more beneficial than the drawbacks. Additionally, the availability of 3D models often aids conservation, as the ability to manipulate, measure and closely examine the models minimises the amount of handling on historic objects, which is of great benefit to fragile objects (Kuzminsky & Gardiner, 2012: 2746).

The taking of regular surveys led to the development of Building Information Modelling (BIM) in architecture, engineering and construction (AEC), which were then adapted for heritage use (HBIM) (Penjor et al., 2024; Pocobelli et al., 2018). The modelling process collates all the information regarding the physical, functional, and intangible characteristics of a heritage site into centralised computer files that can be shared and accessed by anyone involved in the maintenance, repair and general conservation of the site (Antonopoulou & Bryan, 2017). It is not as widespread in its heritage use as in its AEC applications, but it is becoming more prevalent (Antonopoulou & Bryan, 2017; Elbaz et al., 2020; Martinelli et al., 2022; Pocobelli et al., 2018; Z. Zhang & Zou, 2022). The conservation team at NMRN has adapted the HBIM model to create the VIM (*Victory* Information Model) (Thornber & Pacheco-Ruiz, pers. comm. 2023). Both laser scanning and photogrammetry are used to take regular surveys as the conservation programme progresses to monitor structural changes (*Ibid.*). The data from these surveys is input into the model, allowing the team to track changes over time. The model has information on each component of the ship, with details on installation, material, repairs, marks, and more (*Ibid.*). Each component can be isolated from the model and examined minutely (*Ibid.*). Laser scanning and photogrammetry were chosen for this thesis to ensure compatibility with the VIM model.

3.2.1.2 Analytical Techniques

There are many analytical techniques that can be used for cultural heritage to reveal information about materiality, decay, previous conservation treatments and more (Liu & Kazarian, 2022). But due to its uniqueness, value and cultural significance, the methods used should be as minimally invasive as possible (*Ibid.*). There are a number of commonly used methods, most of which are completely non-invasive. There are some that are considered micro-invasive as they require very small samples, but they can often reveal essential information that could not otherwise be determined, and the methods themselves are non-destructive, enabling samples to be reused (*Ibid.*). It can be challenging to balance the needs of analysis with the requirements of cultural heritage, and in some cases, the information from more destructive analysis of a small amount

of heritage material may aid in understanding and survival of a much larger proportion. The methods used in this thesis were non-invasive and non-destructive whenever possible. There were some methods that required destructive sampling, but the information from this destruction enabled greater insights into the DWB, therefore, ensuring a greater chance of survival for HMS *Victory*. A basic explanation of the principles behind and the limitations of the techniques used in this thesis, as well as examples of their use in cultural heritage more widely will be given.

3.2.1.2.1 Scanning Electron Microscopy

Scanning electron microscopes (SEM) obtain images of a sample's surface by moving a low energy beam of electrons across the surface (Ford & Joy, 2024). Electrons have a much shorter wavelength than light, which enables images to be taken at higher resolutions (Nagle, 2019; Omid et al., 2017). The electrons hit the sample surface then bounce back, and are called secondary electrons, backscattered electrons and diffracted backscattered electrons (Mokobi, 2024; Sharma, 2023; Webb & Holgate, 2003). Secondary electrons emitted by the sample detect the morphology and topography, and the backscattered electrons show contrast between the elements in the sample, which, when detected, creates an image (*Ibid.*). The excitation of the elements on the sample surface by the electron beam causes the emission of X-rays, which is then detected by the energy-dispersive spectrometer within the microscope, generating a spectrum of elements present, with peaks approximately corresponding to their relative quantities (Bitossi et al., 2005; Cichocki, 2023; Nanakoudis, 2019; Shukla, 2023). The specimen chambers of SEMs are typically small, limiting the size of the sample (*Sample Preparation Techniques*, 2024). Samples are mounted onto an aluminium specimen holder with a conductive adhesive, usually carbon-based (Raspolini, 2019). The specimen holder then slots into the stage. Non-conductive samples may then be further secured with conductive tape or coated with a conductive coating (*Ibid.*). Alternatively, the sample can be imaged under a vacuum. The vacuum is to prevent the accumulation of electrostatic charge and enhance image clarity (*Ibid.*).

Although SEM requires small samples to be taken from heritage objects, the technique with its high resolution, magnification, and potential for elemental analysis, can reveal valuable information about the materials, composition, and decay that otherwise would not be gleaned (Genestar & Palou, 2006; Pinto, 2019). Tiny cross-sections of paint samples from a Brazilian mural enabled the identification of the stratigraphy, texture, mineralogy and chemical composition of the paints, consequently revealing valuable information about the techniques, pigments and materials used by the artist, Fulvio Pennachi (Magon & Del Lama, 2019). SEM was used to examine the chemical and physical changes of the effects of aqueous-based alkaline conservation treatments on smalt (cobalt glass pigment) in wall paintings (Manship et al., 2023). *Oryza sativa* (rice) fragments, identified with SEM, from paddy straw were found in fragments of ancient decorative earthen plasters from Northwest China (Dighe et al., 2019). This discovery provided a greater understanding of the environment of the site at the time, the materials and techniques used in the creation of the plaster and provided researchers with key information to develop compatible materials for conservation and restoration (*Ibid.*). These are just a few examples demonstrating some of the potential uses of SEM in the analysis of cultural heritage. The biggest barrier to SEM use is access to facilities and equipment. However, many larger heritage institutions and universities will have SEMs that can often manage multiple samples at a time, and may offer an imaging service (*Access Our World-Class Facilities, 2024; Scientific Research, 2024*).

3.2.1.2.2 Radiography

To obtain an image using radiography, an object is placed on a photo detector (digital or sensitive film) and bombarded with X-rays or gamma rays from a radiation source (Magdy, 2023: 9). The X-rays will pass through or be absorbed by the materials present depending on the density of the material (*Ibid.*). The more X-rays that are picked up by the detector, the darker the image will appear. The less X-rays, the brighter white the image. This creates a negative, 2D image, which can cause issues with superimposition and makes it extremely challenging to determine the depth of features (*Ibid.*). Because the radiation passes through the object, it allows for the visualisation of internal structures

and abnormalities that might not be visible (*Ibid.*). The clarity of the image is dependent on the density and thickness of the material and the distance between the object, detector and X-ray source. Adjustments to the energy of the X-ray beam, current and exposure time can be made to allow for differences in material and density (Cronyn, 2005). Exposure to radiation, for both objects and researchers, is a key concern when using radiography (Gibson, 2023). Protective measures must be taken to limit exposure to those imaging and anyone in the vicinity. Many materials (i.e. metals) are able to withstand radiation with minimal to no effects, but in the case of more sensitive materials like inks (higher water content), radiographic images should only be taken when necessary (*Ibid.*).

In addition to the visualisation of internal structures, it is a quick, mostly reliable, and often portable method that has long been used by conservators. It is commonly used in archaeological conservation, particularly for metallic objects ([Fig. 24](#)), as radiographic imaging of concretions of corrosion products reveal what is inside the concretion and provides a key guide for the conservator undertaking conservation work (Cronyn, 2005; Rimmer et al., 2013). For historic objects ([Fig. 25](#)), radiography often reveals valuable information about the construction (Gibson, 2023; Oliveira et al., 2023) and previous conservation work (O'Flynn, 2021). In the case of wooden objects, it can visualise internal damage caused by woodboring pests (more in section 3.2.2).



Fig 9. X-ray of object showing underlying features. © The Trustees of the British Museum

Figure 24: Radiograph of an archaeological metal object with underlying features beneath corrosion layers outlined in red (outline by author). Image taken from Rimmer et al, 2013: 8

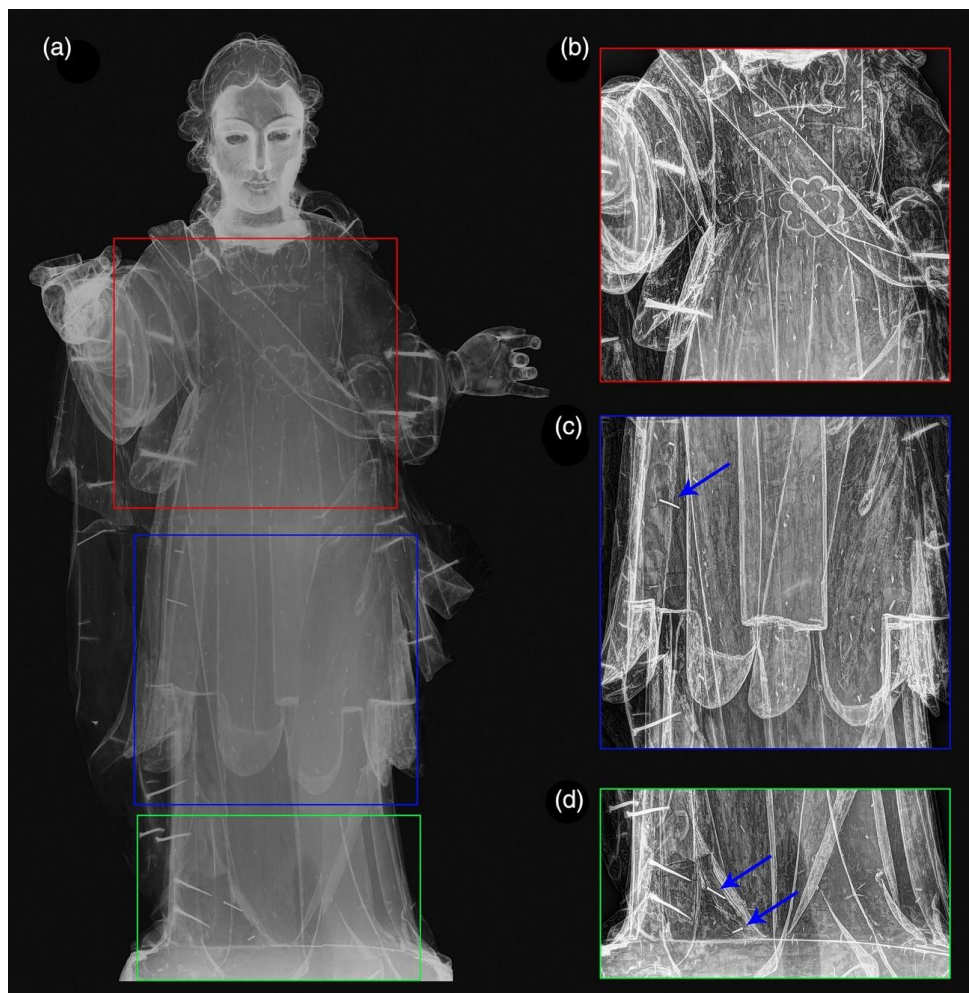


Figure 25: Radiograph image of a wooden statue with enhanced sections showing hidden details, like nails and pins. Image from Oliveira et al 2022: 319.

3.2.1.2.3 Micro-CT

Computed tomography (CT) takes X-ray images incrementally (projections) of an object (Herman, 2009: 27-32; Landis & Keane, 2010: 1306). These projections are then digitally constructed to form a 3D image (*Ibid.*). The better-known form of CT is the type seen in hospitals (Fig. 26), where the X-ray beam and photosensitive detector move within a ring around a static object, usually a patient (Herman, 2009: 5).

Micro-CT works under the same principles, but the beam and detector are fixed, and the object rotates on a stage between the beam and detector ([Fig. 26](#)) (Herman, 2009: 13; Landis & Keane, 2010: 1306). This allows for a higher resolution than can be obtained with a medical CT, but size is limited by the confines of the chamber of the machine (Landis & Keane, 2010: 1306). Although micro-CT can be classed as a non-invasive method in terms of the literature review, it is not always non-destructive, as chamber limitations often necessitate smaller samples. Like radiography, radiation exposure for researchers is a concern, but for most micro-CT machines, the X-ray source, detector and stage are within a lead-lined chamber (Gibson, 2023; Wilson et al., 2018).

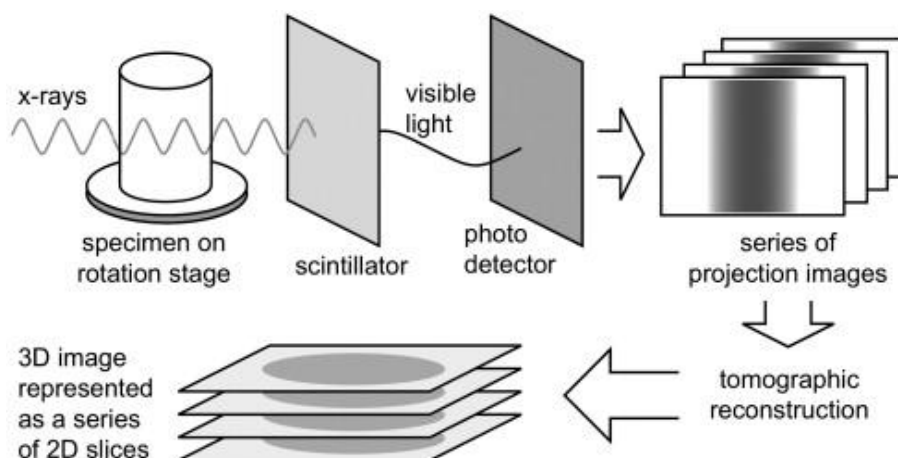


Figure 26: Diagram of micro-CT process to create a 3D image. Diagram from Landis & Keane 2010

The resolution of the 3D image is measured in volume elements, called voxels (Herman, 2009: 31). 2D image resolution is measured in pixels, a square unit. The greater the number of pixels in a given area, the higher the resolution (*Ibid.*). Voxels are essentially cubic pixels.

These voxels can be processed and sorted according to their grey value (density) by setting thresholds in a process called segmentation (Brock et al., 2024). The values are dictated by the radiodensity of the material, given in Hounsfield Units (HU), also called CT-numbers (Broda et al., 2015: 708; Herman, 2009: 32). The HU Scale is a linear transformation of the original linear radiodensity measurement to a scale in which the radiodensity of distilled water at standard temperature and pressure is 0HU, and air is -1000HU (*Ibid.*).

Micro-CT is an invaluable tool for conservators and conservation scientists when examining cultural heritage objects. Where micro-CT particularly excels is in examining wrapped, sealed or furled objects without the need to destructively examine them (Allegra et al., 2016; Gibson, 2023: 3). A cuneiform tablet at the British museum that was wrapped in a clay envelope was imaged with micro-CT to reveal an inscription that had not been seen for >4,000 years without any damage to the object (O'Flynn, 2021). Papyri from Herculaneum were virtually unrolled using the data from micro-CT scans (Stabile et al., 2021; Stromer et al., 2018). The contents of funerary urns can be examined without micro-excavating the contents (Waltenberger et al., 2023), and 3D maps of historic conservation efforts can be generated (Wilson et al., 2018). It is becoming a more common tool to dendrochronologically date wooden objects without taking a sample, and examine the effects and damage caused by fungal attack and wood-boring beetles (De Mil et al., 2016; Van den Bulcke et al., 2008, 2014). Three cornetts, made of wood wrapped in thin leather, from the Rijksmuseum were scanned with micro-CT (Dorscheid et al., 2022). Not only were the researchers able to examine the construction of the cornetts, but they were also able to assess the extent of *A. punctatum* damage (*Ibid.*). Although there was damage to all components, including the leather exterior, the majority of the damage was confined to the upper section of cherry wood, leaving a thin skin of wood, that

was not visible from the outside (*Ibid.*: 6-7). Micro-CT's use for insect development will be discussed in [Section 3.2.2](#).

As micro-CT takes thousands of X-ray images, there are greater concerns regarding radiation exposure to the objects being scanned (Gibson, 2023). However, these are balanced against the potential damage that could be caused by unfurling or unwrapping the object, and the sensitivity of the materials involved. In most cases, the effects from radiation from a micro-CT scan are minimal when compared to the potential damage from more interventive methods.

The biggest limitation to micro-CT as a method for analysing cultural heritage is the lack of accessibility. The equipment is tremendously expensive, and it requires expertise to run, process and interpret the data (Bossema et al., 2024). It is only the largest institutions that have ready access to micro-CT, and although they and other places may offer a service to have objects scanned, this is beyond the reach of many heritage institutions (*Ibid.*). However, with research projects, much like this thesis, it may be possible to work around this. As technology advances, it may become more accessible over time. There have already been investigations into enabling 3D CT-scanning of heritage objects using standard 2D X-ray equipment that show promise (*Ibid.*).

3.2.2 Non-invasive methods of insect detection in timber

The detection of active pest infestations and pest damage has long been a challenge in many industries, including cultural heritage. In the past, detection has relied on the presence of adult insects, visual damage and systematic sampling (Chesmore & Nellenbach, 2001; de Reyser et al., 2005). The latter in particular has been a mainstay for the timber industry, where trees are systematically sampled and cut into to determine active infestations (Chesmore & Schofield, 2010). This is not a viable solution, as the timber is then unusable, generating economic loss (*Ibid.*).

Although the need for non-invasive insect detection has long been identified, it is only in the past 2 decades that it has become an increasingly active area of

research with promising outputs (Mankin et al., 2011; 2021). Much like with IPM, the research began with the agricultural industry (*Ibid.*). It was then swiftly adapted by the timber trade, and in the past few years, is being investigated for use in cultural heritage (de Reyer et al., 2005; Kisternaya & Kozlov, 2007; Le Conte et al., 2014; Lima et al., 2020). This section of the review will examine the methods being applied to cultural heritage, focusing on the detection of woodborers, but will consult and refer to literature from other fields.

3.2.2.1 Bioacoustics

Bioacoustics uses acoustic detection equipment to determine and monitor the presence of insects within materials, by listening for the sounds created by activity (Mankin et al., 2011). Acoustic detection has long been used in the animal kingdom, by creatures such as bats and dolphins (inspired sonar technology), and by many insects (Mankin et al., 2021; Mankin et al., 2011; Takanashi et al., 2019; Virant-Doberlet et al., 2019). Spiders, parasitic wasps and scorpions detect prey through vibrational cues (Virant-Doberlet et al., 2019). Sound waves fall into three categories depending on the frequency: infrasonic, sonic or acoustic (what humans can hear), and ultrasonic (Au & Zwank, 2020; Grogan & Mount, 2023; Thapaliya et al., 2024). Infrasound are frequencies below 20 Hertz (Hz), ultrasound are frequencies >20 kHz, with acoustic frequencies falling between the two (*Ibid.*).

Bioacoustics was proposed as a means of detecting active pest infestations as early as 1909 (Mankin et al., 2011: 30), and was suggested as a method for detecting woodborers by Fisher and Tasker in 1940, but the equipment and technology has not been capable of reliably detecting the faint sounds until relatively recently (Mankin et al., 2011). Investigations into acoustic detection for monitoring of insects began to become a topic of research for stored agricultural products in the late 1980s-1990s (Klaassen & Furgason, 1988), but many were hindered by the limits and expense of the equipment available at the time (Mankin et al., 2021). It is in the last 20 years with advances and decreased costs of equipment that the research into acoustic detection of woodborers has really blossomed (*Ibid.*). This review will provide a brief overview to provide

context for the research, but there are a number of excellent review articles further detailing the state of the research in bioacoustic detection of pests that are worth reading (Kohlberg et al., 2024; Lima et al., 2020; Mankin et al., 2011, 2021).

The noises made by the larvae as they feed and tunnel through wood are incidental, impulse-like sounds of short duration, caused by the breaking of the fibres by their mandibles (Chesmore & Schofield, 2010). There are all kinds of acoustic equipment available, with the most basic being a stethoscope, which was identified early as a means of listening to the sounds (Mankin et al., 2011). However, it is reliant on the listener and the activity of the insects at the time of listening, and is not a suitable method for long-term monitoring. The most success in the detection of woodborers has been had with ultrasonic sensors (Mankin et al., 2011: 31). There are many different types of ultrasonic sensors. The most commonly mentioned in the literature are piezoelectric sensors and accelerometers. A piezoelectric sensor converts the ultrasonic vibrations into an electrical charge that can then be measured (Jiao et al., 2020). An accelerometer (which can contain a piezoelectric sensor) can detect the vibrations caused by the ultrasonic waves (Bhairavi et al., 2020; Mukherjee et al., 2017). Both of these require physical contact with the substrate to detect the vibrations. Laser doppler vibrometers are becoming more prevalent, as they detect vibration amplitude and frequency from the Doppler shift of the laser beam frequency, and do not require physical contact (Zorović & Čokl, 2015).

One of the earlier studies on acoustic detection of woodboring beetles was from the Woodcare project (Section 3.1.2.4), specifically examining the detection and acoustical monitoring of DWB larvae (van Staalduinen et al., 2001). Initial experiments were conducted in a laboratory setting with wood known to contain DWB larvae, before scaling up the experiment to test on timber structures (*Ibid.*). A variety of different piezoelectric acceleration transducers were used, capable of measuring a frequency range of 1-25000 Hz, alongside conditioning equipment, band pass filtering, an amplification and a computer with a converter board (*Ibid.*: 95). Their tests even demonstrated a possibility of distinguishing

between beetle types (house longhorn, DWB, and common furniture) based on the acoustic signatures of the larvae (*Ibid.*: 96). The paper fails to mention the method of attachment for the sensors, of which there is a range of options, from the insertion of nails or screws to the use of adhesives or contact gels (Farr & Chesmore, 2007; Mankin et al., 2011). Although the results demonstrated potential of the method for DWB larval detection in both laboratory and real-life settings, there appears to be no evidence of further work on this research. In the concluding remarks of the conference, Brian Ridout states that “Acoustic detection has now been developed but is not yet commercially available in the UK.” (2001a: 4). He gives no references to support this statement, although presumably he is referring to van Staalduinen et al’s (2001) work. No evidence of commercially available pest detection could be found from anywhere in the world and given the recency of most of the studies on the topic, it seems unlikely that the method is available on a commercial scale.

The late David Chesmore was one of the most prolific and profound contributors to acoustic detection of insects. His work over twenty years used acoustics to detect insects from grasshoppers and crickets to many species of woodboring beetles. His early work (Chesmore, 2004; 2007; Chesmore & Nellenbach, 2001) demonstrated that acoustic monitoring could be used to monitor biodiversity using artificial intelligence (AI) to identify species based on their acoustic signatures. His supervision and work alongside Schofield (Chesmore & Schofield, 2010; Schofield, 2011; Schofield & Chesmore, 2008) tested and developed sensors and methods for use on woodboring larvae detection. Their focus was on imported timbers, but they acknowledge the potential application for historic wooden structures (*Ibid.*). They were able to determine that piezoelectric sensors were the most cost-effective non-invasive device to detect activity (*Ibid.*).

Investigations into bioacoustic detection use for cultural heritage have found success. Kisternaya & Kozlov (2007) incorporated acoustic sensors and stethoscopes into their IPM plan (1998-2008) to monitor woodboring beetle activity following microwave treatment of the timbers at the Kizhi open-air

museum in Russia. They had most success detecting activity May-June, and limited success from July-Aug (*Ibid.*). They suggest that it is because the larvae were too small to detect immediately after hatching (*Ibid.*). Work by Le Conte et al (2014) a few years later on wooden musical instruments were able to detect larvae as small as 1-2mm. The fact that Le Conte et al (2014) were able to detect smaller larvae, where Kisternaya and Kozlov (2007) were not, may be due to the scale (musical instruments vs. timber structures) or equipment sensitivity.

Krajewski et al (2012; 2020) in their investigations into bioacoustic detection of old house borer larvae were able to detect their presence with 70-80% success in lab tests simulating field work, and observed differences in frequency range between species (10kHz house longhorn and 20kHz *A. punctatum*). A similarly high success rate was had by Sutin et al (2017; 2019) in their method testing for Asian Longhorn Beetle and Emerald Ash Borer infested wood.

Krajewski et al (2020) also tested the effects of temperature on acoustic detection of larval activity and found that activity was detected up until 40°C, with a notable decline in detection above 34°C, suggesting a significant decrease in activity. They also noted that house longhorn larvae exposure to 40°C for a week did not cause death but did cease their activity (2020: 6). Creemers (2015) also investigated the effects of lower temperatures on a variety of woodboring beetles, including the DWB, using bioacoustics. He found that DWB activity was about halved every time the temperature was lowered 2°C from 10°C, with activity only ceasing when the temperature hit 1°C (*Ibid.*: 578). He also observed that temperature was a stronger indicator of activity than circadian rhythms for all species tested, but that periods of inactivity can last up to 30 minutes (*Ibid.*: 579).

Much of the other work into the acoustic detection of woodboring beetles in heritage focuses on house longhorn beetle (*Hylotrupes bajulus*) larvae, as they can grow up to 30mm in length (*Hylotrupes Bajulus* (Linnaeus, 1758), 2016). Fiala et al (2014) designed and tested acoustic methods in both lab conditions and outdoors with semi-automatic evaluation and comparison of signals.

Although the prototype appeared successful, no evidence of further work by the authors could be found. Bilski et al (2017) also applied signal processing and AI methods to detect old house borer larvae in furniture and wooden buildings.

Zorović & Čokl (2015) successfully used a laser vibrometer to detect Asian longhorn beetle in poplar logs. Although they are completely non-contact, something highly beneficial when dealing with cultural heritage, the expense and size of the equipment does not make laser vibrometers as accessible when compared to other sensors.

There has been more research into the acoustic detection of agriculturally devastating pests like the Red-palm weevil (RPW) when compared to woodboring species affecting heritage sites. Brandstetter & Hübner (2015) used pattern recognition algorithms to detect characteristic larval noises in an urban area of Mallorca amongst background noise of wind, traffic, speech, electromagnetic interference, lawnmowers and other sounds. Ashry et al. (2020) developed an optical-fibre-distributed-acoustic sensor that was able to detect 12-day-old RPW larvae in an infested tree. Not only is this method completely non-invasive, as the singular fibre optic cable runs from a sensing unit and is simply wrapped around each tree (*Ibid*: 2), but it provides 24-7 monitoring at a relatively low cost (*Ibid*: 1).

Bioacoustic detection of woodborers has been proven to work successfully, as these studies and others demonstrate. However, most of the literature focuses on the development of new methods as technology constantly improves, rather than the long-term application (Kohlberg et al., 2024). This could be a contributing factor to the lack of commercial acoustic monitoring systems. Some attempts at developing systems have been made in recent years (Ashry et al., 2020; Biebl & Wapler, 2023; Rigakis et al., 2021), and it will be exciting to see what develops as a result. What the literature makes clear is that bioacoustics is a successful technique capable of detecting larval activity with a number of different methods. Laser vibrometers are fantastic in that they are completely non-contact, but the expense and size of the equipment do not make it as viable an option for long-term monitoring. Accelerometers and piezoelectric sensors

are more promising in that regard. But the development of a monitoring system and data processing does require expertise. Background noise, a significant challenge in acoustics, can successfully be filtered by tailoring the sensors used and in processing with AI, but again, this requires a degree of expertise. Automated identification of woodboring species has proven to be successful, but further investigations of other species is still required. The remaining challenge is in developing it into a monitoring system specifically for heritage use, as there are the unique challenges of visitors and their effects (footfall, vibrations, speech) to consider. However, something as simple as a stethoscope can be used for quick listening and is easily used by anyone.

3.2.2.2 Ultrasound

Although technically falling under the acoustic category, to distinguish it from bioacoustics for the purpose of this review, ultrasound refers to devices that send an ultrasonic pulse through a substrate to detect objects and measure distances (Au & Zwank, 2020; Demaus, 2001; Grogan & Mount, 2023; Thapaliya et al., 2024). Ultrasonic imaging, most commonly used in medicine and is the form most familiar to many, sends an ultrasonic pulse from a probe into tissue (*Ibid.*). The waves reflect off tissues with different reflection properties, are detected by the probe, and are then converted into an image (*Ibid.*). As sound waves travel better through liquid rather than air, the water content of the substrate will influence the clarity of the resulting image (Unterwieser & Schickhofer, 2011). It is why the method works well for medical and veterinary imaging (*Ibid.*).

There are several different experimental set-ups and methods of ultrasound for use on timber. Ultrasonic attenuation spectroscopy, ultrasonic-echo, through-transmission, air-coupled ultrasonic method, and ultrasonic-computed tomography are a few (Oh et al., 2015). Through-transmission is the method most commonly used to detect defects in timber (*Ibid.*), but they all work under similar principles, and are equally dependent on the moisture content (MC) of the wood for transmission of the sound waves (Teder et al., 2012). An emitting transducer sends ultrasonic impulses through the substrate, which are then

detected by a receiving transducer (Fleming et al., 2005; Jasienko et al., 2013; Kasal & Tannert, 2011; Leininger et al., 2001; Oh et al., 2015). The time it takes for the receiver to detect the impulse is referred to as the Time of Flight (TOF), and is dependent on several parameters, including amplitude, energy and pulse length (*Ibid.*). The recorded signals (time-domain) can then be converted into other formats with algorithms for interpretation (*Ibid.*). The basic principles and an example set-up can be seen in [Fig. 27](#):

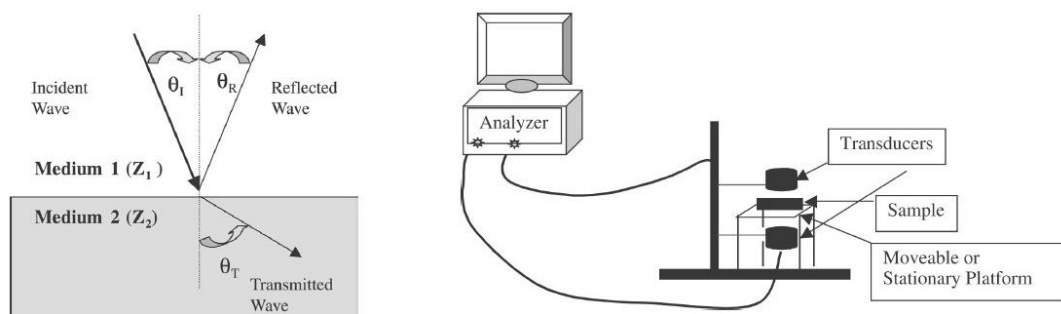


Figure 27: Basic principles of ultrasound detection, with an example set up. Diagrams from Fleming et al 2005: 34

Most of the literature on the use of ultrasound for cultural heritage has focused on the detection of the damage caused by woodborers rather than the detection of the larvae themselves, and the literature suggests it works well detecting voids (Cavalli & Togni, 2015; Jasienko et al., 2013; Kasal & Tannert, 2011; Lee et al., 2013; Leininger et al., 2001; Marchetti et al., 2004; Teder et al., 2012). Fleming et al (2005) were the first to apply ultrasonic methods to the detection of active infestations in timber and remain one of the few to have done so. They examined timber containing larvae with an air-coupled ultrasonic system and found that the system was able to detect holes caused by the woodborers, as well as a larva crawling across the sample surface, but was unable to detect larvae when they were within the holes (*Ibid.*: 36). Although they did not attempt to detect active larval infestation, Oh and Lee (2014) noted that in previous studies of insect damage, the systems used could only detect larger tunnels, not the small initial tunnels formed by larvae early in an infestation. They tested ultrasonic attenuation spectroscopy to see if it was capable of detecting small larval tunnels. While the method was more successful than conventional

ultrasound methods at detecting small tunnels in the timber, it did require pretreatment of the data before processing (*Ibid.*: 25). They retested the method the following year with some improvements to the method (Oh et al., 2015), and had consistent results.

The use of ultrasound for defect detection in wood is well established, and it has proven capable of detecting damage caused by woodboring insects. The research into its use as a means of detecting active infestations has been extremely limited. Only one study expressly testing that function could be found, and their results demonstrated that ultrasound methods would not be able to detect live larvae within wood. Whether technological improvements in the nearly 20 years since the study was conducted would impact results of further investigations is unclear. But it still remains a useful tool in the detection of voids within wood.

3.2.2.3 Thermography

All objects with a temperature above absolute zero emit infrared (IR) radiation (Demaus, 2001: 101; Pitarma et al., 2019: 481). IR is electromagnetic radiation with wavelengths between 400 THz and 300 GHz (Al-doski & Mansor, 2016: 16). Within this range, IR is divided into three bands (definitions vary): far (0.3-37THz), mid- (37-100THz), and near (100-400THz) (*Ibid.*). Thermal imaging, or thermography, detects that radiation with a camera and presents the data as an image (Mercuri et al., 2015; Paoloni et al., 2020). It is a completely non-contact method.

There are two types of cameras capable of detecting this radiation: thermal cameras and IR cameras. Although they sound like the same thing, and are often used interchangeably, they are subtly different. Thermal cameras detect the radiation in the far and mid-IR range emitted by objects as a result of their temperature, displaying the differences between the image subject and its surroundings in an image (Rogers, 2024). Heat (IR radiation) will always travel from warmer bodies to cooler, creating temperature gradients (Demaus, 2001: 101). Thermal cameras do not require a light source to capture images, as the sensor will heat in response to the radiation before converting the reading into

an electrical signal, which is then converted into an image (Rogers, 2024). All thermal cameras are technically IR cameras, but not all IR cameras are thermal cameras. IR cameras detect near-IR that is both emitted and reflected from objects based on the surrounding light (*Ibid.*). While they are able to take images in lower light levels than a standard camera, they cannot take images in total darkness the same way a thermal camera can (*Ibid.*).

There are two different types of thermal imaging: active and passive (Dritsa et al., 2022; Mercuri, 2012; Paoloni et al., 2020). Passive thermography reflects the temperature of an object based on the ambient temperature around it. In active thermography, the object is heated by an artificial source. As materials absorb and reflect IR radiation at different rates depending on their composition (*Ibid.*), this heating will vary across materials. If the object's material is uniform, it should absorb and reflect the radiation evenly across the material (*Ibid.*). If there are any defects or abnormalities within the material, it will absorb or reflect the radiation differently, which will be reflected in the image (Mercuri et al., 2015: 1190). Hidden timbers in a building will often have a higher moisture content than the surrounding wall materials and therefore appear cooler (emit less IR radiation) in the resulting image (Demaus, 2001).

Although insects are poikilothermic (their temperature reflects the ambient temperature) (Keszthelyi et al., 2020: 8), their temperature changes will be less rapid than the surrounding material, and consequently, they will contrast in a thermal image (*Ibid.*). Palmer et al. (2004) used IR video thermography to assess cold adaptation in alpine insects by monitoring insect response to temperature changes.

It has successfully been applied to the detection of social woodboring insects like termites (El-Hadad, 2017: 34-5). Higher moisture areas resulting from termite activity can be distinguished, along with clusters of the termites as they concentrate ([Fig. 28](#)) in one area to feed (James & Rice, 2002).



Fig 1a. Visible image of door jam, no evidence of termite infestation

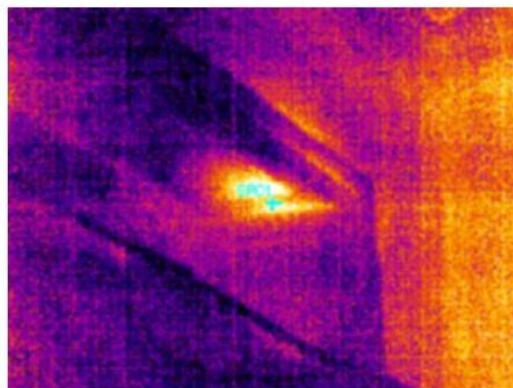


Fig 1b. Thermal image of door jam, with yellow hot spot indicating termite activity.

Figure 28: Normal and thermal image of a door jamb with a termite infestation. The cooler areas in the wood are likely the result of a higher MC, making the contrast of clustered termites starker. Images from James and Rice, 2002: 2

Thermography, in addition to bioacoustics, has also been successfully applied to the detection of RPW-infested trees. Although the larvae themselves are not detected as they are too deep within the timber, the distressed tree's trunk and crown temperature increases as a result of the intensive fermentation of the plant tissue, detectable with an IR or thermal camera (Ghulam Rasool et al., 2020; Massimo et al., 2018; Sobeah et al., 2021; Soroker et al., 2013). A similar effect has been observed in pest-infested wheat (Keszthelyi et al., 2020)

Conde et al. (2012) assessed thermography use on wood by artificially simulating various types of damage caused by fungi and insects on wet and dry wood. They found that they could only detect deformities when the MC differed with passive thermography: if the MC was the same across the wood, no defects could be noted in the thermal image (*Ibid.*: 44). However, this was not the case with active thermography (*Ibid.*). They were able to distinguish defects up to 1.5cm below the surface, but only those above 1x1cm, which meant they were unable to detect smaller defects like insect galleries (*Ibid.*). Pitarma et al. (2019) expanded on the work by Conde et al (2012), further examining the differences between active and passive thermography using the same make and sensitivity thermal camera. They note its use on American wooden railway bridges that had been hollowed out by insect damage but appeared sound on the outside, although they do not provide a reference for this information (*Ibid.*: 481). Their methodology was slightly different, as they packed the artificial galleries with sawdust to simulate frass (*Ibid.*). They were able to detect the

artificial galleries, but it must be noted that their samples were thinner than Conde et al (2012). They also observed that it was easier to detect the galleries at higher temperatures, as there was greater contrast between the surrounding wood (*Ibid.*: 486). Similarly mixed results were obtained by Hoffmann et al., (2013) with larval goat-moths (as a substitute for the Citrus Longhorn Beetle) in maple and poplar. They do, however, provide a thermal image (using active thermography) of *A. punctatum* galleries in a dried lathe that are clearly visible (*Ibid.*: 339).

The use of thermography for the detection of woodboring insects appears to have variable results in the literature, with some reports of success and others of failure. It does, however, appear to be capable of picking up proxies of insect infestations (i.e. moisture content with termite damage). It may be a case where it can be a supporting tool alongside other methods for use in woodboring insect detection.

3.2.2.4 Radiography

A description of how radiography works, and the general limitations can be found in [Section 3.2.1.2.2](#). This section will examine its use as a method for insect detection.

Much like bioacoustics, the potential use of radiography for detecting woodboring larvae was identified early. Fisher and Tasker (1940) used radiography to examine woodboring beetle larvae, including DWB. However, in Fisher and Tasker's and other early studies, the exposure times were long (up to 15 min), and although insects are more tolerant of radiation (Haff et al., 2020), this length of exposure was likely to have killed them. Additionally, the thicker the wood being imaged, the harder it was to detect the larvae (Fisher & Tasker, 1940). Belmain (1998) used radiography to assess DWB larval density in culture samples during the course of his research.

Although there is a long history of use of radiography to detect the presence of woodborers, many of the earlier studies were limited to lab-based settings, due to the lack of, then expense of, portable equipment (Anthony et al., 2005). As

equipment became more accessible, a number of studies were conducted under field conditions. Jansen & Hemming (2011) developed and assessed a method of validation for borehole detection in intact trees using portable X-rays. Wedvik et al. (2016) examined the use of digital radiography for assessing pest and fungal damage to historic timber structures. While the studies found it was possible to image the damage caused by woodborers, the superimposition of features meant that it was impossible to quantify the damage, and often made interpretation challenging (Anthony et al., 2005; Jansen & Hemming, 2011; Wedvik et al., 2016). Applications *in situ* in timber structures were limited to timbers with access to both sides for the placement of the X-ray source and detector (Wedvik et al., 2016: 648).

Nowakowska et al. (2017) used X-ray images to measure the size of old house borer larvae which were then compared to measurements taken upon extraction during tests for treatments. Although the measurements were generally consistent and were accurate for the X-ray images, the experiments also showed that the X-ray images did not always faithfully illustrate the true larval length due to the position of the larvae within the wood or against the detector (*Ibid.*: 86-7). In their reviews of non-invasive pest detection, both Hassan & Nanda (2024) and Keszthelyi et al. (2020) note the success of radiography to detect the presence of pests in wood and agricultural products without dissection and characterise the damage and its extent, but that it cannot be used to quantify the damage. Only the number of individuals can be relatively reliably quantified, but the superimposition of features and the 2D representation of 3D objects prevents complete certainty.

Radiography is an excellent tool for a quick assessment for the presence of pests within timbers without destruction. However, it does have limitations that must be considered, and the health and safety risks associated mean that careful consideration must be used before the application of this method.

3.2.2.5 Micro-CT

As mentioned previously in [Section 3.2.1.2.3](#) (and where a description of how the method works can be found), micro-CT has been used to assess and

visualise the damage caused by woodboring pests on heritage objects (Dorscheid et al., 2022). Although it could be used as a means of infestation detection for small objects, it is not the most practical (lab-based only, long scan times) and is unlikely to be used for detection and monitoring. However, it is included here as it can provide valuable insights to the tunnelling behaviour of woodborers and the damage they cause without having to cut into the wood.

The past 10 years has seen an explosion of investigations into insect pests and wood analysis using computed tomography that have revealed extremely valuable insights and increased understanding (Beaulieu & Dutilleul, 2019; Parracha et al., 2019). The previously mentioned work by Southwell (2017) and Brock et al (2024) are the only ones examining DWB, but there are many other species that have been investigated that demonstrate the use of this technique.

The great benefit of micro-CT as a tool to examine the tunnelling behaviour of woodborers is that a 3D model can be generated, and the sample does not require dissection. Jennings & Austin (2011) were among the first to test the use of micro-CT by examining the larvae and tunnels of wood wasps. They noted its potential as a method to detect the presence of insects in samples and understand tunnelling aspects and feeding biology of boring insects in timber and other agricultural products (*Ibid.*: 162). The tunnelling structures of termites have been extensively studied with micro-CT to better understand the nesting biology, next-gallery system and foraging behaviour (Hassan & Nanda, 2024; Himmi et al., 2018; Keszthelyi et al., 2020). The studies have demonstrated that the termites adapt to changes in the wood and preferentially chose areas of less dense wood fibre, avoiding cracks and knots to follow the springwood (Himmi et al., 2016: 9-12).

Yang et al. (2022) examined the damage caused by *Monochamus alternatus*, and found the galleries were predominantly C-shaped, with a few S- or Y-shaped, and that larvae did not share galleries. Eriksen et al. (2016), in their investigations of the tunnelling behaviour of shipworm (*Teredo navalis*), found that the worms preferentially attacked the radial plane, which means that submerged historic timbers cut along that plane are more at risk of attack than

those cut along other planes. Archaeologists and conservators can use this information to closely monitor those timbers more at risk and manage sites more effectively (*Ibid.*: 122).

As demonstrated by the findings of Eriksen et al (2016), the assessment of woodborer damage in cultural heritage objects can greatly inform IPM strategies in storage, display areas, and *in situ*. This is further evidenced by Dorscheid et al. (2022) (see [3.2.1.2.3](#)) and Arbat et al. (2021), whose examinations of wooden frames with minimal surface damage from a museum store with a suspected termite infestation found severe damage in one frame, suggesting it was the source of the infestation.

This is just a small selection of the studies that use micro-CT to investigate woodborers and other pests. A common factor of all of these studies and others, is the small number of samples examined. This may be due to a number of factors, including equipment access, scanning time, processing time, and expertise access. For cultural heritage objects, this is expected and of little concern, as the investigations are assessing the damage for that particular object. But for the examinations of damage to timber and agricultural products, it is something to be considered, as small sample numbers may not reflect the true nature of the damage caused by the species examined, and caution should be applied in the extrapolation and estimation of damage based on these studies. As more studies are conducted, the available data and consequent sample sizes should increase. There are even calls for the creation of a collective database of scans (Seibold et al., 2022: 1; Yang et al., 2022: 10). Although it has limitations to consider, micro-CT is a powerful tool available to increase understanding of the damage caused by woodboring pests and of the insects themselves. It will be exciting to see what more can be learned in future, particularly with developments in machine learning for image processing (Parracha et al., 2019; Seibold et al., 2022).

There are many non-invasive methods that have applications to cultural heritage. Those recording, monitoring and analytical methods commonly used by conservators and heritage scientists discussed are well established and can

reveal unique insights on materiality, construction and previous conservation treatments. Those used in this thesis were reviewed in further detail, highlighting the limits of each method that must be considered and planned for. The non-invasive detection of insect pests in timber is becoming an increasingly important field of study. Although there are many challenges, numerous methods are being developed and tested, aided by advances in technology. Its use in cultural heritage pest detection is still in its infancy, but it has much potential.

3.3 Conservation awareness and public engagement

This final section of the literature review chapter will provide a definition and brief background of heritage conservation, as well as providing the context for this research. It will examine the reasons why public engagement has not historically been part of the practice of conservation, and why it is important that it should be. In the past 20 years, the necessity of public engagement with conservation has been recognised and engagement methods have been explored. In the examination of case studies employing different methods of public engagement with conservation, the predominance of short-term initiatives will be highlighted to emphasize the need for integration of conservation narratives in heritage spaces. The use of digital tools as future engagement methods with conservation will be examined, as they have become increasingly important with technological advances, and have the potential to overcome many of the issues associated with traditional forms of engagement.

3.3.1 Definitions, context and background

Museums, and by extension other historical sites, have evolved from displays of collections to places of education, learning and social engagement where communication, interpretation, display and interaction with collections are integral (Paris & Ash, 2000; Saunders, 2014). The current definition according to the International Council of Museums (ICOM) is a “not-for-profit, permanent institution in the service of society that researches, collects, conserves, interprets and exhibits tangible and intangible heritage” that is “open to the

public, accessible and inclusive, museums foster diversity and sustainability” and “they operate and communicate ethically, professionally and with the participation of communities, offering varied experiences for education, enjoyment, reflection and knowledge sharing” (*Museum Definition*, 2022). At the very core of this is communication, as it underpins every aspect of the definition (Czachur et al., 2023; Nielsen, 2017).

Communication in museums is a broad, subjective and complex field that is challenging to address adequately in a brief manner (Falk & Dierking, 2000; Kidd, 2019; Nielsen, 2017; Saunders, 2014). There are many excellent books and articles that address and discuss the subject at length (Czachur et al., 2023; Drotner et al., 2019; Falk & Dierking, 2000; Nielsen, 2017; Saunders, 2014). However, a short overview is required to provide the wider context for which this research sits. Communication may appear to be a straightforward premise, where information is transmitted and received, but the reality and practice, particularly in the case of museums and heritage, is often far more complicated than such a definition suggests (Kidd, 2019; Nielsen, 2017). Nielsen (2017) has, in reviewing the extensive literature on the subject, condensed it to “museum communication is the articulation of understandings” (pg. 443), and goes on to demonstrate how this is done through storytelling and the construction of narratives, defining storytelling as a “concept that combines *the articulation of understanding* that defines museum communication and the *engaging narrative* that forms the story” (pg. 445).

Those undertaking the interpretation and presentation of information (the communication through storytelling) have a tremendous social responsibility in the interpretation, care and management of collections as the presentation of this work can influence those receiving the information (Paris & Ash, 2000; Saunders, 2014). Interpretation is a communicative process that helps people make sense of an object, collection, or site (Nielsen, 2017; Paris & Ash, 2000). Heritage conservation is a crucial component of this process, that is rarely acknowledged or presented, despite being a stated component of the current definition of a museum and its communicative core (*Museum Definition*, 2022).

Heritage conservation can be defined as “the care of tangible cultural heritage: buildings, structures and remains in which material interventions are made with the intention of safeguarding and revealing aspects that are valued” (Chitty, 2017: 2). Cultural heritage, whether tangible or intangible, is subject to constant change, whether that be the forces of decay or the wider social landscape (Appelbaum, 2010; Chitty, 2017; Emerick, 2017; Saunders, 2014). Ultimately, the aim of conservation is to understand the stories that the objects want to tell: an object’s biography (Caple, 2006b). And while an object’s story, gleaned by conservators, is communicated to others, the role conservators play in discovering and influencing these stories is not.

The conservation profession developed from restoration, which is much better known. Indeed, people often conflate the two. Restoration has a much longer history than modern conservation. Half-cleaned paintings were exhibited as early as the 18th century and there is evidence of earlier examples (Caple, 2006: 47; McClure, 2013: 163). Modern conservation only became a recognised discipline in the mid- 20th century, and conservators spent the first few decades establishing it as a field of science (Koutromanou, 2015: 5). Although modern conservation work may involve a degree of restoration (and conservators are often called conservator-restorers), modern conservation encompasses a much wider range of skills, ethical considerations, and activities, with the goal of minimising change or managing it in such a way that the rate of change (decay) is as slow as possible (Caple, 2006a).

This care includes a wide range of methods and techniques, all of which are dependent on investigations and research to ensure that the best possible care and materials are used to ensure the long-term survival of the tangible heritage that fulfil as closely as possible the principles of minimal intervention, stability, and reversibility (Caple, 2006a). Without this care, the natural process of decay would rob humanity of the physical remnants of its history. These physical remnants are tangible links that allow for connection with past humans and their lives, often revealing unique, everyday aspects that exist outside of the historical record (*Ibid.*). Conservation is therefore essential for the long-term

survival of heritage. Yet it remains relatively unknown as a discipline (Appelbaum, 2010).

Most conservation work takes place 'behind the scenes', and conservators, many of whom are introverted by nature, are not concerned about the impact their work may have on the public perception of heritage materials (Crutcher, 2018: 1; Koutromanou, 2015: 125). This hidden nature means that members of the public are largely unaware of the work involved in maintaining heritage. The 'public' in this instance refers to anyone outside the conservation profession. There is this assumption that heritage collections just 'exist' and are 'static' when they are in designated heritage spaces (Crutcher, 2018: 2; Miyazaki, 2017: 226). In the case of archaeology, objects are supposedly found, then immediately displayed (Koutromanou, 2015: 22-7). This is not the case. A tremendous amount of work goes into ensuring that the objects are 'readable' (understandable) so viewers can see what they are, what they may have looked like, and how they would have been used; additionally, the objects have to be stabilised and made safe for display (Appelbaum, 2010; Caple, 2006a, 2006b; Saunders, 2014). It is a huge responsibility to carry out this work and the results of the work can have tremendous impact on how the object is interpreted by others in the museum and the public who view it.

It has become apparent in recent years that this hidden nature is not sustainable, not only with regards to transparency of those primarily working in the public sector, but because it contradicts the primary mission of cultural institutions, which is to transform audiences into stewards or custodians of heritage (Bertrand et al., 2021: 1; Internationaler Museumsrat, 2017: 34; McKenzie, 2015). Heritage is a shared point of connection between people, bringing together unique experiences, and allowing for insights and growth, through the telling of stories (Donoghue, 2024; Nielsen, 2017; Saunders, 2014). It is for everyone; therefore, everyone has a vested interest in its survival and should have a say in the decisions behind its care (Appelbaum, 2010; Koutromanou, 2015; Saunders, 2014; Wharton, 2015). But in order to make a well-informed decision, the information needs to be available (Appelbaum,

2010: xxi; Raimundo & Saaze, 2024). By work taking place behind the scenes, this information is guarded and inaccessible (*Ibid.*). There is also the potential loss of novel ideas and contributions, key components of innovation, that can result from a more collaborative approach (Nielsen, 2017; Paris & Ash, 2000; Saunders, 2014). In gatekeeping conservation, while the survival of the tangible heritage for future generations is ensured, the profession and the wider heritage sector in which it sits is struggling to embrace the concept of shared stewardship.

Not only does it contradict the concept of shared stewardship and the very definition of a museum, but the 'behind the scenes' nature has wider material impacts, as this lack of knowledge often extends to those in decision-making positions and those in charge of resource allocation (Appelbaum, 2010; Case Studies of Resilient Heritage Organisations, 2012; *Economic Value of the Heritage Sector*, 2023; Hardaker, 2024). For a career that requires significant training, much of it at a post-graduate level, salaries are low, and there are few career prospects, thereby threatening the long-term sustainability of the discipline and those working in it (ICON, 2024; IIC's Student and Emerging Conservator Conference, 2023). Conservation departments are often understaffed and overworked (ICON, 2024), and while many conservators recognise the need for self-promotion (ICON, 2024; IIC's Student and Emerging Conservator Conference, 2023), the feasibility of such work is not always possible. Most conservation work is routine, and treatments can take long periods of time (Koutromanou, 2015), so engaging the public with the daily work can be challenging.

It is still a relatively rare occurrence for members of the public to witness and learn about conservation (Koutromanou, 2015: 125). However, based on the popularity of television programmes like *The Repair Shop* (Donoghue, 2024), which very much follows the format of presenting the story of objects, it does appear that the appetite to learn more about heritage conservation is there. That being said, efforts are being made by those in the profession to engage with the public (Institute for Conservation, 2024). The rest of this section will

review methods that have been used to engage the public with conservation in the past, examining what was done well and what needs to change for future.

3.3.2 Common methods of engagement with conservation

When examining the literature on public engagement with conservation, there are a number of different methods that are commonly used. These are exhibitions, workshops, special projects, tours, and others. A brief overview of each type with a few examples will be provided, followed by a summary and discussion. Before delving into this review of common methods of public engagement with conservation, there are a few things that must be kept in mind throughout. While public engagement may seem like a straightforward premise, the reality and practice of it are far more complicated (Anagnostopoulos, 2016). What works in one setting might not necessarily work for another, and the case studies given serve as examples rather than models to follow (Anagnostopoulos, 2016; Chitty, 2017; Falk & Dierking, 2000).

3.3.2.1 Exhibitions

Of the methods commonly used to engage the public with, exhibitions are the least prevalent due to the resource expenditure required. Exhibitions are organised presentations and displays of selected items that can be permanent or temporary (*Exhibition*, 2024). They are often centred around a theme, and the items selected represent and reflect the theme directly or a facet of it. Exhibitions guide visitors through the chosen subject, presenting items with further information, usually on an interpretation panel (Williams, 2013a: 170). Although typically physical and static, dynamic, and digital exhibitions are becoming more common. There may be special tours of exhibits that highlight particular aspects of the display and give further information, but generally, visitors are left to peruse at their leisure and may choose the amount of information they wish to interact with. In most standard exhibitions, conservation work (repair, stabilisation, mounts, etc.) is never highlighted or emphasised (Kruger, 2013: 26). Even with specialist tours, unless led by a conservator, it is an aspect of heritage work that is rarely drawn attention to in standard exhibitions and galleries.

Conservation can be a tricky theme to communicate through an exhibition. It is multifaceted, ethically challenging, and much of the work is routine (Brooks, 2008; 2014; Koutromanou, 2015). It is likely because of the challenges that most conservation exhibitions are temporary, and emphasize certain aspects over others (McClure, 2013: 163). *Mission Impossible? Ethics and Choices in Conservation* (2006) was a temporary exhibition at the Fitzwilliam Museum, University of Cambridge (*Ibid.*: 164). The overarching aim of the exhibition was to demonstrate the complex issues, considerations and compromises conservators and curators face when deciding the best treatment for an object (*Ibid.*). The exhibition was subdivided into sections, each with their own theme represented by carefully chosen objects that contributed to the overall aim, guiding visitors through the decision-making process (*Ibid.*: 165). During the run of this exhibition, small signs were added to other objects around the museum that fit within the themes of the exhibition (*Ibid.*). By guiding visitors through the decision-making processes behind conservation, the exhibition communicated the many considerations behind each step as well as the treatments themselves. Additionally, adding small signs to the existing objects encouraged visitors to take the knowledge imparted to them from the exhibition and apply it to the other objects in the museum. While in this instance the additional signs in the museum were linked to the particular exhibit, the example demonstrates that small additions to existing displays could promote conservation and the awareness of it with visitors. Yet this does not seem to be a common practice. It does not appear that feedback from visitors was systematically gathered, but McClure reports that responses were 'very positive', with calls for it to be made into a permanent display.

Conservation: Where Art and Science Meet (2010-2012) was a temporary installation at The Colonial Williamsburg Foundation (USA), where museum volunteers and conservators collaborated to design the exhibit based on the common questions they were asked about conservation during conservation laboratory tours (Williams, 2013a: 170). They decided that tracing the life of an object from its initial manufacture through to conservation treatment, with narrative stops addressing the choice of materials, the actions of decaying

forces, the investigative work required to understand the objects, and some basic theoretical practices would address many of the common questions (*Ibid.*). A conscious choice was made to limit the number of before-and-after images in the exhibit, which have been a staple in much conservation advertising (*Ibid.*: 173). The feeling was that they rely too much on shock value and the conservation process is ultimately minimised as a result (*Ibid.*). Additionally, a series of programming events (tours, workshops, and lectures) were conducted throughout the duration of the exhibit (Balderson & Williams, 2013). Visitor feedback to the exhibition and events was positive, with many responses mentioning the fact that it was a topic they rarely came across or saw, and multiple calls for it to become permanent (Williams, 2013a: 173). A more summative evaluation was not conducted due to staff changes, a fact lamented by the author (*Ibid.*).

There is one exception to the generally temporary nature and singular focus of conservation exhibitions. The Conservation Galleries at the Ashmolean Museum (Oxford) are the only permanent display of conservation in the UK, and one of the few worldwide (*Conservation Galleries*, 2024). There are two galleries: *Restoring the Past: The Leon Levy Foundation Gallery* and *Conserving the Past*. The first gallery shows how objects and belongings were historically repaired or repurposed rather than discarded. The second gallery showcases the work of museum conservators, highlighting the importance of their work and the dangers presented by light, touch and other hazards through interactives (*Ibid.*). Despite being small, the galleries provide visitors with a relatively comprehensive glimpse at the work performed by museum conservators and still manages to acknowledge that they are not able to address all aspects with a simple graphic ([Fig. 29](#)). However, the galleries are on the lower ground floor and not on the main visitor path, nor are they predominantly advertised at the entrance to the museum, meaning most visitors have to actively seek them out. They do benefit from being in close proximity to the café, where visitors may stumble upon them, although this then puts them at higher risk of pests. In her research in public engagement with conservation, Koutromanou (2015) used the Ashmolean Conservation Galleries as a case

study. In 167 questionnaires and 8 interviews, the feedback was primarily positive (*Ibid.*: 100). The author noted that the visitors questioned were not accustomed to exhibitions on conservation, and that many stated they would have liked to find out more and called for expansion of the galleries (*Ibid.*: 101).

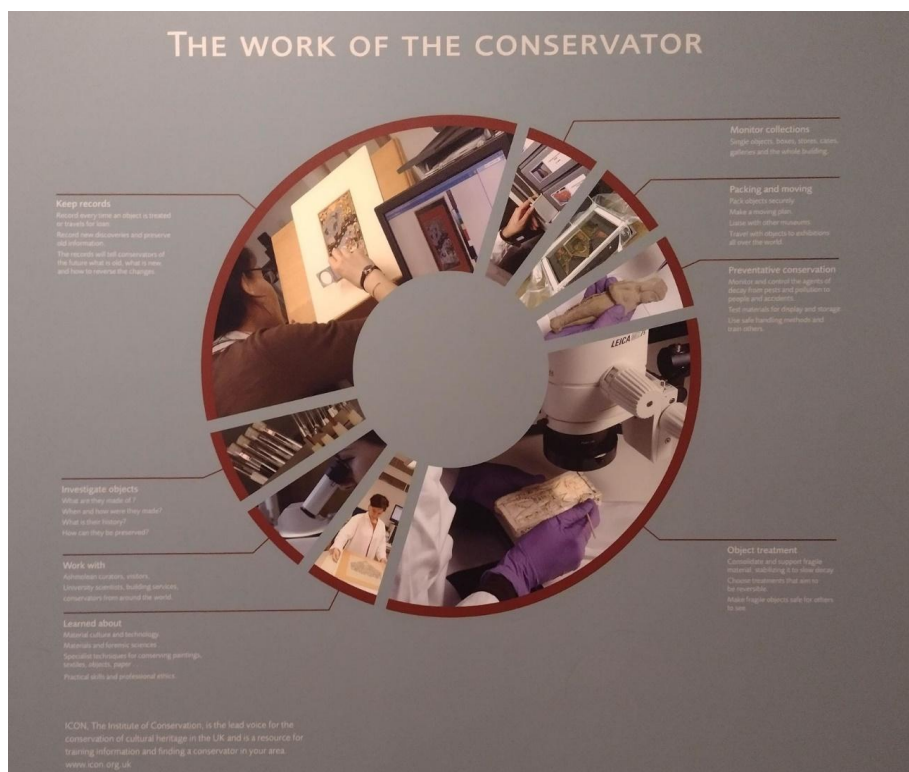


Figure 29: Pie chart graphic showing the approximate breakdown of a conservators work in the Ashmolean Conservation Galleries. There is even a link to the ICON website directing visitors to further resources.

Although only the Ashmolean Conservation Galleries have systematic feedback that was obtained, the general responses reported by the authors are overwhelmingly positive, and in the case of the temporary exhibitions, calls for permanent incorporation are made. People *are* interested in conservation. However, by having conservation as a separate exhibit, temporary or not, it can be viewed as doing a disservice to the profession by isolating it rather than incorporating it into existing spaces. It undermines the message that this is an essential and integral part of heritage institutions.

3.3.2.2 Workshops

A conservation workshop is a scheduled event where participants learn about and discuss an aspect of conservation that usually involves an element of

practical work or activity (*Workshop*, 2024). Most tend to be one-off special events (or series of) as part of wider programming (i.e. *Conservation: Where Art and Science Meet*) and are typically led by conservators.

Koutromanou (2015) conducted two workshop sessions for groups of up to 12 visitors at the Yorkshire Museum, with object examinations and conservation treatments between discussions. Upon completion, participants were invited to participate in a survey (*Ibid.*: 70). Interviews were conducted with volunteers 9-12 months after the workshop to assess long term impact (*Ibid.*). As this was part of a wider research study on the impact of conservation engagement on public perception, there was greater reflection and insights into the limitations of the study that rarely appear in the already limited literature. The author notes that as the researcher, developer, disseminator and surveyor of the workshops, they may have caused a positive skew to the data (*Ibid.*: 71). Additionally, although the workshop was free and clearly stated that no prior knowledge was required, the limited capacity meant that participants had to book a space and were therefore not casual museum visitors, again skewing the data positively (*Ibid.*: 72). To limit the potential impact of positively skewed feedback, the data resulting from the workshops was examined with thematic analysis instead of the degree of success and impact of the method of engagement (*Ibid.*).

Tapini & Gomez-Robles (2017) conducted a six-week project-workshop on stone conservation and urban regeneration to conserve *Fuente Nueva* (new fountain) in an Andalusian town. The goal was, through the workshop and conservation treatment of the fountain, to reconnect the local community with the fountain, which had historically served as a focal point for the town until translocations and changing perceptions altered this (*Ibid.*). As this article was written a few years after the workshop was conducted, the authors report that the workshop, with strong participation and partnership with local authorities, has resulted in a substantial shift in the community mindset, with citizens now actively taking care of the fountain.

Workshops, by their nature, are a more collaborative form of engagement than most of the other methods under discussion. However, there is the risk that

many of them become expert-led and heavily guided, rather than letting participants contribute their own ideas, something that has been raised as a concern with many of the conservation outreach initiatives (Chitty, 2017; Koutromanou, 2015). When designing and leading workshops, particularly in museum settings where they may unintentionally be more exclusionary due to participant limits, conservators should be wary of this. Tapini & Gomez-Robles (2017) as well as others (Modwel, 2017; Rajangam, 2017) note that the specialist model of conservation is not sustainable long-term, and that the public needs to be involved in all stages of heritage management.

3.3.2.3 Special Projects

Special projects, for the purposes of this thesis, is when there is a find or object of significant cultural, historical or national value that requires conservation, to whatever degree. There are many examples of special conservation projects. The current conservation work with HMS *Victory* is one, as is its neighbour at the dockyards, the *Mary Rose*. The recovery of the US Civil War ironclad USS *Monitor* (Nordgren, 2013) and excavation of the confederate submarine *H.L. Hunley* (Rivera & Quinn, 2013) are further examples. These projects (all currently ongoing), which often receive much news coverage and public interest, capitalise on their unique nature.

They generally include the other methods of engagement as part of their programming and may often involve elements of fundraising. However, as the conservation treatments often take years, public and media interest wanes. There may be a resurgence of interest upon completion, but many of the subjects of special projects then cease to highlight the continuing conservation work required to keep the subject stable and on display. The early HMS *Victory* restorations and treatment campaigns ([2.1.3.2](#)) in the 20th century exemplify this, as does the conservation of the Statue of Liberty (USA) in the 1980s (Caple, 2006a). When the work occurs, there is increased public and media interest in the conservation. Once the work ceases, the interest, particularly in the case of the media, fades. If public interest is still there, it becomes less apparent. The Statue of Liberty particularly, although the website currently

states that more work remains to be done to ensure the survival of the statue, there are no details as to what this entails (*Restoring the Statue*, 2024). With the rise of social media and blogs (discussed more fully in [3.3.3](#)), it is becoming easier to directly communicate with the public at all stages of the process with less need for media involvement.

3.3.2.4 Tours

A tour is when a visitor learns about a particular place or topic and can be guided or self-guided (*Tour*, 2024). Conservation engagement tours tend to be facility tours or behind-the-scenes access during a special project (previously discussed), but in almost all cases, spaces on the tour must be reserved ahead of time, even if the tour itself is free.

Winterthur Museum, Garden and Library's (USA) conservation facility was one of the earliest conservation facilities to offer tours to the public (Price & Stoehr, 2013: 9). The tours were initially limited to special groups and members except for the Country Fair, when it was opened up to all visitors (*Ibid.*). The authors report an overwhelming response, with long lines out of the building entrance, but lament the end of the Country Fairs and tours in the 1980s (*Ibid.*). It was not until 2000 that a designated conservation Tour Team was created, working closely with Public Programs to regularly schedule public tours (*Ibid.*). It later became a designated part of the Public Programs department, one of the few to have conservation as a central subject, but the tours are no longer led by conservators (*Ibid.*: 10). Instead, conservators and the education department created designated training guides and redesigned the tour, to include information packets for all participants and two focus labs (*Ibid.*). Although the popularity of the tours does often strain resources, by having designated non-conservator guides for the majority of the tour, yet still allowing tour participants to ask questions in designated focused labs, the demands on conservator's time is lessened, yet the public is still provided a unique and accurate tour.

In spite of the popularity, the Winterthur conservation tours now occur only once per month and tickets must be purchased and booked in advance ('Conservation Tour', 2024). A similar scenario occurs at The British Library with

its Conservation Studio Tours. The Conservation Centre at the National Museums Liverpool ran tours and had a designated exhibition area, but despite winning the European Museum of the Year award in 1998, sadly closed its doors to the public completely in 2010 due to budget cuts (*Collections Care*, 2024). Tours of facilities, already relatively rare, are becoming rarer.

3.3.2.5 Others

There are four other common methods of engagement that are not as easily categorised, and while common, have little in the way of literature. The first is lectures or talks, but these are only ever discussed as part of a wider project and rarely in any detail. Rivera and Quinn (2013), as part of the *Hunley* conservation staff, briefly describe giving public lectures to universities, schools, social clubs, and the Institute of Archaeology and Anthropology (University of South Carolina). The lectures at the Institute are part of a Sport Diver Archaeology Management Program, where amateur divers and others are taught about underwater environments and their effects on materials (*Ibid.*: 249), but no further details are given of the other lectures, nor is there any description of the attendance of the lectures.

Next, is conservation on display or *in situ* conservation. This normally takes one of two forms. If the object or item to be treated is too large, difficult or impossible to move, then conservators will come and treat the item *in situ*. This is often the case with wall paintings, furniture and sculptures, and may range from something as simple as dusting, to more interventive work. If the item is on the visitor route, then visitors will be able to witness the work. Alternatively, usually in museum or other more formal settings, a temporary or permanent conservation lab or workshop allows the public to see conservators at work, often with interpretation panels with additional information. These have been classed distinctly from those conservation spaces which require tours for public access to distinguish between levels of access. Both forms allow the public to directly question conservators, which while beneficial from a public engagement side, as it adds an element of personal connection, can at times be frustrating for conservators, as it disrupts the working process. The conservation work on

HMS *Victory*, in addition to being a special project, also fits within this category. The Imperial War Museum (Duxford) has a designated Conservation In Action hangar where conservation work takes place every weekday on a permanent basis (*Conservation in Action*, 2024). Most other heritage institutions may have conservators working in front of the public on a less regular or as needed basis. The British Museum had a temporary conservation lab as part of *Conservation in Focus*, a temporary exhibition (Koutromanou, 2015). The Coronation Chair at Westminster Abbey was recently conserved prior to the latest coronation (*Coronation Chair Prepared for Historic Role*, 2023).

However, this method has the great benefit of engaging interest in the more mundane, everyday aspects of conservation, something that other methods struggle to do. Small explanations, written or verbal, can help garner visitor interest in the everyday aspects. Children, however, often find the simple actions enamouring (Crutcher 2018: 10), something the Museum of London took advantage of in their biannual clean of a Roman mosaic (Ganiaris & Lang, 2013: 214-15). The event was hugely popular, and staff were often overwhelmed by the number of participants (*Ibid.*). However, it does not appear that the event has been run again since 2009.

The second method is visible or open storage. Although this could be argued to not be related to conservation, Crutcher (2018) states that “providing access is itself conservation, as barriers to artifacts are removed and the public is invited to participate in, rather than consume, heritage” (pg. 15). Beamish Museum (County Durham), Lapworth Museum of Geology, and Brooklyn Museum’s Luce Center for American Art all have accessible storage, and it is becoming more widespread (Fairley, 2023; Maynard, 2014; Murphy, 2016). Not all of these open storage areas are fully accessible, as many, like the tours described earlier, require booking for access.

Finally, there is volunteer engagement with conservation (Grammatikou, 2013). This is when volunteers directly participate with conservation work, and in small institutions, the only conservation work may be done by volunteers. NMRN has a designated volunteer conservation sewing group who make Tyvek® (synthetic

high-density spun-bound polyethylene material) covers for storage as well as other conservation volunteers to help with large scale tasks such as cleaning, and visual inspections of mould and pests. Similar volunteer schemes exist in the Museum of London, English Heritage, the British Museum, the National Trust, and many other museums and heritage institutions, from small to large (Ganiaris & Lang, 2013; *Our Conservation Volunteers*, 2024; *Volunteer*, 2024; *Volunteer British Museum*, 2024; *Volunteer with Us*, 2024). Although training is given and the volunteers carry out much of the work, the work is rarely truly collaborative, and it falls into the unsustainable specialist model (Grammatikou, 2013).

For a relatively young area of study, there is already a significant amount of work on the subject of public engagement with conservation, but not all of it is published, so the literature is still limited. This means that much of the work done is reliant on word-of-mouth dissemination and lacks robustness. There is still much that needs to be investigated. Those that are published have highlighted the challenges of presenting conservation due to the nuances and numerous considerations involved (Appelbaum, 2010; Brooks, 2013; Price & Stoehr, 2013; Williams, 2013b), but there are a number of things that can be concluded from the examples presented above.

Firstly, the efforts are predominantly led by conservators. As the experts of their profession, this means that the information is accurate. But the risk is they continue the unsustainable specialist model, where experts speak and people listen, contradicting the concept of shared stewardship (Marçal, 2019). Additionally, these efforts are often on top of existing duties and tasks conservators have to fulfil as part of their jobs, putting more work pressure on those who already have much to do. The task of engaging the public falls to the conservators, rather than the designated public programming teams of museums and heritage sites (Crutcher, 2018: 12). Museums and heritage sites use public programming to provide activities that deepen the understanding of exhibitions, overall missions and research ('Resource Library', 2023). Not having conservation as one of the integral components of regular public

programming and relying instead on the conservators themselves, makes it difficult to have longer lasting, established efforts. In the few cases where it is a regular feature of public programming, such as at the Winterthur Museum, the results are well received, and it has caused profound perception shifts for visitors and the conservators themselves (Price & Stoehr, 2013). However, even successful cases like the Winterthur Museum, have seen the impact of these activities diminished due to reduced numbers of tours and budget cuts

This is the biggest takeaway from all of the methods and their respective case studies (apart from the Ashmolean Conservation Galleries): they are all *initiatives* (Crutcher, 2018: 5). This key word, commonly used in the literature, suggest that efforts are made, things are started, but there is rarely a follow-through or long-term change. The initiatives often also lack a clear central narrative, despite all addressing conservation as a topic. Clear narratives have been identified as key to museum communication in order to make meaning and connect with visitors (Falk & Dierking, 2000; Nielsen, 2017).

By having these short-term, often one-off events, the behind-the-scenes nature of conservation is perpetuated. Workshops, tours, and lectures often have limits on numbers. The limited timeframe of temporary exhibitions may prevent people from seeing it. Special projects eventually end, or the conservation work takes decades, and interest in the project will fade unless significant efforts are undertaken to maintain that interest. Even events that could become regular calendar fixtures, like the biannual cleaning of the mosaic at the Museum of London, rarely become so. This then creates the impression that the public is 'allowed' a glimpse or is given temporary entry to conservation and the conservators themselves and may be allowed to undertake some work, but they are not allowed to stay, completely contradicting the nature of shared stewardship and cultural heritage itself. While this is unlikely to be the intention of the conservators themselves, this situation will continue to perpetuate unless conservation and its narratives are incorporated permanently into existing heritage spaces.

Yet the interest in conservation is clearly there, as demonstrated by the popularity of the events when they take place, and the success of things like The Repair Shop. Community outreach and engagement has been recognised as one of the key cornerstones of public engagement with cultural heritage, and by extension, conservation. By providing members of the public with accurate information regarding conservation, they can then become collaborators in the conservation of cultural heritage, thereby protecting heritage through the public (Crutcher, 2018: 17), preventing amateur restoration work, and fulfilling the concept of shared stewardship. This effect currently appears to be limited to the workshop method of engagement and is a relatively rare occurrence.

These methods are still valuable for public engagement and should continue to form part of the conservation engagement repertoire, but many are resource heavy or extremely limited in participant numbers. Instead, they should support more permanent efforts. Conservation should be firmly embedded into wider public programming and into the narratives presented within heritage spaces. Although this will require initial resource investment, over time, the resource costs would be far less. And the efforts do not have to be big. The International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) created a framework for museums and sites to develop their own self-guided conservation tours (Grammatikou, 2013; Grattan, 2004). The *Mission Impossible?* exhibition at the Fitzwilliam Museum, in adding further explanatory panels to the objects on permanent display, although in this instance linked to the specific exhibit, demonstrates a relatively small change that can incorporate conservation narratives into existing heritage spaces.

3.3.3 Digital engagement tools and conservation

Coinciding with the recognition of the need for public engagement with conservation has been the rapid development of digital technology and its implementation within cultural heritage spaces. However, as the studies described above demonstrate, there is a distinct lack of use of digital tools for engagement with conservation. Digital tools are widespread and variable. Designated websites, blogs, social media, virtual reality (VR), augmented reality

(AR), and gaming platforms are a selection of the available tools. Many have been used in cultural heritage spaces, but rarely by conservation. This lack of alternative means of public engagement became starkly apparent with the COVID-19 pandemic and associated lockdowns.

This section will examine the few case studies where digital tools have successfully been used to engage the public with conservation. Further references from digital engagement in cultural heritage spaces may be alluded to, but as that is a distinct and substantial subject in its own right, those references will only be discussed with regards to how it might benefit conservation public engagement efforts.

Three models of digital technology for visitor engagement have been identified within cultural heritage (Hildred et al., 2022). The first is alternative, where digital tools provide an alternative method to engage with cultural heritage (*Ibid.*). Virtual exhibitions and digital collections are an example of this model. Next, is additional, which adds a new element to the interpretation of heritage (*Ibid.*). Games for children, interactives, and social media are examples of additional models. Finally, there is augmentational, where the digital adds to the physical, AR being a prime example (*Ibid.*). Augmented reality allows users to see the real world with virtual objects superimposed or composited into the space (Scavarelli et al., 2021: 258). Many early attempts using digital tools in heritage spaces relied too heavily on the novelty of technology, and did not contain a comprehensive narrative (*Ibid.*). The technology is meant to aid and enhance visitor experience and interpretation, and conservation work is ideally suited as a narrative component.

Luxford & Thickett (2013) made use of an interactive video as part of a small exhibition on historic veneer and marquetry furniture, communicating the role and importance of monitoring equipment and research. The video showed images of marquetry samples and asked visitors to indicate whether the samples were damaged or not, allowing them to share their opinions and conclusions on object damage (*Ibid.*: 66). Although this was a small study, it is a good example of an additional model of digital technology use and provided

valuable data for the researchers on the successful communication of concepts through the exhibition. Svodoba (2013), during the course of a special project to conserve the Carolina Room at Colonial Williamsburg, used the common methods of conservation engagement (i.e. lectures, tours, workshops) alongside digital methods such as an online exhibition, electronic field trips, podcast interviews, and online resources. Those in-person visitors appreciated having something unique for them, and the digital methods were able to reach a much larger audience (*Ibid.*). This case study demonstrates that the more traditional methods and digital methods (in the alternative and additional models) work well together to support the visitor experience and engagement. These earlier examples were more limited to the technology available at the time, but since then, technological development has exploded, and a greater number of digital tools are available and are easier to use.

NMRN themselves have flagged digital technology as an area for improvement (Sheldon et al., 2024) and have developed a number of initiatives to this end. The Barracuda project at the Fleet Air Arm Museum (FAAM), an NMRN branch in Somerset, is aiming to conserve and restore a Barracuda plane (WWII), primarily recovered from the Solent, using as many original parts as possible from wreck sites across the UK (*Barracuda Live*, 2024). The work is being undertaken in front of the public, but in order to communicate the challenges facing the conservation work, a VR experience of the Solent excavation has been created for visitors (*Ibid.*). Virtual reality experiences create an artificial environment that is experienced through sensory stimuli provided by a computer and where participant actions partially determine what happens in the environment (Scavarelli et al., 2021: 258). This allows them to explore the underwater wreckage and the conditions in which the pieces suffered damage, providing the opportunity to explore an aspect that previously would have been inaccessible.

Another special project making use of digital tools to engage the public with conservation is Operation Night Watch (Rijksmuseum Amsterdam), the conservation treatment of which was undertaken on public display (*Operation*

Night Watch - Rijksmuseum, 2024). Although the treatment stage has now finished, a dedicated section of the Rijksmuseum website remains with blogs, images and videos of every stage of the process, as well as high resolution interactive images and details of research techniques (*Ibid.*). The interactive images are incredibly detailed, to the point that inclusions within the paint are visible, and clicking on annotations brings up details and further images of relevant tools. There is a reconstruction of what the image originally looked like, with details of how the research and investigation revealed the original painting. Every single aspect of the project is detailed in a clear and concise manner, and the website is user friendly. It is an incredible resource that allows viewers from anywhere with an internet connection to see Rembrandt's painting at a level of detail that would be impossible in the gallery setting, and emphasises the conservation research that made this possible.

A number of cultural heritage institutions from Latin America (headed by Mexico) are making use of digital tools to shift the traditional standard in which the public receive State action in the field of cultural heritage to a model where the public are generators and active participants (*Games Laboratory - Policy Monitoring Platform*, 2020; *Keck Award 2022*, 2022). To achieve this, a series of online video games were created and:

“The project promoted game development, education, restoration and culture, highlighting the importance of the use of digital technology and playful products as an important tool for preventative conservation and risk management of paleontological, archaeological and historical heritage.” (*Keck Award 2022*, 2022)

One game from the project, *Camino a la conservación* (Road to Conservation), allows the user to excavate and clean various fossils in a conservation lab, with information on the fossils and tools used appearing at each step. The games were activated at different national events over 3 years, with participants from 9 different countries (*Ibid.*). The games provide a fun, engaging way of providing conservation education for a wide audience.

Digital tools have also been successfully used to consult and collaborate with the public. Hazel Wong, a PhD student at the University of Cardiff, made use of 3D technologies to present different levels of treatment options as an engaging and immersive way to engage new audiences in conservation decision making (Wong, 2024). A 3D scan of a lotus shoe was used to model three different levels of conservation treatment: no treatment, stabilisation, and full restoration. These were then presented to focus groups where participants were asked for their thoughts on what treatment should be conducted. Although this is only a small scale study, it shows how digital technology and tools can be used to collaborate with non-conservation and heritage audiences. Social media is an excellent tool for collaboration. The Houses of Parliament: Restoration and Renewal Programme (R&R) eschewed the traditional consultation approach and instead used social media channels ([Fig. 30](#)) (*Restoration and Renewal Instagram Post*, 2021) alongside more targeted means (online platforms, workshops, school visits, tours, panels, etc.) to find out what the public wanted from the R&R programme (*Public Engagement Strategy*, 2020; *Understanding the Public's View 2020-2022*, 2022). Social media was also used by Mickletz & Perkins Arenstein (2019) to bring attention to IPM.



Figure 30: Restoration and Renewal Programme's Instagram post calling for participants (*Restoration and Renewal Instagram Post*, 2021)

The use of online platforms opens up access to anyone with an internet connection and minimises the need for heritage sites to have their own infrastructure. This does bring risks with intellectual property and licensing, as well as hidden environmental costs. Although generally touted as environmentally friendly, digital content is hosted on servers, which require substantial power to run and cool (Mitrani, 2013). There are also risks of technological failures whether online or with interactive digital technology. While digital tools can open up historic sites to those unable to visit them in person, those without access to the internet or digital devices, may feel excluded or disenfranchised. Collaborations with libraries, schools and other public services may assist in preventing this disenfranchisement. These all must be considered when developing and creating digital public engagement tools.

Digital tools have the potential to be a valuable asset for public engagement with conservation, but until relatively recently, they have been underutilised. Although these examples are all expert-led, these projects, in communicating widely and regularly with audiences throughout every stage of the project, and asking for collaboration, normalises the presence of these projects and the

discourse around conservation. This normalisation is key to raising awareness of conservation, and digital tools, already so well integrated in daily life, will help achieve this. Their educational use can enable the shift of the public from consumers of heritage to participants and stewards. Additionally, they are able to add an extra dimension to the traditional methods of engagement, reach wider audiences beyond the museum visitor, and can be used to add conservation narratives to existing heritage spaces with minimal need for physical changes. The case studies highlighted above show many different possible applications and uses for digital methods of engagement with conservation. However, despite increased use and adoption for conservation use in recent years, little research has been done with regards to the long-term impact and future work is required.

3.4 Final Summary

The literature reviewed on the topics of investigation has highlighted several points. Firstly, despite a long history of knowledge, remarkably little is known about the DWB. The lack of clear methodology in many of the earlier DWB studies undermines their findings and conclusions. It is only the few later studies from the 1990s onwards where confidence in the findings is had. There is still much to be learned about the beetle, and the investigations from this thesis will contribute novel information to the body of knowledge.

Secondly, the use of non-invasive methods in conservation is well-established. Each method has its merits and limitations, but when applied effectively, can reveal valuable information. The use of non-invasive methods for the detection of insects is becoming more established, but the challenges facing each method, and its application means the topic is still very much in the research and development phase and it may yet be some time before systems are commercially available. The literature, however, demonstrates the potential of the different methods for use in cultural heritage contexts. The preliminary investigations testing methods for use on HMS *Victory* as part of this thesis will provide valuable insights for the conservation team into suitable methods that warrant further investigation.

Finally, although the need for public engagement with conservation has been acknowledged and called for, few of the investigations and efforts have been permanent or long-term, as the methods commonly used to engage the public do not generally lend themselves to long-term solutions. Nor do many make use of engaging narratives (Nielsen, 2017). Digital tools, despite their flaws, have the possibility to address these issues without the need for conservators' physical presence and physical structural changes. They can easily be incorporated into existing heritage spaces and enhance the visitor experience. And it is clear that the interest in conservation is there. The research from this thesis will demonstrate original ways of presenting conservation research to the public in a digital format and assess visitor responses to the information presented.

4 INVESTIGATING DEATHWATCH TUNNELLING

4.1 Introduction

The damage to historical wooden material during a DWB infestation is primarily structural, and is caused by the tunnelling behaviour of the larval stage (Belmain, 1998; Fisher, 1937b). Externally, the damage may be minimal, presented by exit holes created by the adults (*Ibid.*). The internal damage, however, can be far more extensive (*Ibid.*). In the case of Westminster Hall, some of the roof timbers had been completely hollowed internally, while the external surface displayed minimal damage (Baines, 1914).

Historic investigations into the tunnelling of woodboring beetles were limited to severely damaged material or destructive analysis (Fisher, 1937a; Munro, 1928). The advent of non-invasive technology, like micro-CT, allows for assessment of the tunnels with minimal to no destruction.

Managing a large, long-term infestation like the one found on HMS *Victory* is challenging. The implementation of successful IPM strategies depends on a thorough understanding of all aspects of a pest species: the lifecycle, their habits, and behaviours, with the goal of using the knowledge of the insect and the environmental conditions of the building to disrupt the cycle to reduce population numbers and manage (ideally eradicate) the infestation.

This is where this project intervenes. By understanding the tunnels in a timber and the extent to which the larvae are dependent on fungal attack may give an indication on what is occurring in other timbers of the ship, particularly those timbers that are structurally integral to its stability and cannot be removed for assessment. To be able to estimate or predict the potential level of damage and whether interventive measures are necessary would be a great benefit to the conservation team, facilitating and streamlining their work.

4.1.1 Aims and objectives of investigations into tunnelling

The aim for this section is to identify any trends within the wood caused by the DWB tunnelling via micro-CT in samples obtained from a deck plank with evidence of beetle activity. There are four main areas of enquiry:

1. Tunnelling: Are there any discernible trends?
 - a. What characteristics of wood structure attract DWB? Do the tunnels follow particular features of wood i.e. early vs. late wood, in line with or against wood fibres? Are they going towards external surfaces?
2. Internal and external damage: Is there a correlation between surface damage and internal damage as proposed by Brock et al., 2024?
 - a. Can the relationship be used to predict areas of active infestation and risk?
3. Fungal relationship: Is it possible to determine areas of fungal decay with micro-CT and whether the DWB prefer those areas?
 - a. What is the relationship between DWB and fungal activity?
4. Larvae and Beetles: Are there any larvae and beetles present in the plank studied? What information might they reveal about lifecycle and tunnelling behaviour?
 - a. What can the *in situ* locations of beetles and larvae reveal about the tunnelling behaviours? Can their direction or origin points of be determined?
 - b. What is the range of tunnel width? Are they consistent or is there variation? Is there evidence of sharing or reuse of tunnels?
 - c. Can lifecycle stages be identified within samples? Is there a distinct beetle and larval size distribution? Does the date of plank extraction have an impact on larval size?

To address these questions, a deck plank with characteristic brown and white rot ([Appendix C](#)) decay (McCaig & Ridout, 2012: 186-197) and DWB activity was scanned with micro-CT, and the resulting images segmented to highlight

the tunnels, beetles and larvae present. By separating and identifying these features, the questions above could be addressed.

This chapter presents the investigations into this area. [Section 4.2](#) details the materials and methodology. [Section 4.3](#) discusses the results and is followed by concluding remarks.

4.2 Materials and Methodology

4.2.1 Deck plank

An oak deck plank ([Fig. 31](#)) from HMS *Victory* showing clear signs of active DWB infestation (adults in blunder traps near the plank, fresh exit holes, frass) and evidence of fungal decay ([Appendix C](#)) was designated for scientific study.

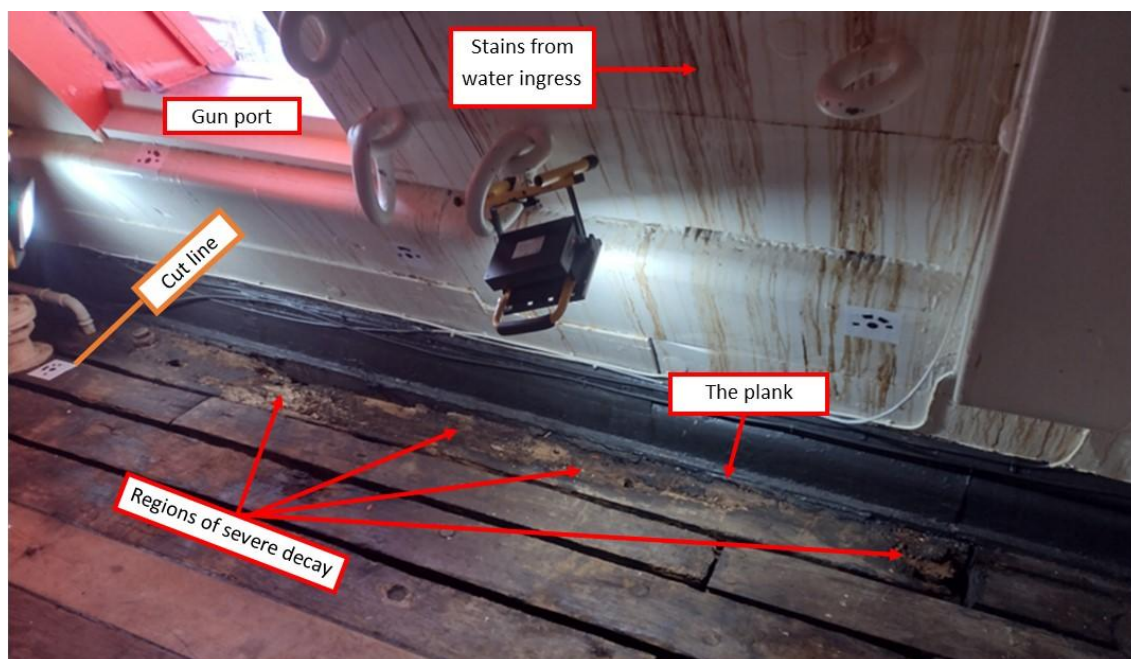


Figure 31: Annotated photo of plank *in situ* for context. The regions of severed decay contained both beetle and fungal decay.

The plank was located along the starboard edge of the middle gun deck (MGD), aft of the quartermaster's cabin, between MGD beams 19-23 and gunports 11 and 12 ([Fig. 32](#)). Documents suggest that it was installed in 1949 (Thornber, 2021), and at one point was a temporary access point to the port side of the ship (Davis, personal communication 2024). Evidence of water ingress from the gun ports and upper gun deck was clear on the sides of the ship and caused

localised saturation and subsequent fungal decay and surface abrasion on the plank.

Middle Gun Deck

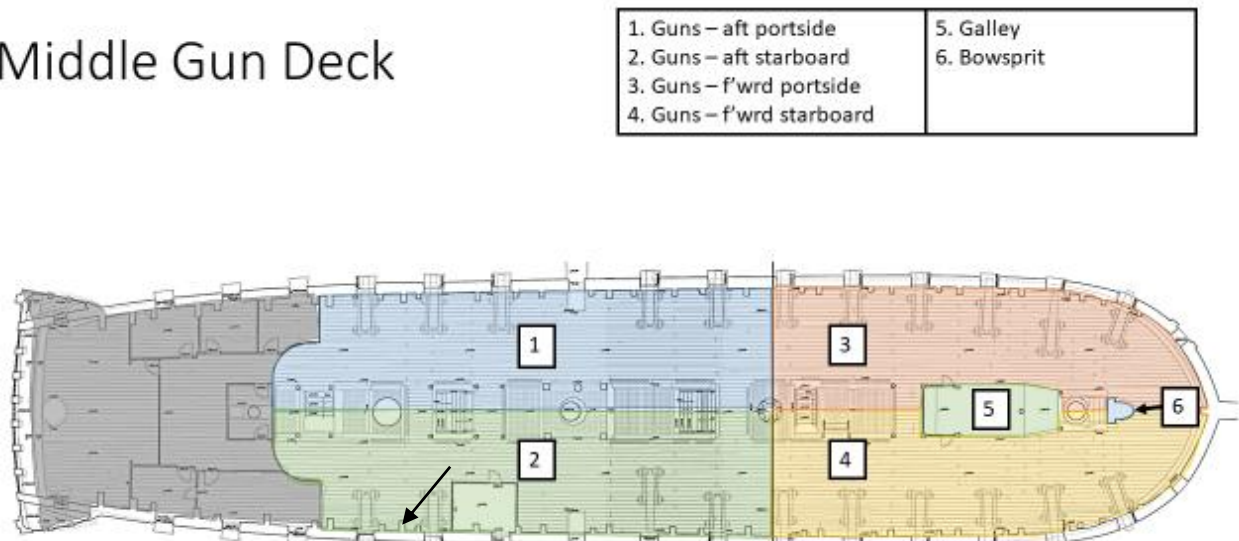


Figure 32: Deck plan of Middle Gun Deck with location of deck plank (indicated by arrow) used for analysis. Deck map from NMRN records.

Approximately 2.5m (length) of the plank were extracted in January 2022 by a shipwright using a combination of chisels and power tools; fastenings were cut around and the fore end of the plank cut a few centimetres fore of a defunct copper-alloy water pipe. The width varied along the length of the plank, averaging ~183mm with a maximum of ~221mm. Once lifted, the plank was placed into a custom box and transported to the shipwright's workshop, where the pipe was removed using a power saw. The plank was wrapped with Tyvek® and a barrier erected around the working area to prevent damage.

Once the pipe had been removed, the plank was replaced into its box, and carefully rewrapped with plastic and sealed, before being frozen for 3 weeks at approximately -35°C to kill any infestations within the plank (Daikin RA R32 Split & multi split M Series freezers). Freeze treatments are a common and effective method of killing pest infestations in objects (Pinniger & Winsor, 2011), and was performed to prevent the spreading of any pests (DWB or others) that may have been present in the plank to any future storage or laboratory spaces the plank may be kept in. After the 3 weeks had elapsed, the plank was transported in its box to Cranfield University. While the vibrations caused by transport may have dislodged some frass, it is unlikely to have had a significant impact on the study

when compared to the vibrations from power tools during sampling (details in [Section 4.2.3](#)).

4.2.2 Surface recording

The micro-CT chamber and detector are limited in size. The maximum area that can be scanned in a single scan is 12cm x 12cm, which results in a voxel size of 137 microns (*Nikon CT*, 2024). Smaller samples allow for higher resolution of images, but risk loss of material during cutting and too many small samples can lead to increased scanning time (du Plessis et al., 2017; Hipsley et al., 2020). Larger samples, however, may not provide the resolution required to see the wood features and any beetles and larvae (*Ibid.*). Brock et al. (2024) and Southwell (2017) were able to get good resolution in samples ~40mm (w) x 40mm (h) x 120 mm (l). As the deck plank in this study was significantly longer than the wood used by Brock et al. (2024) and Southwell (2017), consequently resulting in more samples, a compromise had to be struck between size, time per scan and number of samples. It was decided that ~50mm (w) slices of the plank would allow for sufficient resolution (see [Section 4.2.3](#) for sampling methodology).

Prior to any sampling taking place, a complete record of information of the surface that might later be damaged by sampling and 3D models of the original geometry of the plank were required. The plank was recorded *in situ* by the archaeology team and after removal using laser scanning and photogrammetry. Descriptions of how the methods work can be found in [Ch 3 Section 3.2.1](#). The methods were selected to be compatible with the methods used by the on-site archaeologists and enable integration into the VIM. Additionally, the 3D models had potential of incorporation into public engagement prototypes ([Chapter 6](#)).

4.2.2.1 Laser scanning

An Einscan Pro 2x handheld laser scanner using the basic scan settings was used to create the model in the imaging laboratory at Cranfield University. The scanner, connected to a laptop with EXScan pro v.3.7.3.0 software, was slowly moved manually across the surface of the plank while monitoring the live

building of the model. Adjustments to the brightness of the camera were regularly made to enable the scanner to distinguish between the painted and non-painted surfaces.

Each side of the plank was scanned, and the final model stitched together using the EXScan Pro software by matching features from each scan. This created a to-scale model with most surface details but did not record colour or finer surface details, like exit holes ([Fig. 33](#)). Add-ons to the scanner that record colour and surface details exist but were unavailable at the time of scanning.

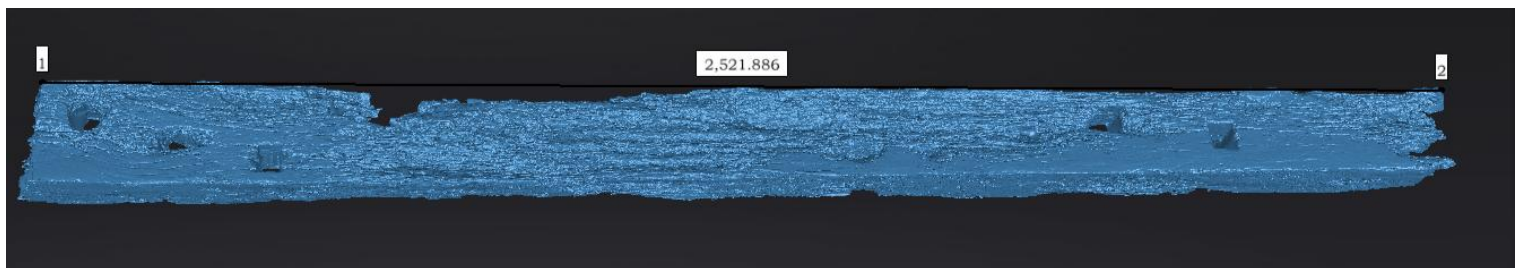


Figure 33: Screenshot of the laser scan model of the plank created by the author.

4.2.2.2 Photogrammetry

High-definition photos of each side of the plank were taken with a Motorola G9 play phone camera using fluorescent and ambient light. These were uploaded to Agisoft© Metashape Pro (v. 2.0.4), a photogrammetry software, and grouped into two clusters or chunks, one for each side of the plank. The photos for each chunk contained the sides of the plank to aid with alignment, which enabled the software to match images together. Dense point clouds were generated by the software on medium resolution for each chunk. Medium resolution was chosen as it provided sufficient level of detail and minimised processing time. An initial removal of background points was done to minimise extraneous data. The dense clouds were then used to create an initial mesh for each side to aid with marker placement. Features of note, such as exit holes and paint edges, were given markers of the same number in each chunk. The chunks were then aligned with the markers and merged together. Removal of extraneous points on the dense cloud of the merged chunks was done before creating a mesh and a texture file. A more thorough removal of extraneous surfaces and other points was done at this stage.

This model has surface texture, details and colours, but is not to scale ([Fig. 34](#)). Although Global Positioning System (GPS) locator points for scale can be used in photogrammetry, these were not available at the time. The laser scan model provides the scale model. The lack of geolocator data for the photogrammetry model meant a smaller file size that could be more easily used for the public engagement prototypes. It may be possible to combine the models in future.



Figure 34: Screenshot of photogrammetry model created by the author.

4.2.3 Sampling and categorisation

The plank was designated into four ~650mm sections based on its orientation in the ship: Fore (F), Centre-Fore (CF), Centre-Aft (CA), and Aft (A). These zones were then cut into thirteen ~50mm samples, counting from the fore end of the plank ([Fig. 35](#)).

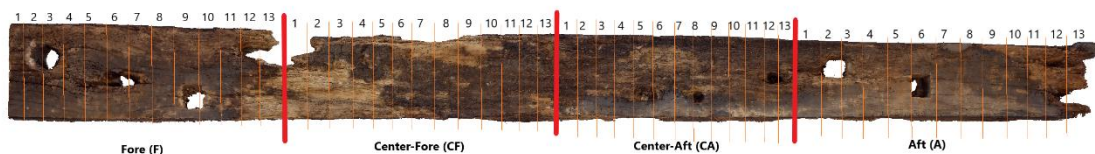


Figure 35: Sample assembly map on complete plank, with approximate locations of each sample. Not to scale.

Each sample was then given a designated code based on the section and number location and stored in individual bags. For example, CF11. The sampling and mapping were done to aid in reconstruction and stitching together of tunnel maps later in the process, and to assist with systematic sampling.

Measurements were marked out on the box edges and the plank cut using a jigsaw ([Fig. 36](#)). Due to the thickness of the plank in some areas, the jigsaw was unable to cut all the way through, requiring the plank to be flipped over to complete the cut. Another method, like a bandsaw or circular saw, would have resulted in cleaner cuts. However, this would have required handling and

moving the plank across campus to a workshop and further assistance. The method and available equipment used enabled the author to safely perform the sampling without assistance within an afternoon. The vibrations caused by the jigsaw caused fragmentation, surface loss, and dislodged frass. Although every effort was made to collect as much material as possible, there was inevitable loss. The loss of frass would not have had an impact on the tunnel volume (empty tunnel would remain), but the fragmentation and loss of surface are likely to influence calculations of wood volume and volume of loss. This will be discussed in greater detail in the [results and discussion](#).



Figure 36: The author cutting the plank with a jigsaw on the storeroom floor (phone on stand).

The samples were photographed using the Motorola G9 play phone camera, then categorised according to the estimated number of exit holes on all external surface counted in photographs ([Table 2](#)). External surfaces in this instance refers to the outer surfaces of the plank. Cut surfaces are not external surfaces. The exit hole count was done twice with several months between counts to mitigate bias. However, due to surface loss during the cutting process, the number of exit holes is only an estimate.

Table 2: Plank sample categorisation

Category	Definition	No. of Samples
A	≤ 25 exit holes	15
B	$25 < x \leq 45$	21
C	> 45	7
D	Too damaged to count exit holes	9

This categorisation was added onto the location code for each sample. For example, CF11B. A ~50% subsample of each category was selected randomly for scanning to allow for a greater understanding of the spread of damage across the plank and reduce the amount of time required for scanning and post processing. It was not possible to be completely random for Category D, as some samples were so badly fragmented they were physically impossible to scan ([Fig. 37](#)). Instead, the samples with the largest remaining fragments were chosen. This does introduce a level of bias to the research. However, even if those fragmented samples were scannable, there was insufficient material remaining to map the tunnels. By selecting those with the largest fragments

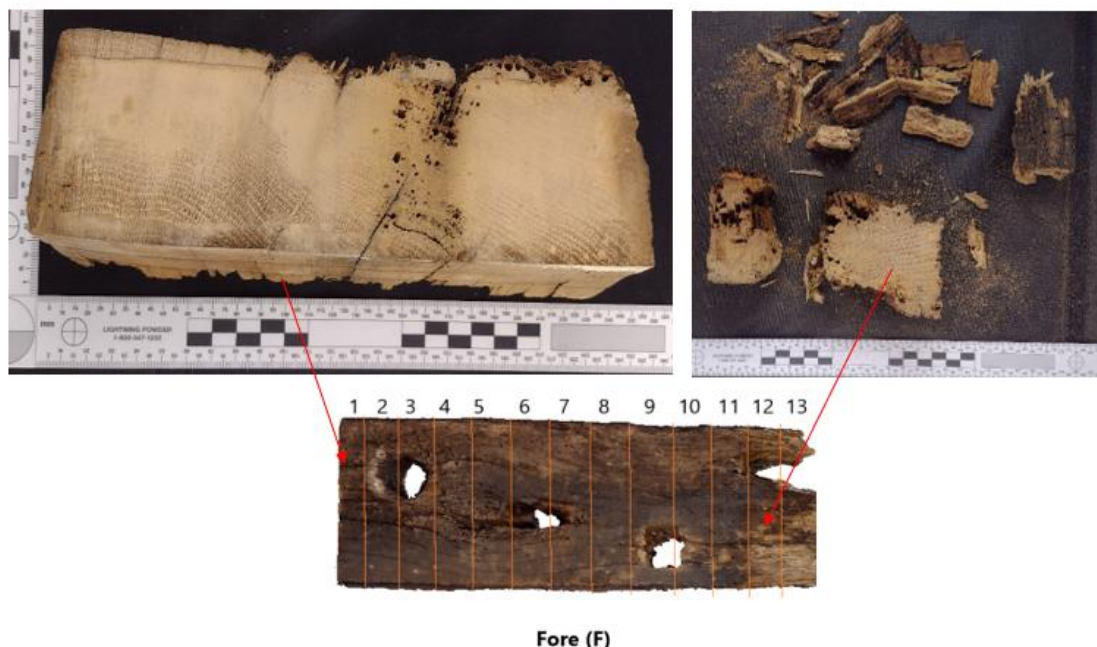


Figure 37: Two samples with contrasting levels of loss and fragmentation and their approximate locations on the plank. On the left is sample F1. This was the least degraded section of the plank and held up well during cutting. On the right is sample F12. This was one of the samples that completely fell apart during the cutting process. A number of exit holes can be seen on the smaller fragments suggesting they had once formed part of the surface.

remaining, sufficient material was available to be able to get a clearer understanding of the DWB damage in an extremely decayed area. The amount lost varied across samples, with no material lost on the more robust samples, and substantial loss on others ([Fig. 37](#)). Quantifying the amount of loss is challenging due to the presence of holes from fastenings and the high level of degradation and loss caused by decay prior to cutting.

4.2.4 Micro-CT

Micro-CT was used to visualise and determine the internal tunnel volume and presence of beetles and larvae in each of the samples. A Nikon XT H 225 micro-CT scanner (Nikon Metrology, Tring, UK) with a Perkin Elmer XRD 0820 flat panel detector and tungsten reflectance target was used to scan the samples at 110 kV, 90 μ A and 1s exposure with 720 projections (2 frames per projection) with a resultant voxel size of 85 microns.

The initial basis for this research was to expand on the work done by Southwell (2017; Brock et al., 2024). These samples were scanned at 110 kV, 45 μ A, and 354ms exposure, with 1571 projections (2 frames per projection) at a resultant voxel size of 137 microns. These settings were chosen to optimise resolution within a limited time period for analysis, but also taking into consideration sample size. As time was not a limiting factor for this thesis, settings could be enhanced to decrease voxel size, thereby increasing resolution of observed features, while still being comparable.

Samples were wrapped in cling-film to prevent fragment and frass loss inside the machine and mounted vertically using custom Ethafoam® (expanded polyethylene foam) mounts (*Ethafoam*, 2024). This low-density foam did not interfere with image quality. Fragmented samples were scanned together whenever possible using foam support, but in cases of separate scans, the images were stitched together during processing.

All samples were scanned with the same settings for consistency. However, some samples had paint on exterior surfaces, and some did not. Energy dispersive x-ray fluorescence (EDXRF) analysis of the paint conducted prior to

scanning indicated it was titanium-based and should not affect the X-rays. However, lead (Pb) was present in the results, likely due to historic use of lead-based paints on the ship. Small flecks of high-density appeared in the images, and with the thickness of some of the paint layers created areas of density and scattering in some of the images. However, beetles and larvae were still visible within the clear wood structure.

Higher resolution micro-CT and Scanning Electron Microscopy (SEM) images were taken of smaller subsamples from A6A and CF5D (~25mm (w) x 20mm (l) x 75mm (h)) to determine whether fungal hyphae and decay could be seen in the samples. The same micro-CT (Nikon Metrology, Tring, UK) with tungsten reflectance target was used to scan the 6 smaller samples at 79-80 kV, 55 or 65 μ A and 500s exposure with 720 projections (2 frames per projection) at a resolution between 47-75 voxels. The micro-CT samples were mounted on an Ethafoam® stand with double-sided sticky tape. The SEM used was a Hitachi SU3500 SEM. The A6A wood subsample imaged was secured to a 100mm dia x 4.5mm x M4 Hitachi specimen stub with conductive carbon tape. The frass (extracted from CF5D subsample) was pressed onto to a 25mm dia x 13.5mm x M46 Pin-type Hitachi M6 stub with a conductive carbon adhesive disc. The SEM images were taken at 20.0kV under an 80Pa vacuum.

4.2.5 Data processing

4.2.5.1 Initial Set-up

The micro-CT data was reconstructed with Nikon CT Pro 3D (XT 6.3.1, Version 6.3.7545.25500) software and converted to a Floating Point Volume graphics file (.vgl).

This file was imported into Dragonfly ORS (*Dragonfly ORS*, n.d.), a 3D visualisation and analysis software (Comet Technologies Canada Inc, Montreal, Canada). The image data was cropped to make file sizes more manageable and remove as much of the background as possible. In cases of fragmentation and separate scans, all image files were loaded into a single .orsSession file and manipulated using the Flip/Rotate and Translate/Rotate tools. Once the

images of the fragments were aligned, they were merged with the 3D stitching tool.

To make all features visible and as clear as possible, a custom Look Up Table (Victory Greyscale, an adjusted in-software Greyscale LUT) was created for the 2D image views. A Look Up Table (LUT) determines how regions of intensity arrays or scalar values are coloured and displayed (*Welcome to Dragonfly's Online Help*, 2022). A similar process was done for the 3D views by adjusting the in-software Wood LUT to create a Victory Wood LUT. Contrast and brightness were adjusted for all views using the Window Levelling controls.

4.2.5.2 Segmentation

Segmentation is the process of dividing an image into sets of voxels that share characteristics, with the ultimate goal of altering an image into something easier to analyse (*Welcome to Dragonfly's Online Help*, 2022).

There are two key things to note about segmentation: there is no universal technique that will work for all images, and no method of segmentation is perfect (Reznikov et al., 2020; *Welcome to Dragonfly's Online Help*, 2022). While the methodology described in this section was applied to all samples, minor adjustments had to be made throughout the process to allow for differences such as density and features across samples. While every effort was made for the results to be as accurate as possible, the nature of segmentation does not allow for complete accuracy. It was also the most time consuming part of the process, with each sample taking several weeks to process fully. However, the information gleaned still provides valuable insights into the tunnelling behaviour of the DWB on HMS *Victory*.

Wood is a challenging material to segment and becomes even more so when subjected to fungal decay and insect damage (Seibold et al., 2022). For this thesis, segmentation was done by voxel greyscale value, dictated by the radiodensity (HU-value) of the material. The background to any CT scan (micro or otherwise), is air, which has an HU value of -1000. Empty tunnels and wood vessels are also filled with air. Frass-filled tunnels have similar HU values to

those of the surrounding wood. The more decayed the wood, the less dense it gets, and the closer the HU value becomes to that of air, making it challenging to distinguish features. While the human eye can distinguish these differences, it is not feasible to manually segment all the tunnels from the thousands of images making up each sample. This was one of the struggles found by Brock et al. (2024) and Southwell (2017) during their investigations, and prevented complete mapping and volume determination of the DWB tunnels in the scanned samples. Since the data collection stage of those investigations, new software and tools for segmentation have become available that aid the process significantly.

The in-built Artificial Intelligence (AI) Segmentation Wizard in Dragonfly ORS allows the user to train AI using frames of manual segmentation. Models for each sample were trained using approximately 10 manually segmented frames ([Fig. 38](#)). Having a unique model for each sample mitigated differences in shape and density. The wood, air/background, empty tunnels, and frass-filled tunnels were identified as unique Regions of Interest (ROI). This was achieved using the Otsu method of thresholding, which uses an algorithm to separate voxel intensity into two classes, foreground and background (Otsu, 1979). Greater accuracy was achieved with the models by segmenting empty and frass-filled galleries separately before merging the classes together later. Not including the background air or tunnels that opened to the surrounding air in training frames resulted in higher accuracy as well. Three models were trained for each sample and the model with the closest match to the training frames was selected and applied to the sample. The AI provided the initial segmentation for all samples, with varying levels of accuracy. All samples were manually finished using the various ROI tools available on Dragonfly ORS.

This segmentation resulted in a multi-ROI containing the wood, air (background and within wood vessels), frass and tunnels. The volume of each class could be calculated by the software and separated out to aid in visualisation.

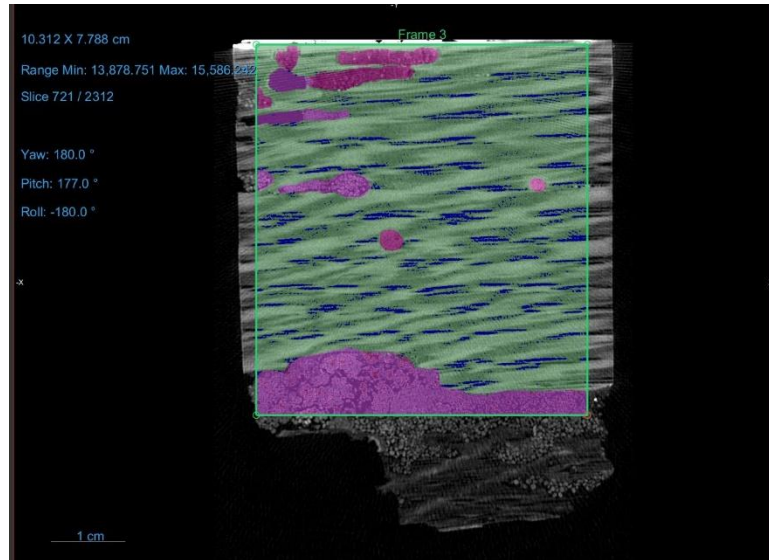


Figure 38: Training frame for AI model. The wood is highlighted in green, the wood vessels (air) in blue, and the tunnels and frass in 2 shades of pink..

All larvae and beetles in each sample were identified visually and their location noted with the Point annotation tool, labelling each in order of discovery. This was done separately from the main segmentation to allow for regular discoveries throughout the processing period. These were manually segmented into a multi-ROI using the Define Range tool and the ROI Painter (multi-slice) on the 2D views.

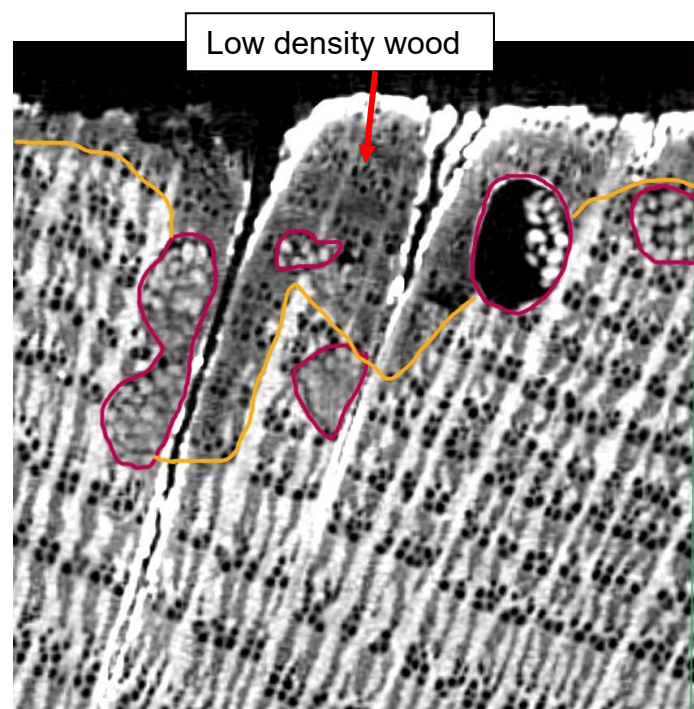


Figure 39: Annotated micro-CT image showing region of low density wood in sample A10A outlined in yellow. Tunnels are outlined in pink.

Once the segmentation of samples into wood, tunnels, and surrounding air was completed, further segmentation of each ROI could be performed. Ten of the scanned samples were randomly selected to examine the relationship between low greyscale density (more fungally decayed) wood ([Fig. 39](#)) and DWB galleries (see [4.3.4](#)). The wood ROI of the selected samples were segmented by defining the low Otsu value range and creating a new low-density wood ROI. This was then refined manually with the Connected Components tools.

4.2.5.3 Measurements and Statistical Analysis

Once segmentation was completed, the analysis function was run to calculate the volume of the tunnel and wood ROIs. To determine the approximate original volume of each sample when the plank was first installed, measurements of the largest dimensions (height, width, and approximate length) were taken with the ruler tool in order to approximate how much material had been lost since installation. This was done for mostly intact and reconstructed samples. The amount of remaining wood was subtracted from the estimated original volume to calculate the approximate percentage lost (response variable). This value and the tunnel percentage of the total volume were plotted against the estimated number of exit holes per sample (predictor variables) and a Locally Weighted Scatter Plot Smoothing tool (LOWESS), which creates a smooth line through the scatter plot, was used to help identify the variable relationships (Glen, 2013). MiniTab™ regression analysis was then used to assess models of best fit to model the relationships between the variables.

Measurements of the beetles and larvae were taken with the ruler tool, and conducted twice, with several months between measurements to assess intra-observer error. A small sample (20 individuals) was also measured by an independent person to check for inter-observer error. The mean of these measurements was calculated and plotted to determine trends.

4.3 Results and Discussion

Data and additional calculations can be found in [Appendix C](#).

4.3.1 Tunnel and area of loss volume and surface damage

The scatter plots ([Fig. 40](#)) comparing the estimated number of exit holes with the percentage of wood lost and the tunnel percentage of the total volume show correlations between the variables (confirmed with T-tests and correlation coefficients) and a statistically significant relationship (p -values < 0.05). Logarithmic trendlines best fit the data and were confirmed with residual plots ([Appendix C](#)). Although R^2 (measures % of dependent variable variation in the model) is not high for either model, the nature of the data is unlikely to allow for a higher percentage. However, the models can still be considered a decent fit due to the low S (standard error of the regression) value.

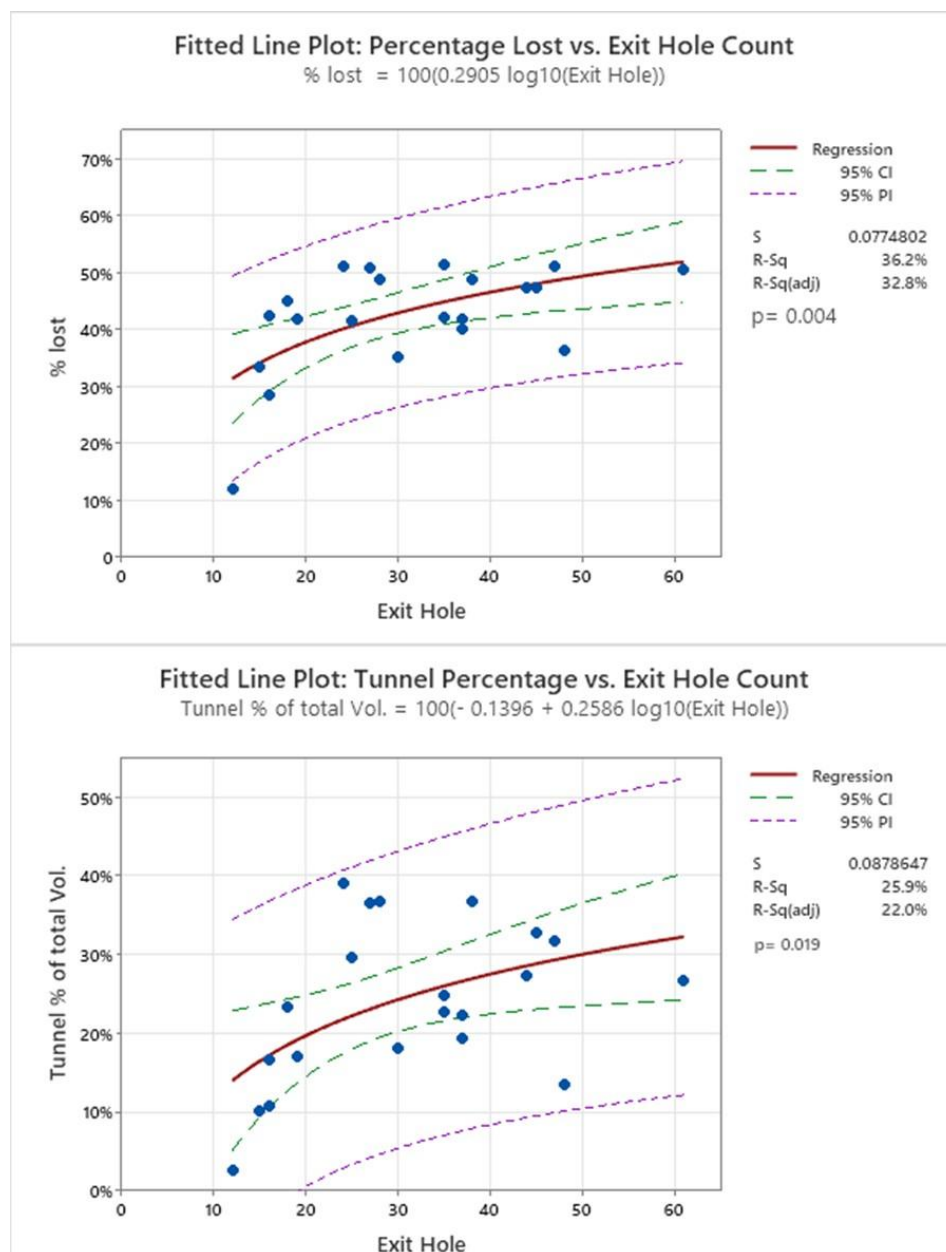


Figure 40a (above) and b (below). (a) Scatter plot of exit hole vs % lost (b) Scatter plot of exit hole vs tunnel % of total volume, both plots with logarithmic regression models.

There are some caveats to consider with regards to the data. The most degraded samples were too damaged to estimate the exit hole count and original volume and so do not appear on the plots. Their lack of inclusion limits the accuracy of the model as the more extreme degradation is not represented. Surface loss during sampling may also have impacted the exit hole estimates. If this work is to be repeated, the exit holes should be counted prior to sectioning. So, while it is clear that there is a relationship between internal and surface damage, a larger sample size with samples from other sites would enable a more accurate model.

Although the Southwell (2017) and Brock *et al* (2024) data from micro-CT and digital images was similar to the data from this thesis, it could not be directly compared using the same methodology. They calculated the % of the tunnels of the outer surface area of the samples, rather than the exit hole counts, as the unknown provenance of their timber meant that outer surfaces could not be determined. The determination of surface area is a more challenging process than exit hole count and is not something that could easily be achieved by those on site. Exit hole count is easier data to collect and monitor, especially for *in situ* timbers, from which the internal damage can be estimated.

A larger sample size from other sites may also alter the trendline and subsequent model for predicting amount lost. Although the logarithmic trendlines were the best fit for the generated data, when examining logarithmic models more widely, they are characterised by an initial sharp increase before tapering off, but they continually increase without bound. With regards to wood consumed by larvae, this is not a realistic model. Instead, a logistics growth model may be more accurate, as it is characterised by initial slow growth, with a period of moderate to rapid growth, before reverting back to slow growth (Alexander, 2021; Strang & Herman, 2016). It also has an upper limit that cannot be exceeded (*Ibid.*). However, for the purposes of this thesis and the existing data, a logarithmic model remains the best option.

In the meantime, the logarithmic model can be used as a rough guide for the timber on *Victory*. This relationship means that the external damage, in the form

of exit hole counts, can be used to estimate the internal damage, either in the percentage of wood lost or the tunnel percentage of the total volume.

4.3.2 Low density wood and fungal decay

Fungal decay is known to cause a profound impact on the cellular structure of wood and often results in loss of mass and density (Beaulieu & Dutilleul, 2019: 1184; Goodell et al., 2020: 6; McGovern et al., 2010). In the 10 samples that were further segmented to examine the relationship between the beetle tunnels and low density wood, there was a clear visual relationship between the two ([Fig. 41-2](#)). This relationship was more apparent in sample A6A than A4A, as the latter had a large area of loss and was next to a fastening point, where metal ions may have acted as an inhibitor. However, the majority of tunnels for all samples further segmented are in areas of lower density wood (more fungally decayed). In cases where the tunnels go through apparently sound wood, it could be that the larvae are following fungal decay that is not yet visually apparent in the micro-CT images (see [4.3.3.2](#)).

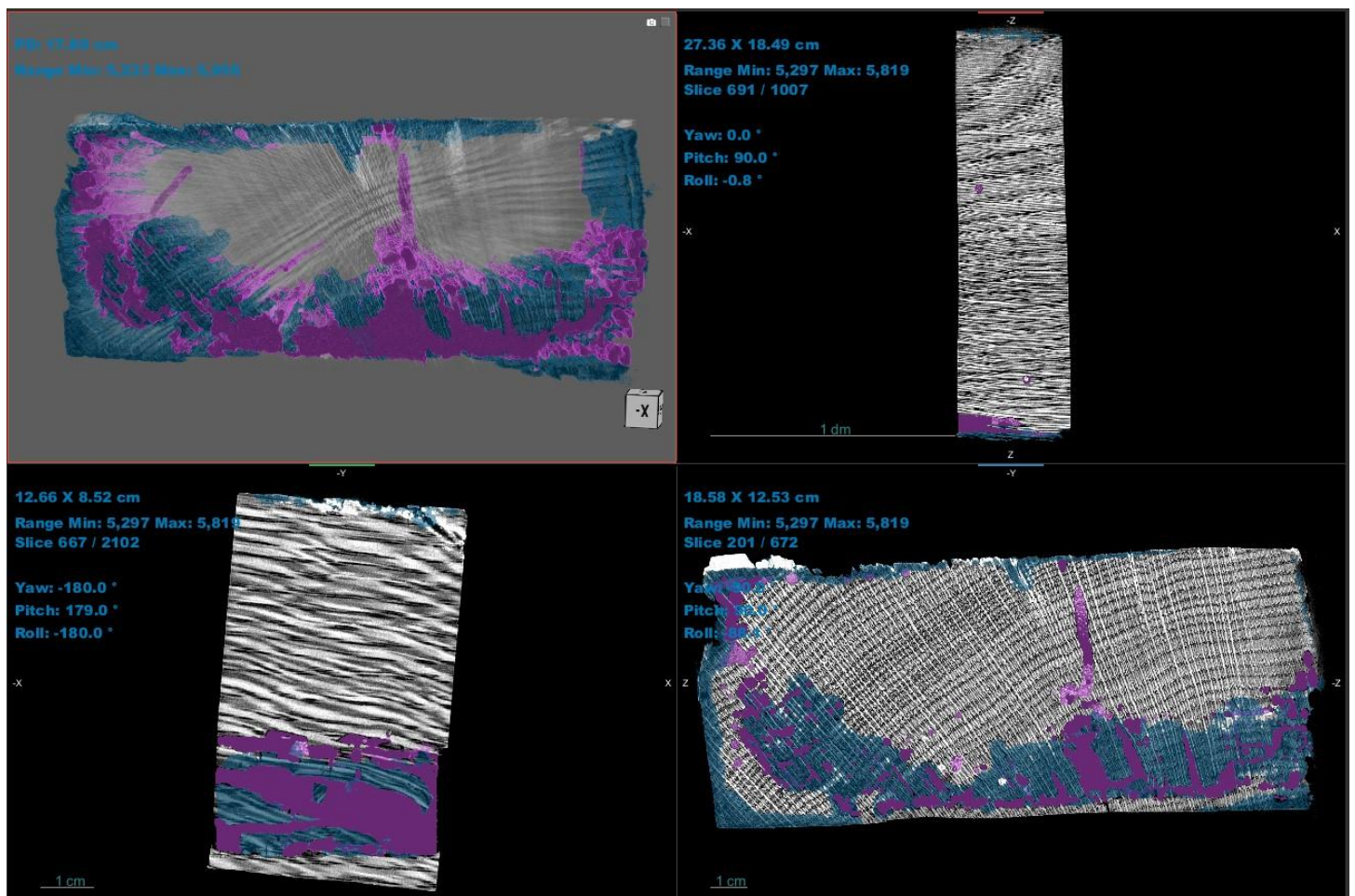


Figure 41: micro-CT segmented images of sample A6A with tunnels (pink) and low-density wood (blue). The majority of the tunnels are concentrated in the blue areas, but some move away from the low-density areas into the more ‘sound’ wood.

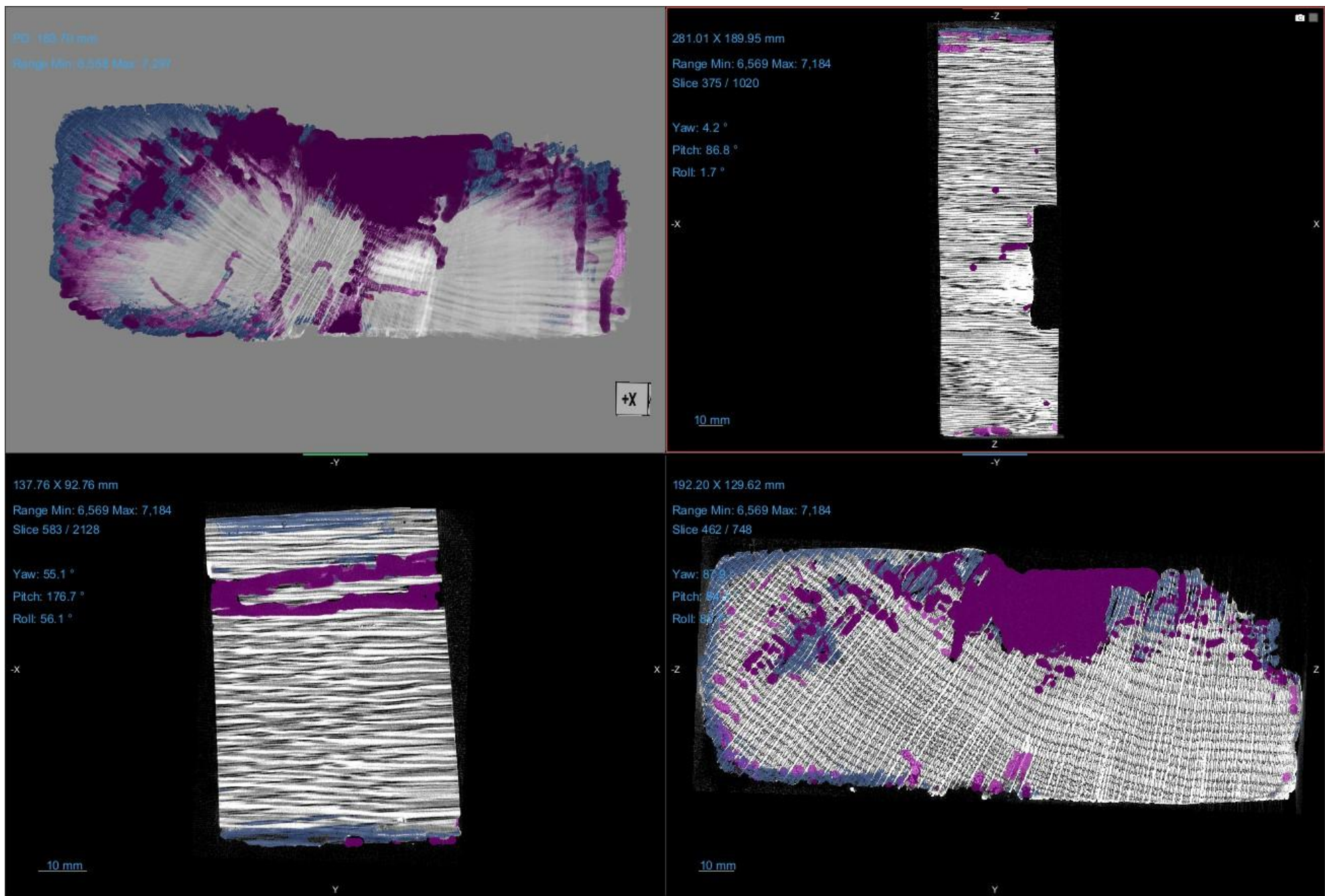


Figure 42: micro-CT segmented images of sample A4A with tunnels (pink) and low-density wood (blue). The area of higher density (bright white) was next to the fastening and may have absorbed metal ions.

Upon further examination of subsamples from samples A6A and CF5D under SEM, fungal hyphae can be seen within the wood vessels in both the less dense and more 'sound' wood ([Fig. 43](#)). The less dense wood has lost wood structure in a manner consistent with fungal decay (Islam et al., 2017; Schwarze, 2007). Given the presence of fungal hyphae in the wood vessels and the concentration of tunnels within the lower density wood suggests the larvae make use of the fungal decay to aid their passage ([Fig. 44](#)). This is further supported by the presence of what appear to be fungal hyphae and spores in the larval frass (more details in following section).

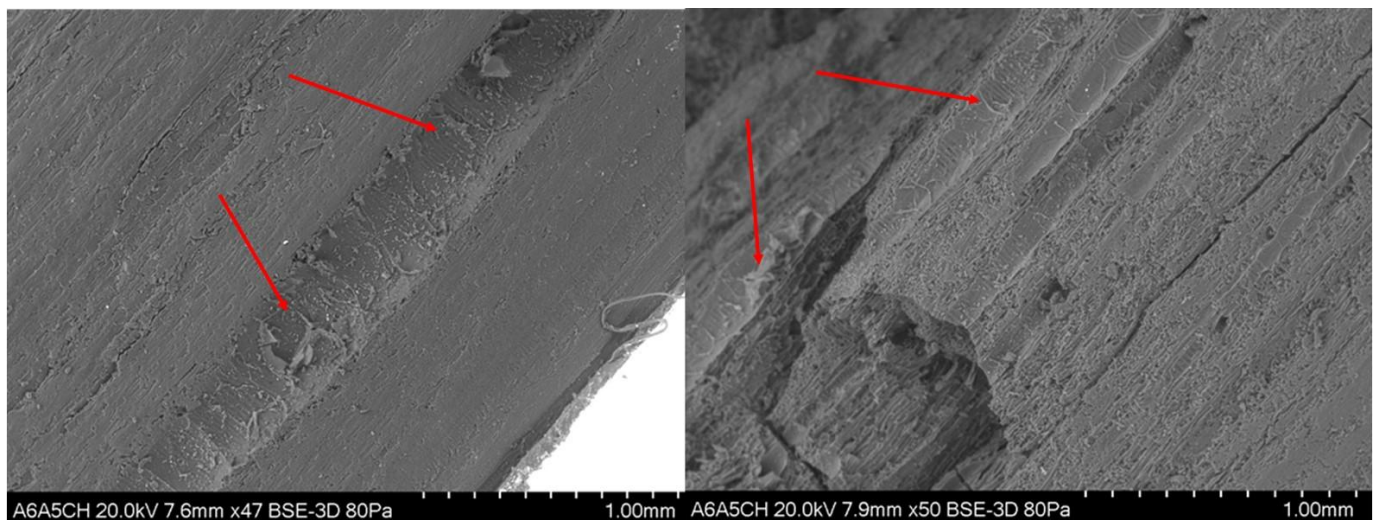


Figure 43(a) and (b): SEM images of sample A6A-5 of (a) wood vessel cross-section in more 'sound' wood containing fungal hyphae. (b) exposed wood vessels containing fungal hyphae in low density (more decayed) wood.

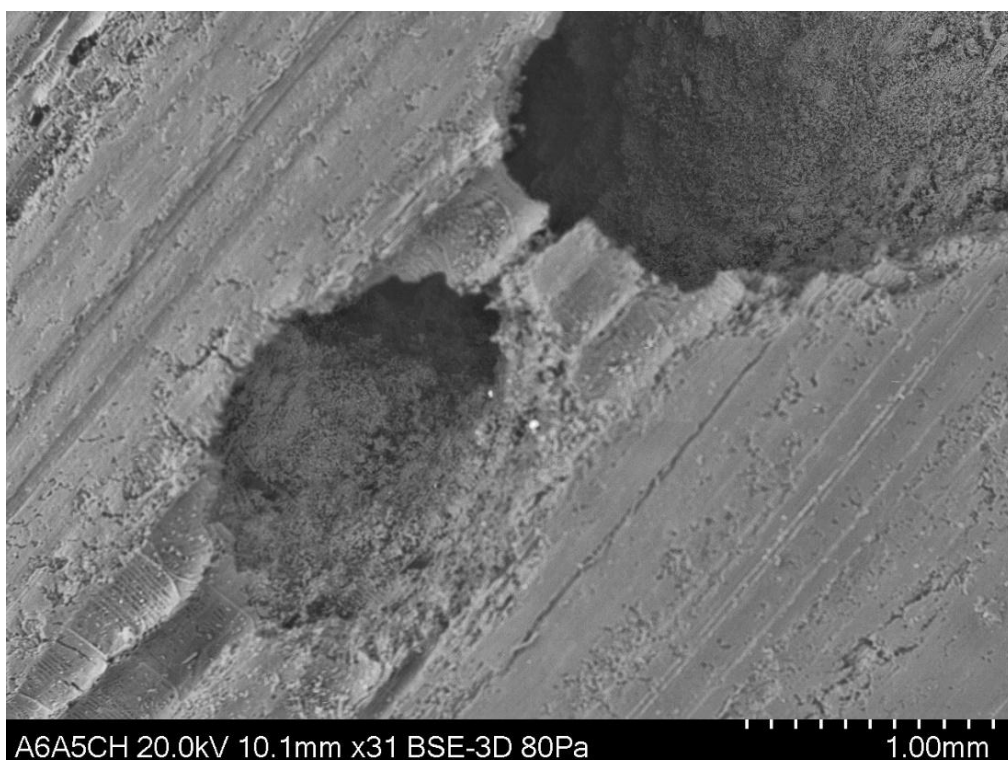


Figure 44: SEM image of a DWB tunnel running along wood vessels with fungal hyphae

Higher resolution micro-CT scans of the wood show fine cracks in areas of low density around the tunnels that were not visible in the original scans ([Fig. 45](#)). Some cracks appear to radiate out from the tunnels, while others are confined to one area between rays but are concentrated in the lower density areas. Interestingly, some of the cracks between rays ([Fig. 45b](#)) have the characteristic cubical cracks of brown rot ([Appendix C](#)). It could be that the fungal/beetle relationship is more symbiotic in that the larvae initiate tunnels along paths of fungal attack, and the fungus makes use of the tunnels to expand attack further (Menendez, 1990: 211).

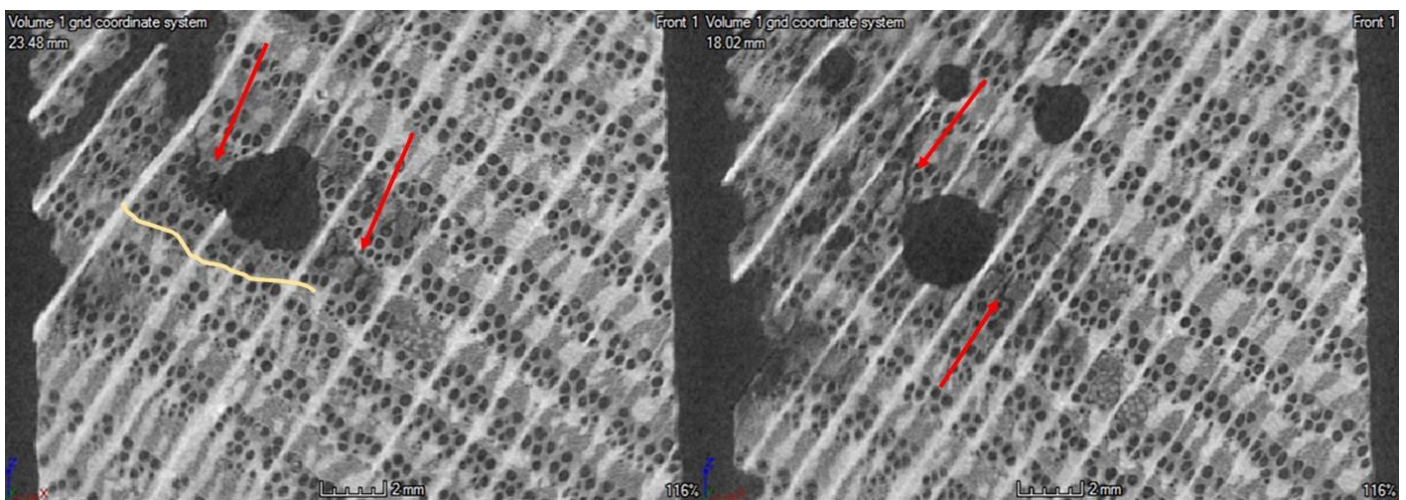


Figure 45(a) and (b): Higher resolution micro-CT images of sample A6A with red arrows indicating cracks radiating from tunnels and those between rays. The yellow line in (a) indicates the line where the greyscale value changes from the more decayed wood (darker grey) around the tunnel to less decayed wood (lighter grey).

It has long been supposed that there is a close relationship between the DWB and fungal decay, similar to other species of woodborers (Fisher, 1940b; Ridout & Ridout, 2001). This is supported by the fact that DWB infestations often occur in structures where water ingress is an issue. However, the research into the relationship was often hampered by the available techniques at the time and the exact nature as yet remains elusive. These results contribute visual evidence of the presence of fungal hyphae linked to DWB tunnels and the preference for low density wood.

Investigations by Belmain (1998) and Jefferys (2021) found that the beetles eschewed undecayed wood, preferring instead fungally decayed older wood, or

even cellulose discs treated with wood-decaying fungus. This was expanded upon by Nair (2023), who examined Volatile Organic Compounds (VOCs) from modern, archival, fungally degraded, and DWB-ravaged wood, and found that the larval-damaged wood had a unique pattern of increase in terpenes and a decrease in aldehydes. More testing of greater numbers of beetles with more specific compounds is needed to understand what exactly it is that attracts them. This would be aided by examining other woods that DWB have been found in, for example willow and pine, for commonalities to see if it is a specific fungal species that they are attracted to, or if a number of different factors attract them. The work conducted thus far, and the further investigations proposed all focus on the more mobile adults and are linked to oviposition preferences. While it would be supposed that the eggs would be laid on wood that is most conducive to larval development, there is the possibility that larval preferences are distinct from the oviposition preferences of the adults. It would be challenging to study, but not impossible.

4.3.3 Beetles, larvae, and frass

Within the 26 samples scanned, there were 54 adult beetles, 65 larvae and 1 pupa identified and located.

4.3.3.1 Size and distribution

The length, width, and surrounding tunnel diameter of individuals was determined whenever possible. The full set of measurements and mean calculations can be viewed in [Appendix C](#). The measurements of the adult beetles predominantly fell within the expected range of 5-9mm in length ([Fig. 46](#) – orange points). Those outliers are likely due to measurement errors or damage to the beetle body and/or head. There was a bigger range in the sizes of the larvae across the samples ([Fig. 46](#) – black points). This could mean one of two things: either there are several different woodboring species present, or the larvae are all DWB but at different instar stages. Three distinct groups appear within the larval measurements ([Fig. 46](#) – circles). Given the sizes of the adults present, it is likely that they are all DWB at different stages, but without anatomical and genetic investigations into the individuals, it is not possible to be

certain. As it is yet unknown how many instars stages the DWB larvae go through prior to pupation, and whether the number varies with differences in surrounding environment as is the case for other insects (Bleiker & Régnière, 2015; Esperk et al., 2007), this is something that requires further investigation.

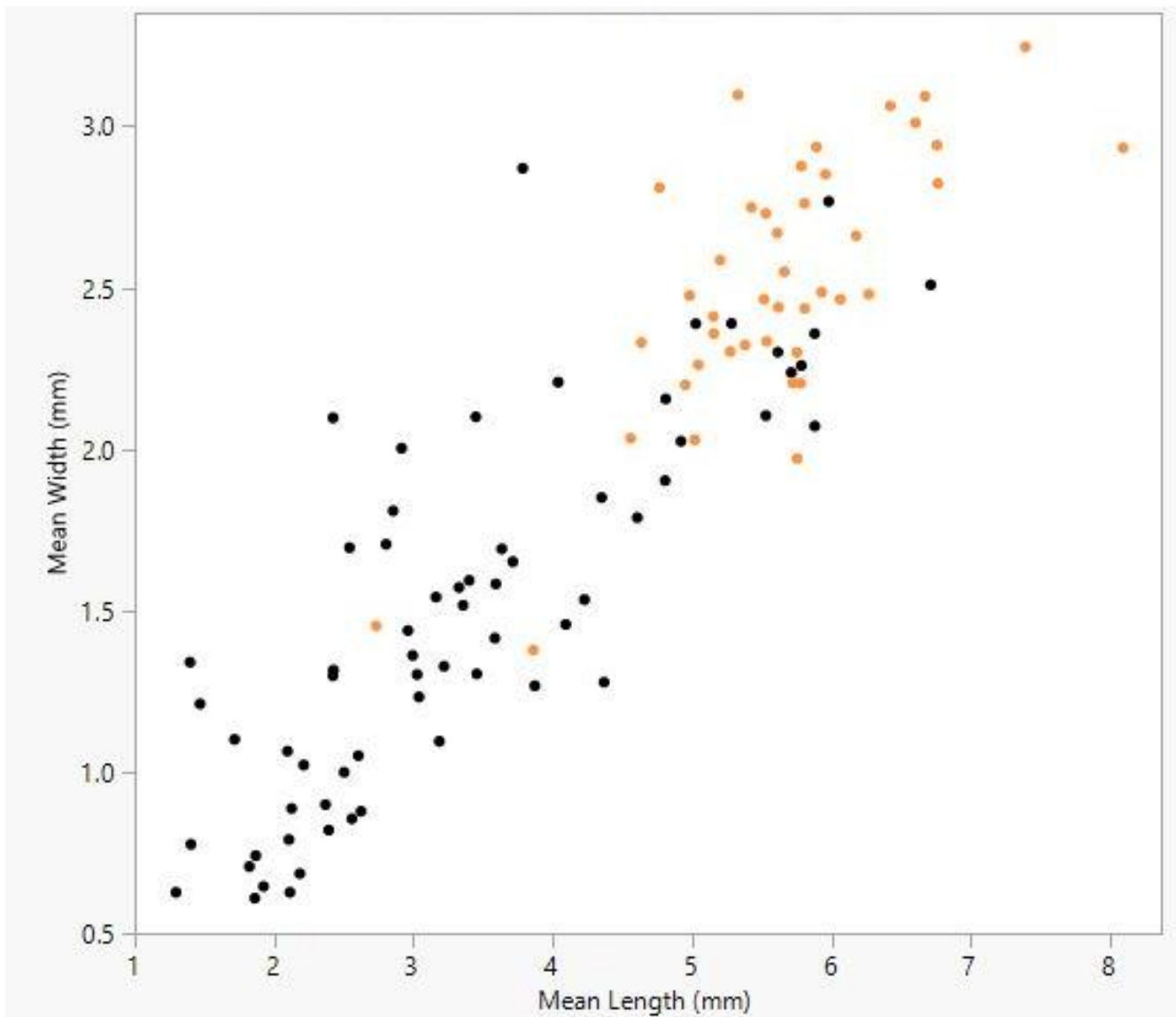


Figure 46: Scatter plot of mean length and width of beetles (orange points) and larvae (black points), with three distinct clusters appearing for the larval measurements.

As would be expected, the tunnel diameter immediately surrounding the individuals is reflective of the width of the beetles and larvae ([Fig. 47](#)). The data is suggestive of a tapering point for a maximum tunnel diameter, but the diameters were only taken where there was an individual present. Further measurements of tunnel diameters across samples are required, though this will be challenging with the merging of tunnels (further discussed in the following section).

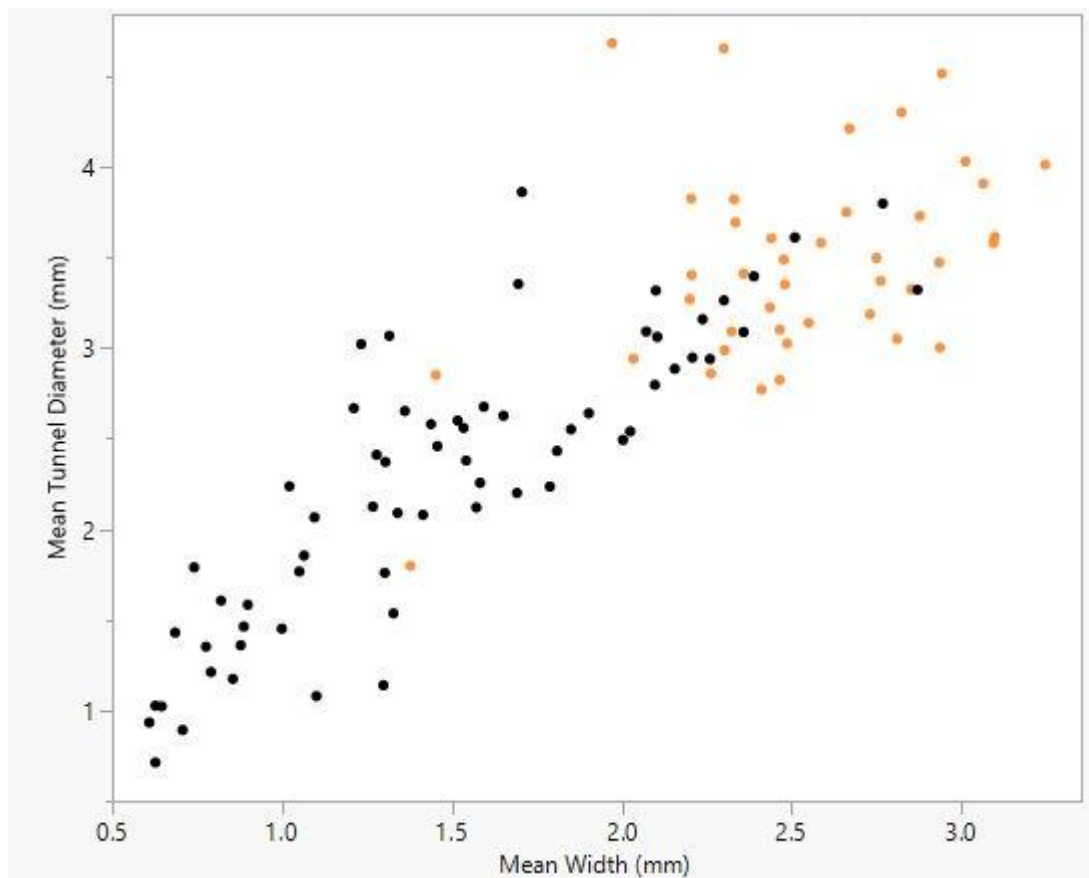


Figure 47: Surrounding tunnel diameter of beetles (orange points) and larvae (black points) compared to mean width of insect.

The spread of beetles and larvae across the different levels of damage (see [sample categorisation](#)) varied considerably ([Fig. 48](#)). Larvae were most concentrated in Category D, but were then more populous in Category A, with the least amount in C. Although the numbers were adjusted to allow for the differences in number of samples (dividing the number of individuals by the number of samples), this difference may have caused unexpected influence.

The beetles were more evenly spread across the categories, although they were slightly more concentrated in B and C.

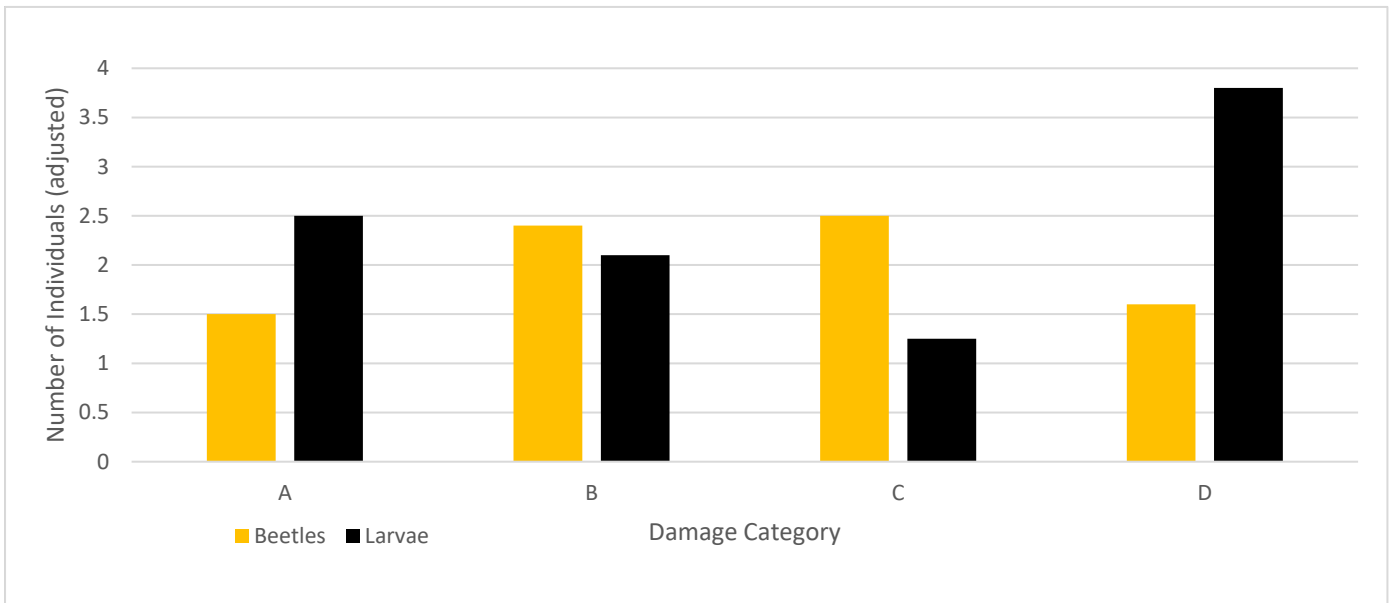


Figure 49: Bar chart of beetle and larval distribution across damage categories

There was also variation in numbers of beetles and larvae across the plank samples ([Fig. 49](#)). Larvae were mostly concentrated at the Aft end, with the second highest concentration in the Centre-Fore area, which was the most degraded. The adult beetles were most concentrated in the Centre-Aft area, with the rest spread more evenly across the rest of the plank. When comparing

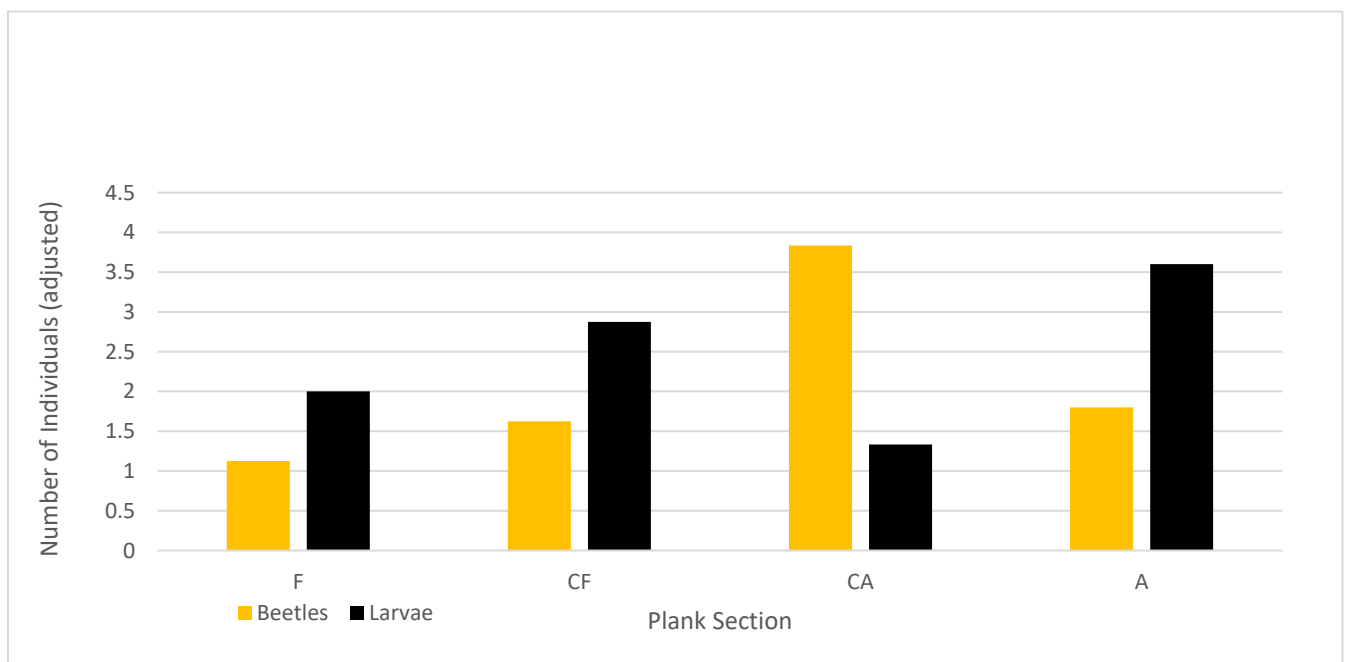


Figure 48: Spread of beetles and larvae across plank sections

the distribution of beetles and larvae across the plank, there appears to be an inversely proportional relationship, with beetles concentrated in areas there were less larvae, and larvae concentrated in areas with fewer beetles.

4.3.3.2 Beetle & larval tunnels

There are several distinctive trends to the overall tunnel maps that can be identified and reveal valuable information with regards to the DWB tunnelling behaviour.

The tunnels generally follow the path of least resistance, following the longitudinal fibres of the wood and the rings of early wood, as larger wood vessels means less resistance ([Fig. 50](#)). This corroborates the findings of Brock et al. (2024) and Southwell (2017). The tunnels are primarily concentrated in areas of low density wood and run between the rays. Those tunnels that branch away from the rest suggest fungal decay that cannot yet be seen in the micro-CT images. These trends are consistent with previous observations, but with a clear, replicable method and concrete evidence (Fisher, 1940b; Kimmins, 1933). When examining the tunnels containing beetles and larvae, the merging of tunnels meant that it was extremely challenging to completely follow an individuals' tunnel to determine its point of origin. However, it was possible for a few individuals and there were still several interesting observations that could be made.

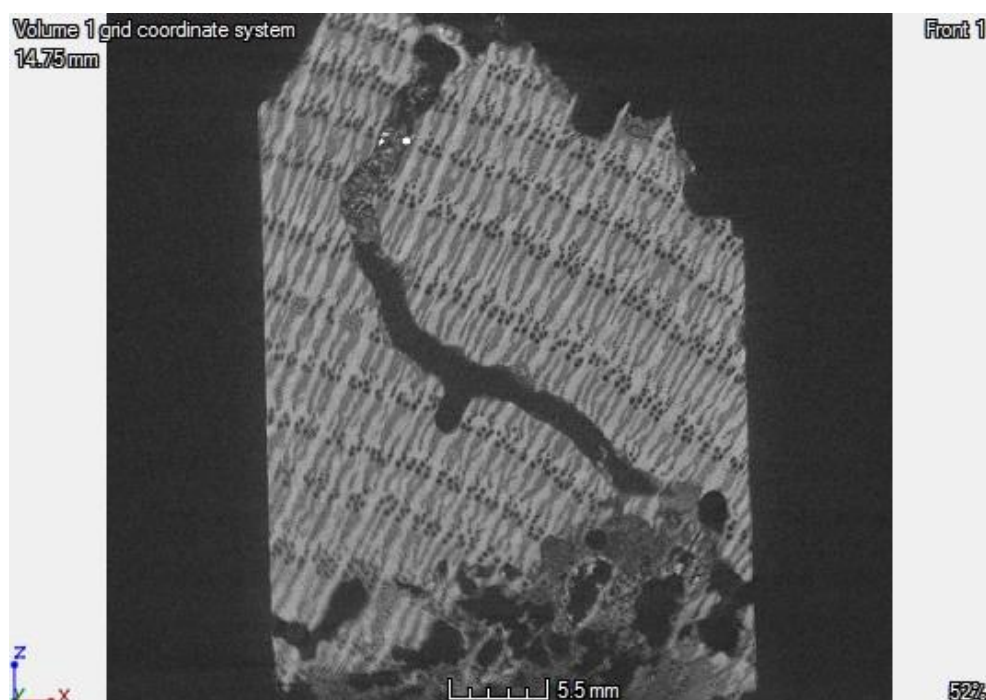


Figure 50: High resolution micro-CT image of sample CF5D3 of a tunnel running along the earlywood rings before branching off, suggesting a path of fungal decay that is not visible in the micro-CT image.

In several samples, most notably A4A, there is a distinguishable beetle in what appears to be a completely frass-filled tunnel. The tunnel is mostly isolated in the more 'sound' wood and has a right angle ([Fig. 51](#) - green tunnel). Given the beetle's location midway through the tunnel, it is unlikely that the tunnel was created by the beetle. The direction of travel ([Fig. 51](#) - black arrow) suggests it came up from the bottom of the plank. It is in a cavity, with the tunnel behind it packed with frass with more packed frass in front of it, suggesting it travelled through the frass. Is this beetle digging through the frass, which then resettles and compacts behind it? Or is it possible that the beetle is consuming the frass? The adult beetles have never been observed feeding in the past, and while it is still possible, it does seem unlikely. The other possibility is that the cavity is a pupation chamber built by a larva from which the adult beetle was unable to emerge due to the lack of access to an area of sufficient space or due to the freezing of the plank.

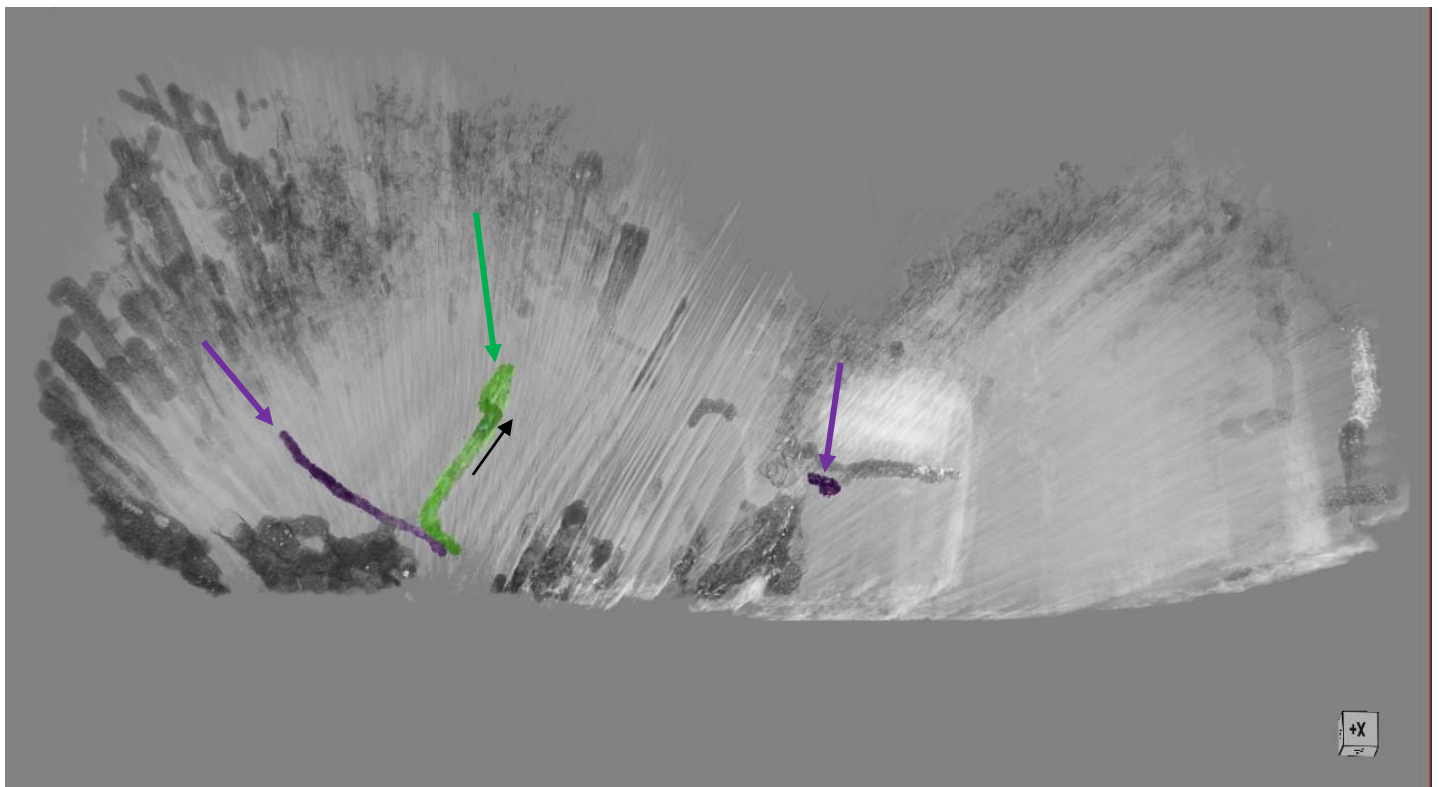
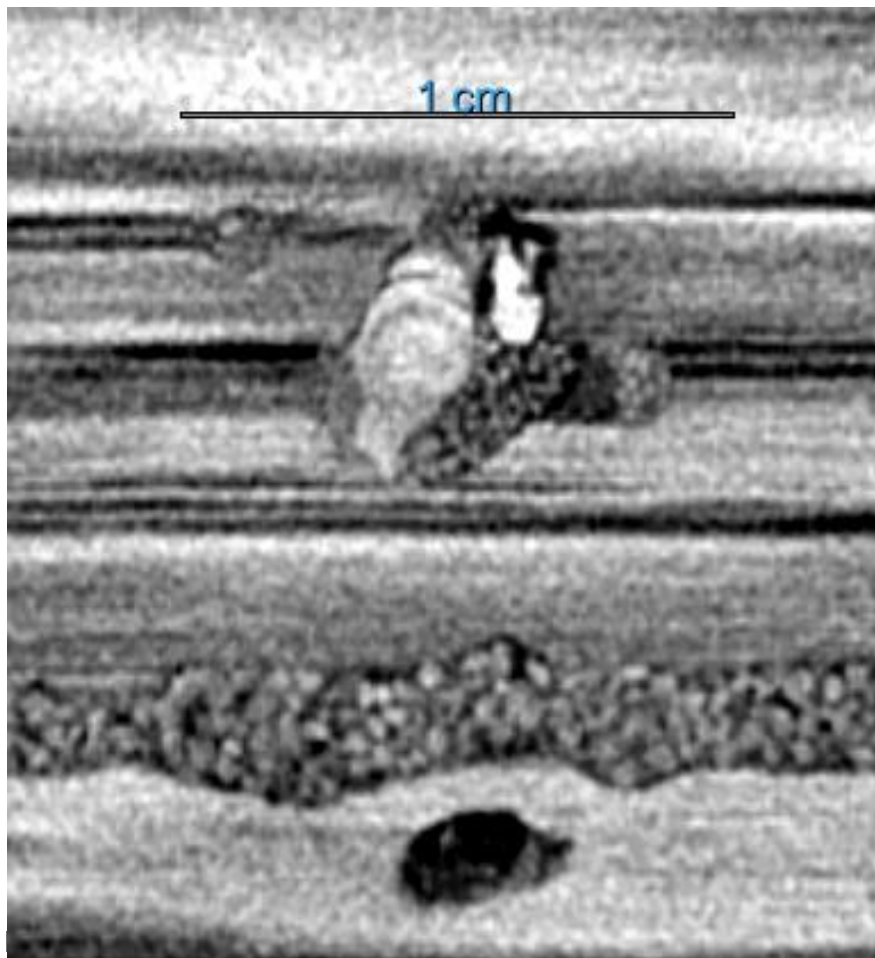


Figure 51: Location of beetle (green) and larval (purple) tunnels in Sample A4A. The black arrow indicates the direction of travel of the beetle. The frass is visible behind and in front of the beetle, and the lack of other tunnels in the area suggests that the beetle has moved through the frass. This has not previously been observed but is clear evidence of tunnel reuse.

In sample CF3D, there is a larva making new tunnels immediately adjacent to and partially through frass-filled ones ([Fig. 52](#)). Sample CF5D also has evidence of a tunnel forming through frass, although no insect was found in this tunnel ([Fig. 53](#)). Not only does this demonstrate reuse of tunnels by larvae, but it also suggests consumption of frass. This brings up the question of whether there is any remaining nutritional value in the frass and whether there are any benefits to consuming the pre-digested remains of wood. Is it easier for the larvae to digest, particularly when newly hatched, or is something added to it in the digestive process that makes it more beneficial? Or is consuming the frass simply a means to get through it and it has no nutritional benefit? Investigating the chemical composition of the frass and comparing it to fungally degraded and undecayed wood should reveal information on the nutritional components and allow for these questions to be addressed.



new tunnel amid a frass-filled ones.

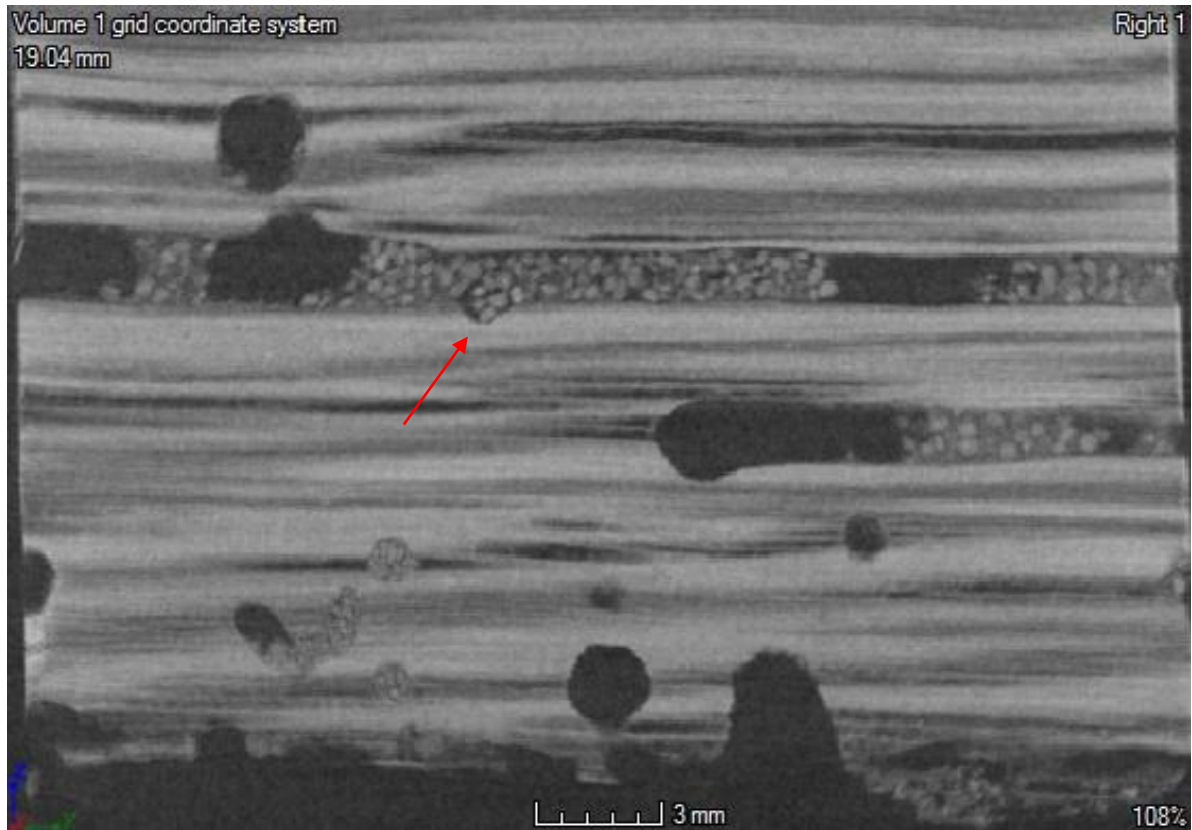


Figure 53: High resolution micro-CT image of sample CF5D3 image showing tunnel within another frass-filled tunnel. Although no individual was found in this tunnel, the shape within the frass suggests one moved through, creating this other tunnel.

Kimmins (1933) mentions that the larvae can move both forwards and backwards within the tunnels, but can also turn around to face the other direction, which may also explain why it is so hard to determine the point of origin for the larvae. This is further supported by the surrounding tunnel diameters of the larval tunnels ([Fig. 47](#)). Most of the larvae are found in tunnels ~1mm wider than the larva's widest point, providing sufficient space for movement if the tunnel is not surrounded by or packed with frass.

Not only is it clear that existing tunnels are utilized by both larvae and beetles, but wood features like cracks are also exploited. In sample CA2C ([Fig. 54](#)), the tunnels containing beetles are clustered around cracks in the wood suggesting their use as egress and ingress points.

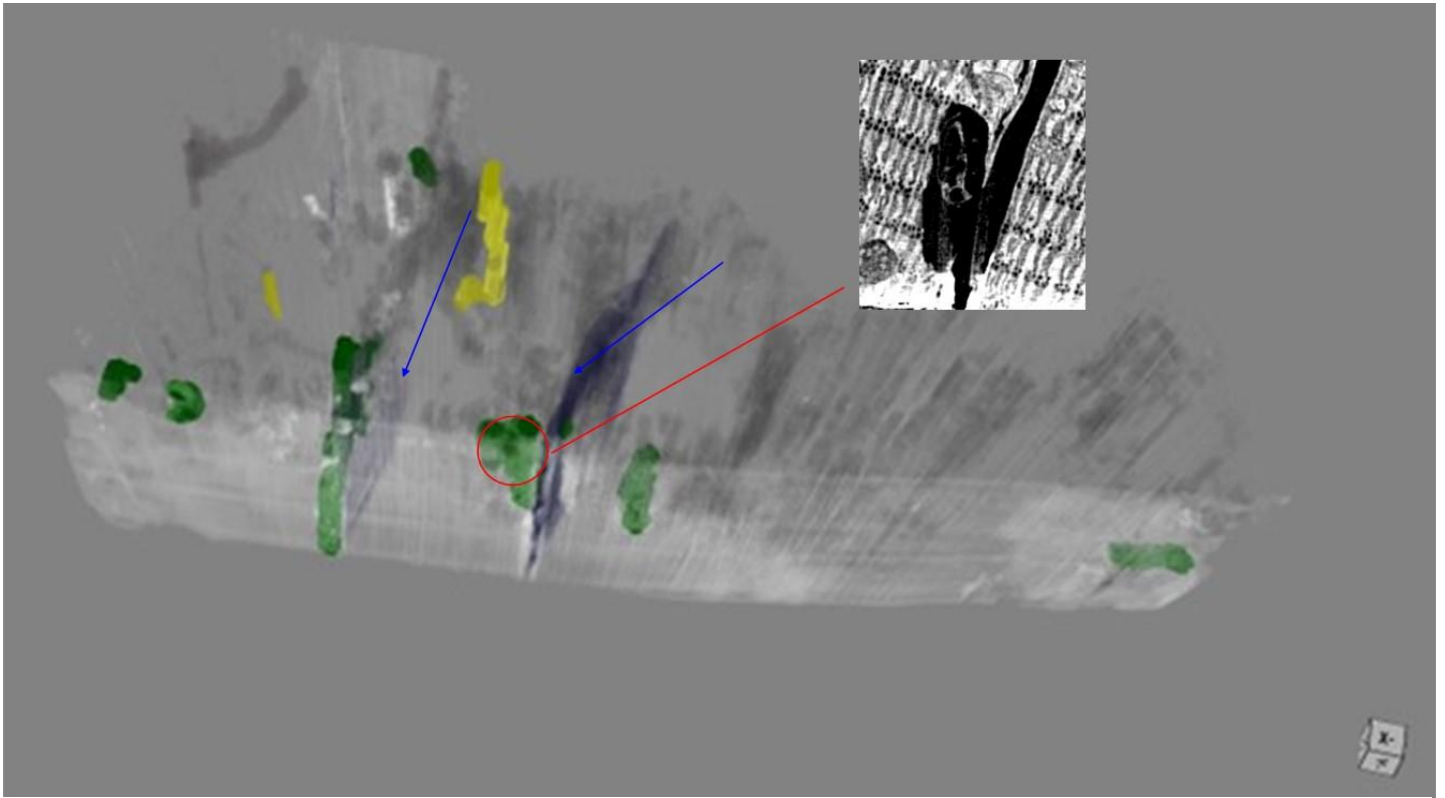


Figure 54: 3D tunnel map of CA2C. Cracks in the wood are shown in blue and indicated by blue arrows, larval tunnels in yellow, and beetle tunnels in green. There are several beetle tunnels clustered around and radiate from the large crack, suggesting that they used the crack to get into the wood or were about to emerge and use the crack to exit.

The reuse of tunnels and use of wood features along with the exit hole count for the plank suggest that the beetles are able to use internal spaces for mating. The combined tunnel cavity at the bottom of the plank was spacious enough for mating to occur and would have protected the beetles and any eggs laid.

In samples with high numbers of beetles, those located in cavities near the external surface of the plank, facing outwards and without exit holes ([Fig. 55](#)) were likely about to emerge when the plank went into the freezer. This holds with previous observations that larvae make pupation chambers near the wood surface. The use of wood features and existing tunnels, however, implies that this surface does not need to be an external one.

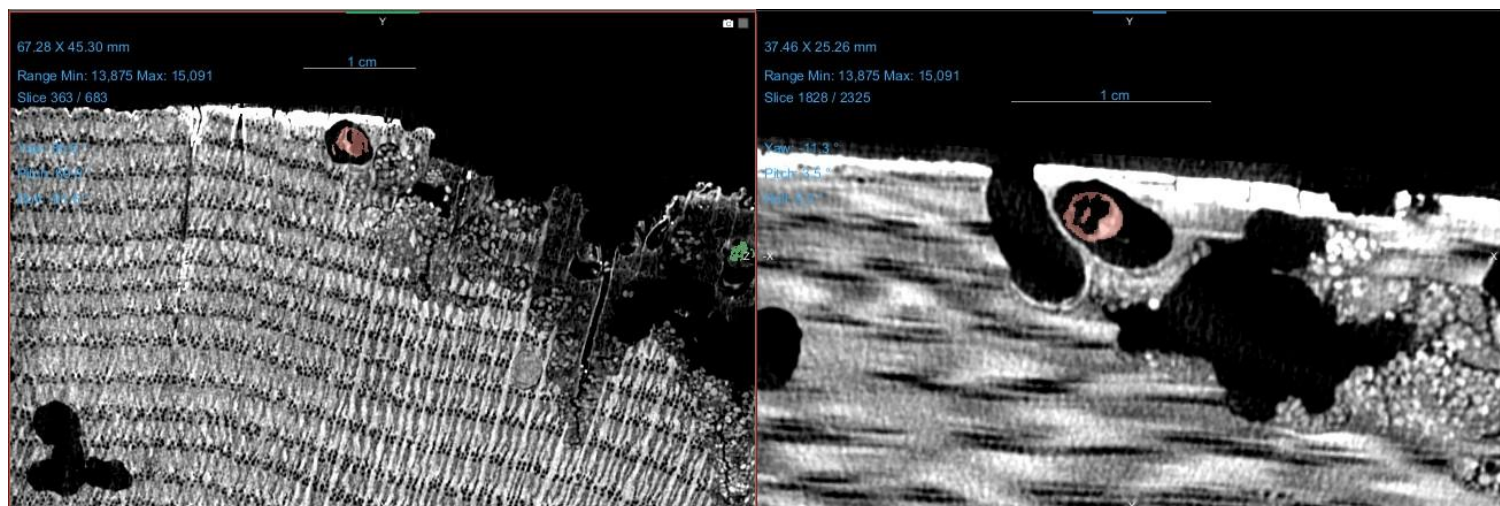


Figure 55: Micro-CT images (YZ and XY views) of a beetle in pupation chamber near top surface of plank in sample CA2C

Those located in small chambers adjacent to an exit hole are likely using the pre-existing pupation chambers to lay their eggs in a protected environment. This is consistent to previous observations of the use of cracks, crevices and old exit holes for egg laying (Fisher, 1938; Hickin, 1975; Kimmins, 1933). Given the number of individuals identified, there are almost certainly eggs present. Unfortunately, no eggs were identified on the scanned samples as their small size and similarity in shape and size to the frass pellets made them impossible to distinguish. It is possible that the eggs may not have survived the freezing process, but this is unlikely given the number of beetle and larval carcasses that were well-preserved at the time of scanning. The similarity in shape and size to frass, along with the presence of beetles in frass-filled tunnels suggests that the beetles might camouflage eggs amongst frass, which was observed by Fisher (1938: 164). Previous observations of oviposition have been limited to small samples of wood and surface examination. If mating can take place within cavity spaces, then so can oviposition, meaning that not all oviposition behaviour can be observed.

The use of frass for egg camouflage is contradictory to Belmain (1998), who observed that DWB frass is unattractive to oviposition (the beetle chose to oviposit away from frass, pg. 103). His frass was obtained from the culture used for study, which was reared on decayed modern oak (pg. 118). Given that he also demonstrated a preference for centuries-old oak, this result may be due to the fact that the frass was from modern oak. It would be worth repeating the

study to address this issue. The potential larval consumption of frass would also present an issue if eggs are being hidden in frass, as it increases the risk of eating the eggs. Cannibalism has been noted in other woodboring species when larval density is high (Cymorek, 1975) and was observed in DWB by Menendez (1990: 214), so it is not without precedent. While there may be a nutritional benefit for the larvae if this is the case, it would reduce the number of eggs from which viable larvae could hatch. However, the inversely proportional spread of beetles and larvae across the plank, mentioned in [Section 4.3.3.1](#), suggests that the beetles could be taking precautionary measures to lay eggs away from the larvae.

The final observation for this section can be seen in [Fig. 56](#). Ridges along the side of the tunnel are consistently spaced and sized, which given the hydrostatic pressure used by the larvae to consume the wood, indicates these are bite marks.

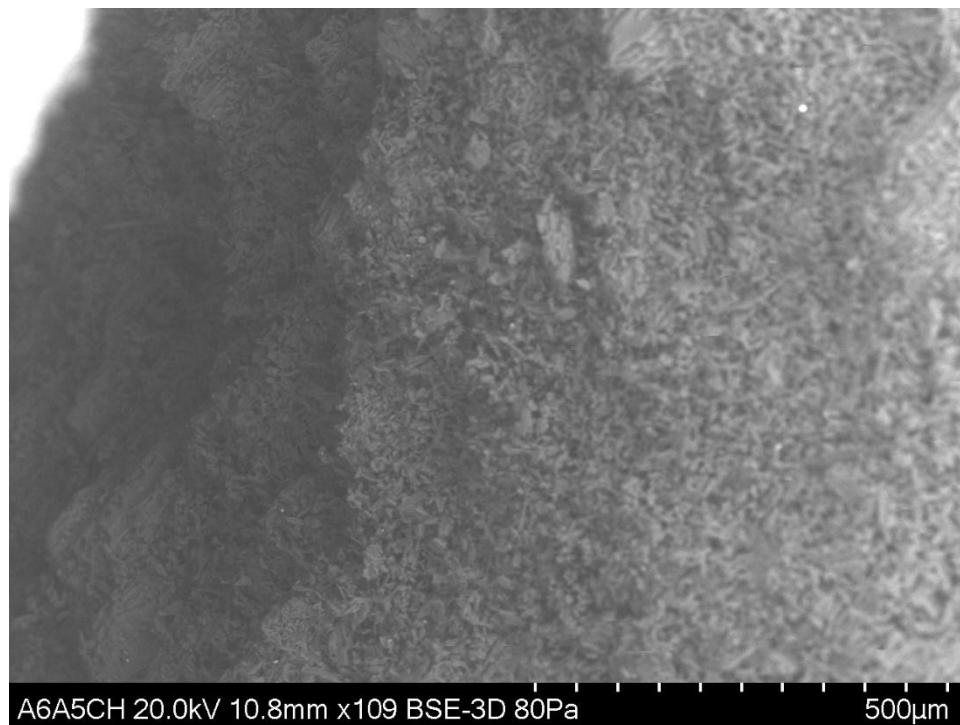


Figure 56: SEM image of the side of a DWB tunnel with bite marks

4.3.3.3 Frass

A small sample of frass examined under SEM revealed many points of interest (Fig. [57-8](#)). The frass is formed of compacted fragments of wood, in which

distinguishable wood features can be seen. It may be possible in future to closely examine the fragments to identify the features to determine what

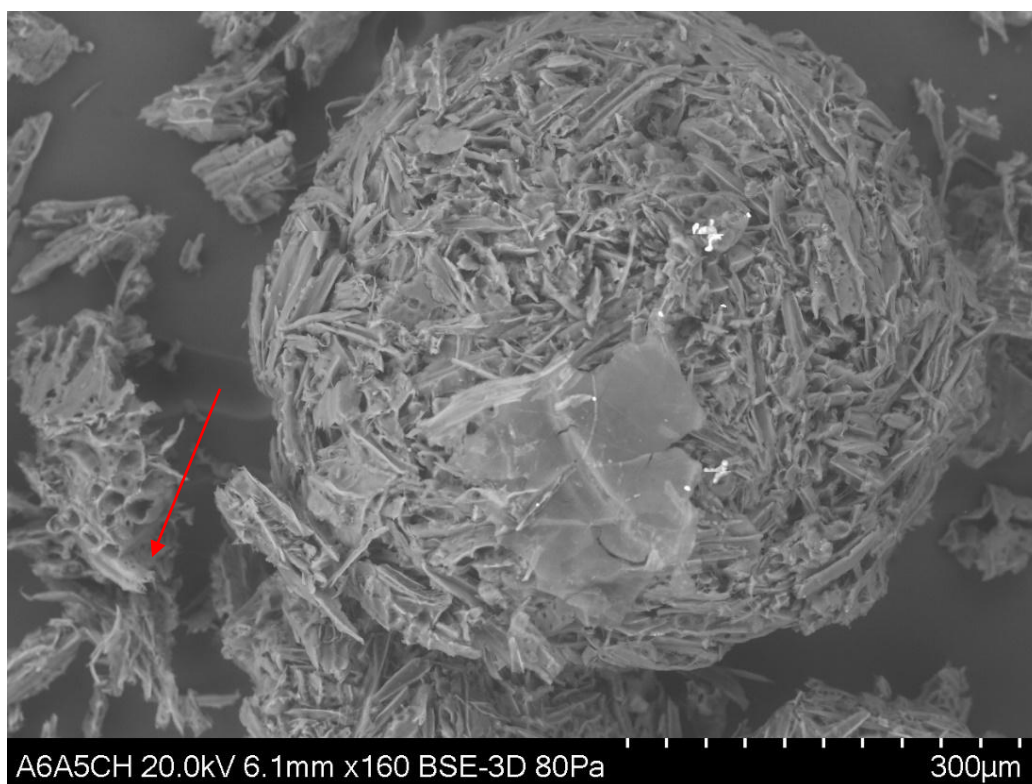


Figure 57: SEM image of a piece of frass made of compacted fragments and frass fragments with a possible mycelial mat. Wood features, like vessels (arrow), can be distinguished amongst the fragments. features are being consumed.

Closer examination found clear fungal hyphae within the fragments of the frass pellet ([Fig. 58a](#)). It is unclear whether this was ingested and excreted by the larvae or grew on the frass after deposition. Smaller organisms are also visible. These may be fungal spores ([Fig. 58b](#)), which given the presence of hyphae seems likely. Fungal species *Neoacrodontium gallicum* and *Aspergillus rouenensis* were extracted and cultured from DWB frass in France, but the paper focuses solely on the fungi and not on the potential information this may reveal about DWB (Crous et al., 2022). However, they may also be yeast cells. Maxwell-Lefroy (1924), Campbell (1929), and Fisher & Parkin (1930) all mention having isolated yeasts from *Xestobium*. But as these were no more than a sentence (Maxwell-Lefroy, 1924: 263) and a short letter to *Nature* (Fisher

& Parkin, 1930), no methodology was ever described, and the results have never been replicated since. SEM images ([Fig. 58c](#)) of yeast cells tend to be of higher resolutions than those taken for this research (Osumi, 2012; Tang et al., 2014), making comparison difficult. It is an area that warrants further investigation by taking samples from frass and larval digestive tracts for confirmation and identification.

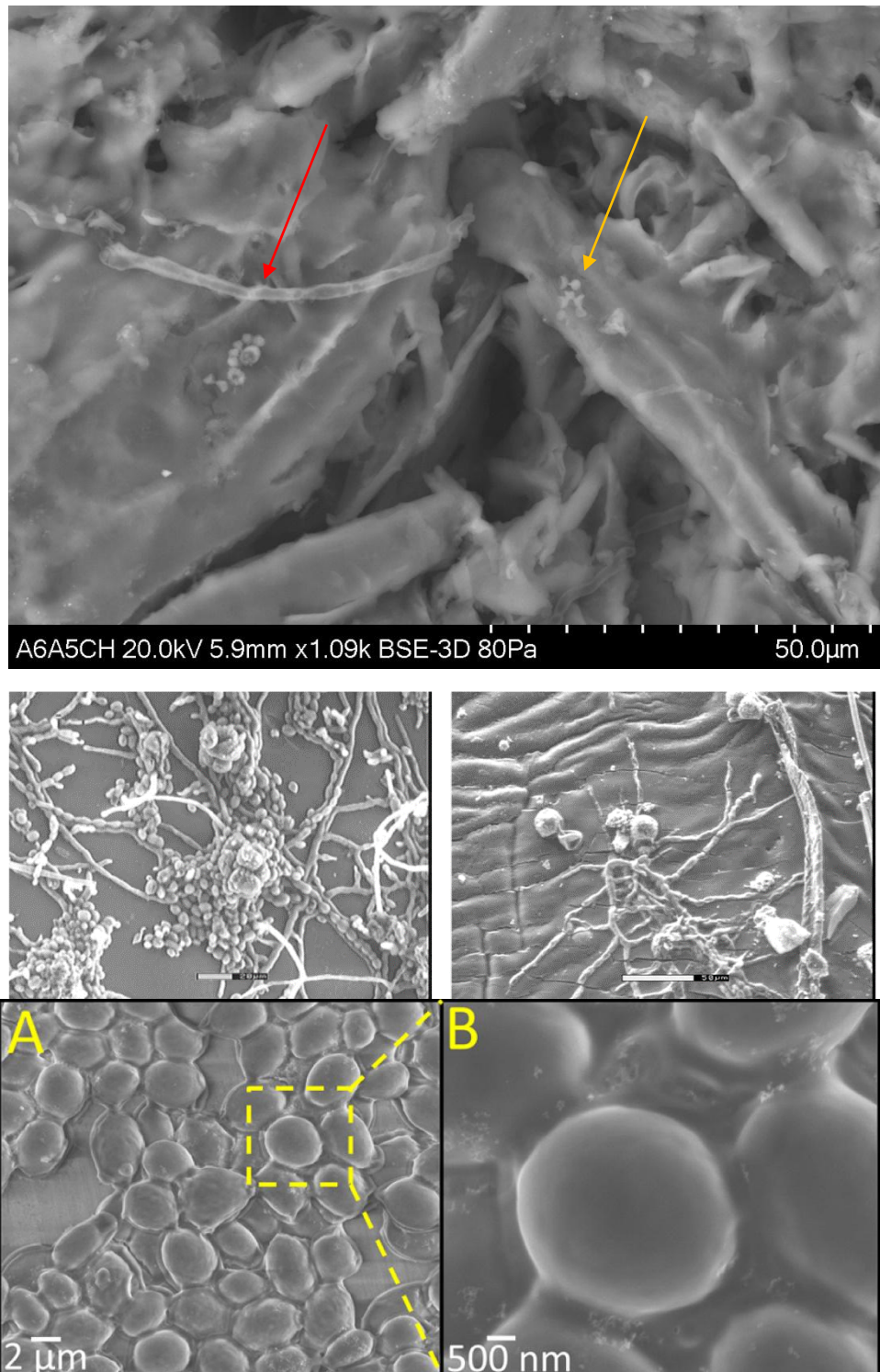


Figure 58(a), (b) and (c): (a- above) SEM image of fungal hyphae in frass (red arrow). The smaller (yellow arrow) cells indicated may be fungal spores or yeast cells. (b- middle) Comparative SEM image of fungal spores and hyphae from Goodell et al 2020: 12. (c- bottom) Comparative SEM images of yeast cells from Tang et al 2014: 5

4.3.4 Future research

From the results of this research, there are a number of points for further investigation that were identified. Clear trends of preferences for certain wood features were identified in the results, and there was further support for the relationship between internal and external damage first noted by Southwell (2017) and Brock *et al* (2024); however, both would be aided by comparisons to other sites with DWB-infested material to examine whether these findings hold true elsewhere. HMS *Victory* is unique in that it is exposed to the elements by the coast. All other DWB infestations have been reported in historic buildings (Baines, 1923; Belmain, 1998; Fisher, 1937b) that tend to be more sheltered. The damage on *Victory* may be an example of extreme or worst-case scenario that may not be true of other sites. The deck plank examined for this study was an example of severe DWB damage and the loss of material may have influenced the results. By examining timbers from a variety of sites and differing levels of decay, a more accurate model predicting internal damage from the visible external damage can be created.

Although much information regarding DWB tunnelling behaviour was revealed during this research, the lack of knowledge around larval development prevented a deeper understanding. A live culture of DWB has been established at London Zoo (further details in [Ch 5](#)) to enable further research into the species. This culture could be used to monitor larval development from egg to pupation, track larval movement, and possibly determine the amount of wood consumed (further discussion in [Ch 5 section 5.3.3](#)). Tracking of the adult beetles in the culture using bioluminescent powder (Belmain et al., 1998) may help determine the distances travelled after mating, but before oviposition. Adults and larvae from the culture could also be used further investigate the relationship between fungi and the DWB through dissection of the digestive tract and by exposing them to choice chambers of different wood and fungal types. This would also be aided by further high resolution micro-CT and SEM examination of historic or current DWB-infested timber and frass from other sites. Taking fungal samples from both for identification of species would also be beneficial.

In addition to analysis of fungi from DWB frass, the first evidence of which has been provided by these investigations, further examination using such methods as SEM to determine whether wood features can be identified in the remaining fragments, may reveal further information regarding the wood consumed. Although Nair (2023) examined FTIR spectra and conducted VOC analysis of DWB frass and infested wood, the fact that there was no distinction between the two in the results means that any unique properties to the frass are not visible. Examining the frass more minutely with these methods and others may reveal further chemical distinctions. This, along with further investigations into the digestive enzymes present in the larvae, the last studies for which were conducted in the late 1930s (Parkin, 1940), may be able to determine whether any material in the frass has been digested multiple times.

In its efforts to better understand the DWB infestation on *Victory*, the NMRN conservation team has also collaborated with the Darwin Tree of Life project. This is a large-scale collaborative project between multiple institutions to sequence the genomes of 70,000 eukaryotic species in Britain and Ireland (*Darwin Tree of Life*, 2024). It is part of the wider Earth BioGenome Project with the ultimate goal of sequencing the genomes of all Earth's eukaryotic organisms (*Earth BioGenome Project*, 2024). The information gathered will contribute to the understanding of evolution, and of species and their ecosystems, as well as aiding wildlife conservation efforts.

Beetles from HMS *Victory* were captured by the ship keepers and sent to the Tree of Life team for sequencing. The sequence has now been completed, and although analysis remains to be done, preliminary analysis revealed fungal and bacterial DNA alongside the beetle DNA (Holland, personal communication 2024).

The genomic sequence may help determine whether the infestation on *Victory* originated from a single population or if there were multiple waves of infestation. Knowledge of the DWB genome, gene expression and biochemistry, has the potential to greatly increase the understanding of the species on a targeted level. It may aid in the understanding of the relationship between fungi, bacteria

and the beetles. Additionally, it may prove or disprove Fisher & Parkin's (1930) work on the presence of yeasts in DWB. It will be interesting to see where this research goes in future and how it contributes to the understanding of the infestation on *Victory*.

4.4 Conclusions

The results from this section revealed valuable information regarding DWB tunnelling behaviour and has responded to the initial questions raised under the topics of inquiry.

1. Tunnelling: Are there any discernible trends in the tunnels?

The beetles make use of early-wood vessels in the formation of tunnels and show a preference for lower density wood, as most of the tunnels are concentrated in this area. The tunnels generally follow the longitudinal fibres, more commonly referred to as the grain pattern, but those tunnels branching across fibres may be following fungal decay that cannot be seen at the scanned resolution.

2. Internal and external damage: is there a correlation between surface damage and internal damage?

There is a correlation between the internal damage and the surface damage, further supporting the initial findings by Southwell (2017) and Brock *et al* (2024). The number of exit holes on external surfaces can be used to approximate the percentage of wood lost on HMS *Victory* using a logarithmic model. Approximately 43% (6099.03cm³) of the plank has been lost during the 73 years it was installed.

3. Fungal decay: Is it possible to determine areas of fungal decay and whether the DWB prefer those areas?

The resolution of the initial micro-CT scans did not allow for visualisation of fungal hyphae, but different densities within the wood samples were identified. Based on previous studies (Beaulieu & Dutilleul, 2019: 1184; Goodell *et al.*, 2020: 6; McGovern *et al.*, 2010), these were surmised to be more fungally degraded wood. Further examinations under SEM found fungal hyphae present

in the wood vessels of the low density and more sound wood, as well as in DWB frass. The low density wood had lost wood structure in a manner expected of fungal decay, but the presence of hyphae in the sounder wood suggests that fungal decay is in progress but has not yet altered the wood to the extent that there is a visible difference in the density. Higher resolution micro-CT scans revealed fine cracks in the low density wood, some of which radiated out from DWB tunnels. These results support a close relationship between the DWB and fungal decay and hint at a symbiotic relationship with regards to attack patterns.

4. Beetles and larvae: What can the locations of beetles and larvae reveal about the tunnelling behaviour?

Due to the merging of tunnels, it was not always possible to determine points of origin and changes in tunnel diameter. What was clearly evident was the reuse of tunnels and exploitation of wood features like cracks. Beetles and larvae will travel through existing frass-filled tunnels. The presence of beetles within frass suggests the possibility of oviposition within the frass as a means of protection for the eggs. If this is the case, it would contradict previous findings (Belmain, 1998). SEM images of DWB frass, of which these are the first taken, showed fungal hyphae and either fungal spores or yeast cells.

Much remains to be learned about the DWB, and any information revealed enables conservators to tailor and adapt the pest management and treatment strategies to suit any infestations they may be faced with. This research has provided a valuable contribution to the general understanding of the species through the examinations of the tunnelling behaviour on HMS *Victory*, provided concrete evidence of previously theorised behaviours, and corroborated findings of previous studies.

5 NON-INVASIVE DETECTION OF ACTIVITY

5.1 Introduction

The current system of monitoring and identifying areas of active infestation predominantly makes use of blunder pest traps placed strategically around the ship (*Victory IPM Strategy*, 2023). These are checked on a regular schedule and species identified and counted (*Ibid.*). On rare occasions, a thin sheet of Japanese tissue paper is applied to an area that has suspected activity. However, this can only be done on small areas or areas not visible to the public (Davis, personal communication 2024). Adult beetles, upon exiting the pupation chamber, will create fresh holes through the paper, indicating activity. These are simple, low-cost, and effective means of keeping track of species present and the presence of infestations. The presence of many individuals of a single species on one trap is indicative of an infestation (Child & Pinniger, 2013).

In the case of woodboring beetles like the DWB however, there are some serious drawbacks to these methods of monitoring. It is not possible to monitor all the nooks and crannies in the ship, even with the best possible placement of traps and tissue paper, so infestations in certain areas might go undetected until it spreads to a more accessible area. The tissue paper depends on the emergence of the adults, and the blunder traps are dependent on individuals (almost exclusively the more mobile adults) crawling across the traps, by which point, the structural damage has already been done to the timber. It is also impossible to determine where the beetles may have originated from, as they have been observed to fall between gaps in the timber to lower decks of the ship. Should they crawl over a blunder trap after recovering from the shock of the fall (they have been observed to be stunned for a short period of time before moving again), it is entirely possible that the beetle may have come from an upper deck than the deck the trap has been placed on.

Therefore, a more active monitoring method that enables detection of larvae in the timber would be extremely beneficial in the management of the infestation in

enabling more targeted interventive treatments, the need for which was identified in the HMS *Victory* Research Strategy (Davis, 2021).

5.1.1 Aims and objectives of non-invasive detection

The aim of this section is to determine whether areas of active infestation can be detected and more actively monitored through non-invasive methods. The work in this section will assess potential methods for further inquiry and will lay the foundational groundwork for future investigations by addressing the following:

- Identify suitable methods that may be appropriate for use on HMS *Victory*.
- Are these methods worth investigating further? Are they suitable for use on the ship and cost-effective for the museum?

5.2 Materials and Methodology

Several potential methods for testing were identified from the literature (Al-doski & Mansor, 2016; Chesmore & Schofield, 2010; Csóka, 2020; Demaus, 2001; Keszthelyi et al., 2020) for preliminary feasibility tests.

The primary methods chosen for testing are as follows:

- Bioacoustics
- Thermography
- Radiography

These methods were selected for a variety of reasons. The first and foremost was the ease of applicability to the ship and for the *Victory* conservation team. Other considerations included equipment availability, ease of use, availability of expertise, cost effectiveness, and potential for future investigations.

Bioacoustics and thermography especially could easily be adapted into existing IPM monitoring and do not require specialist expertise to interpret results, although specialist help may be required for further method development. Small scale tests using ultrasound, and an acoustic camera were also conducted and

will briefly be discussed but were not the focus due to required expertise and equipment access.

A live culture of beetles housed at London Zoo (ZSL) was in the process of being established during the course of this project, and the wood in the culture was occasionally used for the small scale tests described in this section. Details on the establishment of the culture can be found at the end of this chapter.

5.2.1 Bioacoustics

A basic medical acoustic stethoscope, a piezoelectric accelerometer, and an acoustic camera were used for bioacoustics testing.

Four areas of known beetle activity (common collection sites for adult beetles, fresh-looking exit holes and frass) were selected for testing on the ship: (1) where the bowsprit joins the ship ([Fig. 59](#)), (2-3) two areas in the carpenter's walk on the orlop deck, and (4) an infested piece of pine in a crawl space under the shop in the hold. The bowsprit is on the visitor route, so was tested prior to visitor opening hours to minimise potential background noise.

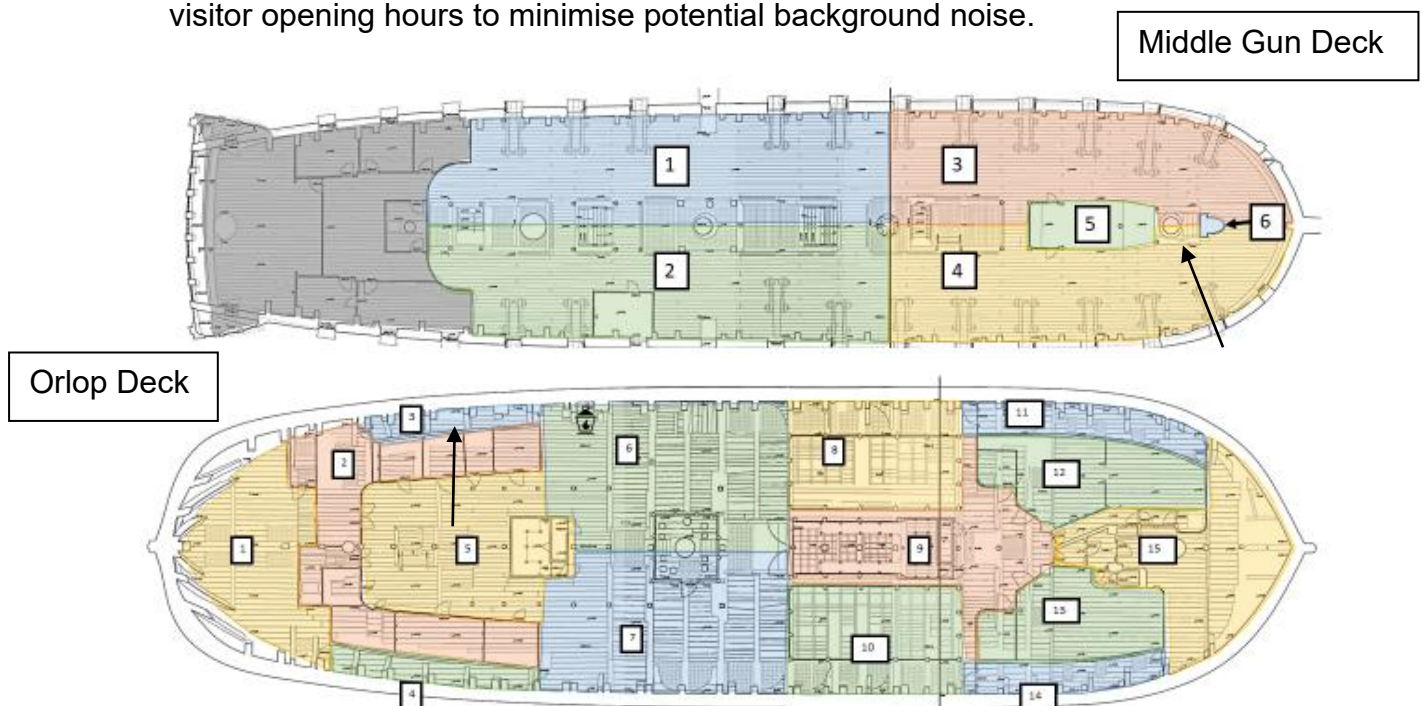


Figure 59: Testing locations (arrows) for bioacoustics on the MGD (above) and the orlop deck (below). Deck maps provided by NMRN.

Further tests were conducted in the conservation laboratory in Storehouse 12 of Portsmouth Historic Dockyard on infested wood in a polyethylene container with beetles collected from the ship that were to establish the live culture.

The stethoscope head was pressed against the wood in several places for each area ([Fig. 60](#)) and the wood in the lab to listen for larval activity. Both the diaphragm (detects higher frequencies) and bell (lower frequencies) side of the stethoscope head were tested (*Anatomy of a Stethoscope*, 2024; 'Stethoscope Parts List', 2022).



Figure 60: Testing a stethoscope on areas of suspected larval activity next to a fresh-looking exit hole on the timber connecting the bowsprit to the ship. Image courtesy Dr Fiona Brock

Following a background reading on the steel bowsprit (no chance of beetle or larval activity), the piezoelectric accelerometer (Bruel and Kjaer type 4367 with charge amplifier type 2635) was attached to the timber with a small amount of petroleum-based wax, and left for 2-3 minutes, observing the converted sensor information on a laptop screen. This was done in several places in each area of testing. The same method was employed for the wood in the culture.

Recordings of the adult beetle tapping were also collected on the ship and in the lab for reference. The reference recording was obtained by placing 3 beetles on a piece of paper directly on the accelerometer sensor. The tapping could be prompted by the researchers tapping on a nearby surface. Although it was not the intention of the experiment to record the adult tapping, an adult tapping around the bowsprit was detected during one of the recording sessions, and a comparative reference was needed to confirm the sound. It also had the benefit of providing a copyright-free recording of the ominous tapping that could be used for the public engagement research ([Ch. 6](#)).

The data was converted to a video (audio and visual) format with Matlab. Further filtering to isolate sounds and remove background noise on the audio file to aid identification was done with WavePad Audio Editor Software (v. 19.30) and Audacity Software (v. 3.6). The adult tapping is distinctive, non-incident and easy to identify. Larval activity is more challenging to distinguish. Larval sounds are of short duration and impulse-like, created by the breaking of wood fibre by the mandibles (Biebl & Wapler, 2023: 16; Chesmore & Schofield, 2010: 46).

An attempt to test an acoustic camera was also made. An acoustic camera is an optical camera and microphone array that is used to visualise sound sources and can isolate specific frequencies (Gray, 2023; Zimmermann & Studer, 2010). Professor Marc Holderied of Bristol University brought the camera to HMS *Victory* for testing around the bowsprit. The plan was to set up the camera to determine whether any adult tapping, or larval activity could be detected and the location of the sound source. Unfortunately, equipment failure on the day meant that no results were obtained.

5.2.2 Thermography

An FLIR Handheld Thermal Camera (Model E4 1.2L) was taken to the same areas of known beetle activity described in the previous section and the developing culture on March 8th and May 11th, 2023. Images were taken using a passive thermography method to see if larvae or beetles could be detected near the surface of the timber by pointing the camera at the timber and capturing an

image. This simple method was used to reflect how the equipment would be used by the conservation team. As the literature demonstrates ([Ch. 3 Section 3.2.2.3](#)), results with thermographic detection of woodborers can vary. However, should the method fail to detect the insects, it was hoped that the experiment would yield useful results with regards to moisture content of the wood.

5.2.3 Radiography

Three different 'levels' of radiography were examined to establish suitability for use, and the experiments often served multiple purposes. The levels relate to the size of the timbers that were imaged. Small-scale tests were conducted on wood fragments and off-cuts, with the largest fragment ~135 (l) x 100 (w) x 150 (d) mm at its widest point. Small scale X-rays of culture wood were conducted with the veterinary department at ZSL to assess potential as a monitoring method for development. The wood fragments were placed directly on the detector plate (Fujifilm D-EVO III Viewing and Acquisition System) and set on the veterinary examination table (object-to-film distance (OFD) 0cm). The portable X-ray source (Veterinary X-rays Ultralight 200) height was adjusted to include all samples on the detector plate (focus-to-object distance (FOD) ~100cm). Images were taken at 60kV, 40mA, and 0.08s in January 2024 and May 2024.

The X-radiographs of the deck plank (~ 250 (l) x 22 (w) x 7 (d) cm) taken prior to sampling to check for any hidden fastenings or features that may have hindered cutting, served as the mid-size tests, and were conducted with Dr Mark Viner. The plank was laid on a table, with the detector plate (Canon CXDI 410C Wireless X-ray detector) and X-ray source (Poskom PXM 40BT Plus portable X-ray machine) on a dolly that would slide above and below the table ([Fig. 61](#)). Images were taken in sections along the plank at 75kVp and 2.5mAs.

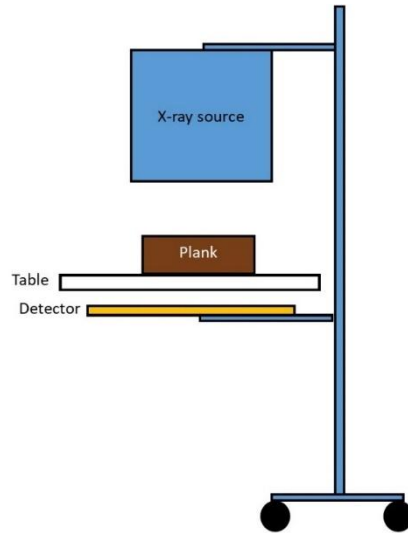


Figure 61: Cross-section set up of plank X-ray. OFD was <5cm and FOD ~90cm. Diagram not to scale.

The large-scale tests were conducted as part of a commercial study. X-radiographs of the ship's timbers (>30cm in thickness) were taken in the shipwright's working area on the scaffold ([Fig. 62](#)) and on *in situ* frames ([Fig. 63](#)) by Dr Mark Viner on behalf of Cranfield University as a commercial entity, who kindly shared the resulting images. The same X-ray equipment as the mid-size tests was used. Workshop and *in situ* images were taken at 80kVP and 6.4 mAs, with an FOD of 137cm and an OFD between 30-40cm (Viner, 2024). The radiographs for each sample were sharpened with either a small structure or bone algorithm (specified on images) (*Ibid.*).



Figure 62: Radiography set up in shipwright working area. Image courtesy Dr Mark Viner, annotations by author



Figure 63: Radiography set up for *in situ* timbers. Image courtesy Dr Mark Viner, annotations by author

5.2.4 Other methods

5.2.4.1 Ultrasound

As discussed in [Ch 3 Section 3.2.2](#), ultrasound is dependent on the MC of wood. The high moisture content in some areas of HMS *Victory* (the hull for example can be $\geq 30\%$) should make this feasible, but the results from ultrasound examinations are often challenging to interpret, and there is a great degree of variation in the timber MC across the ship (Davis, personal communication 2024). A small scale test was conducted with a portable medical ultrasound (GE Versana Active Console with 4C-RS 2-5MHz Convex Probe) at London Zoo on wood designated for the culture. The first test involved pressing the probe against the wood. For the following test, a polyethylene bag was filled with tap water and placed on one of the wood samples. The probe was pressed into the bag until it came in contact with the wood surface. The real-time ultrasound image was displayed on a computer tablet screen.

5.3 Results and Discussion

5.3.1 Bioacoustics

5.3.1.1 Stethoscope

Four people tested the acoustic stethoscope in the bowsprit area in March 2023, but only 2 were able to distinguish a soft rhythmic, crunching sound with both the diaphragm and bell sides of the head thought to be larval munching. Tests conducted on smaller pieces of wood known to contain larvae struggled with the rough surface, which prevented full contact.

The use of a stethoscope is clearly subjective, as it is reliant on the listener's aural sensitivity, ability to filter out background noise (a particular problem on HMS *Victory*), and knowledge of sounds. It is also inhibited by the surface to which the head is pressed. Without full contact, the vibrations will not be fully amplified by the stethoscope.

The subjectivity and need for human involvement do not make the use of a stethoscope a practical option for long-term detection and monitoring. However, the speed and ease with which detection can be done, and the ready availability and affordability of equipment might make it a suitable interim solution, particularly during the replanking work, where normally hidden timbers are revealed, and it has been proven successful in the detection of wood-borers in orchards (Vishwajeet et al., 2023: 27). Some of the issues presented may be mitigated by the use of an electronic stethoscope, as sounds can be amplified and recorded, but these are significantly more expensive than a traditional acoustic stethoscope and raises issues regarding the adaptation of medical software for cultural heritage use.

Shipwrights, shipkeepers and conservators could be given training and reference recordings of larval activity, and individual stethoscopes for detection in timbers where activity may be suspected.

5.3.1.2 Accelerometer

The accelerometer was able to detect an adult beetle tapping between nearby timbers around the bowsprit that was audible to human ears ([Fig. 64](#)). This tapping was confirmed with the reference recording taken in the lab ([Fig. 65](#)). The differences between the graphs are due to the distance between the vibrational source (beetles) and the sensor, interference, and the material through which the vibrations travelled (wood vs. paper).

Without a reference recording of larval activity, it was difficult to determine whether the recordings taken around the bowsprit had detected any vibrations as a result of larval activity, and this became one of the driving reasons behind the establishment of a DWB culture. Several vibrations of potential larval activity ([Fig. 66](#)) in recordings taken in the conservation lab were identified, but at the time, it was unknown whether larvae were present in the wood. It was also extremely challenging to later filter out the background noise that was picked up.

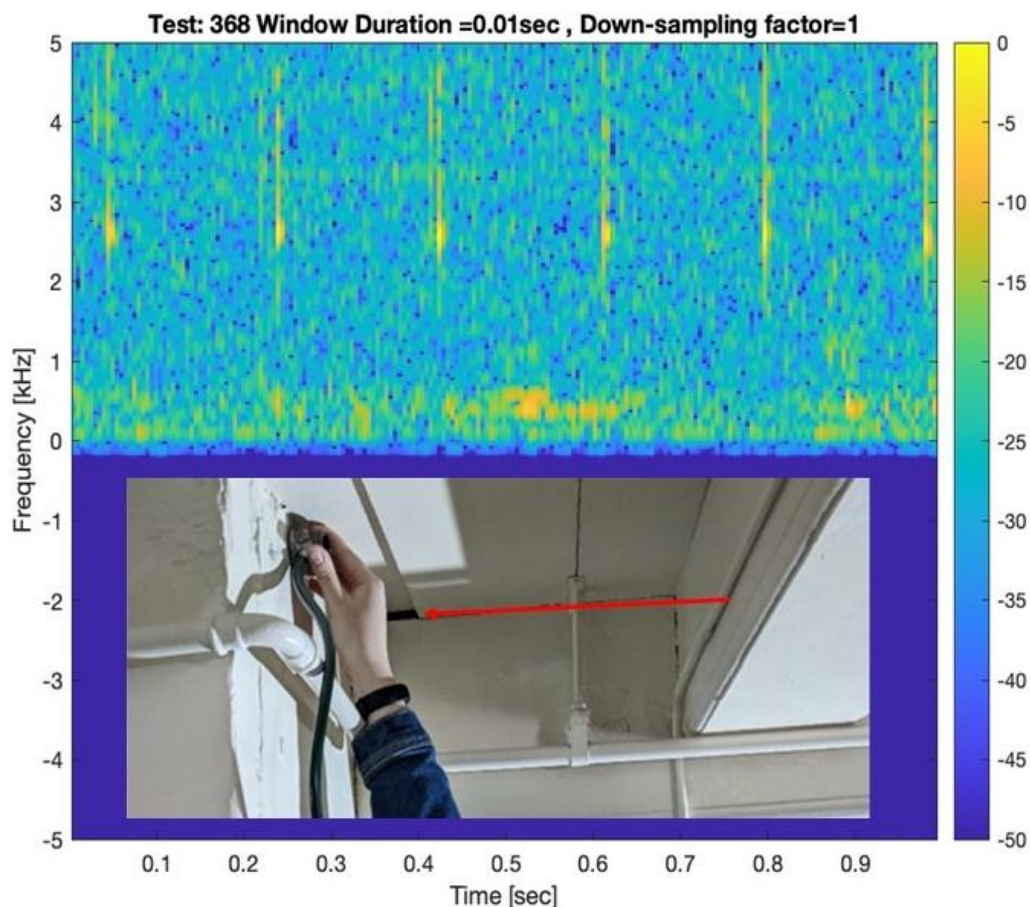


Figure 64: Visual representation of beetle tapping recording around the bowsprit. The approximate location of the beetle (based on the source of the sound) is indicated by the arrow.

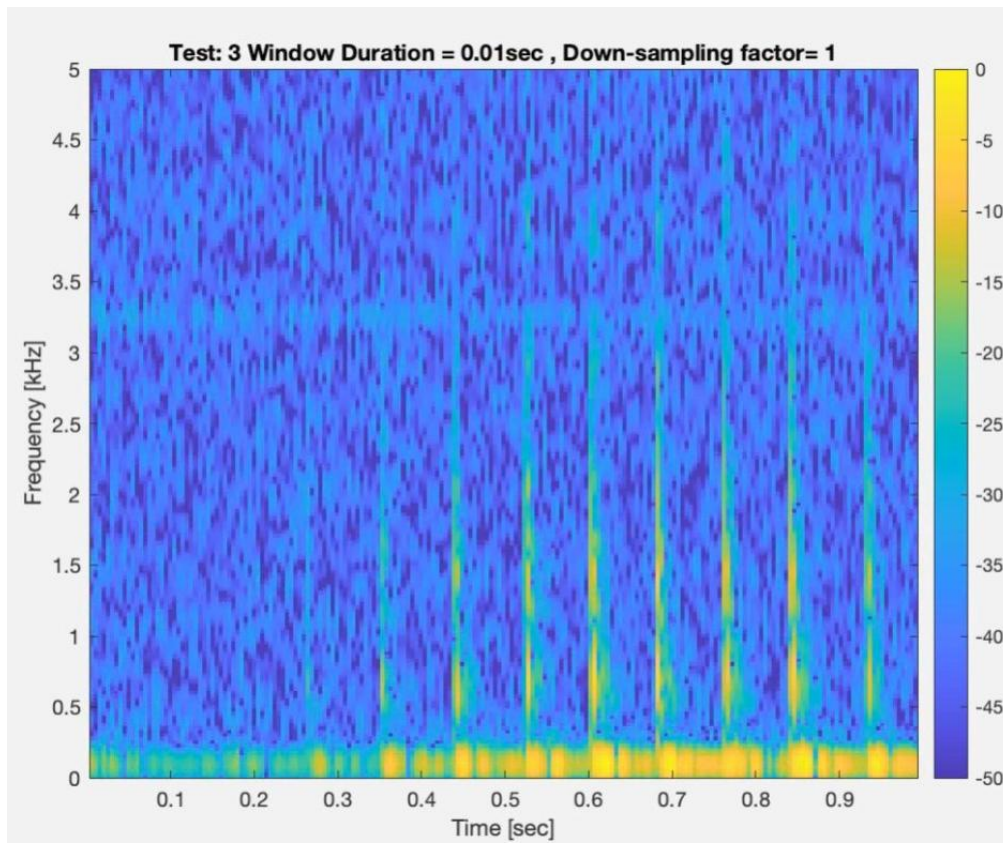


Figure 65: Visual representation of reference recording of beetle tapping on paper directly on sensor.

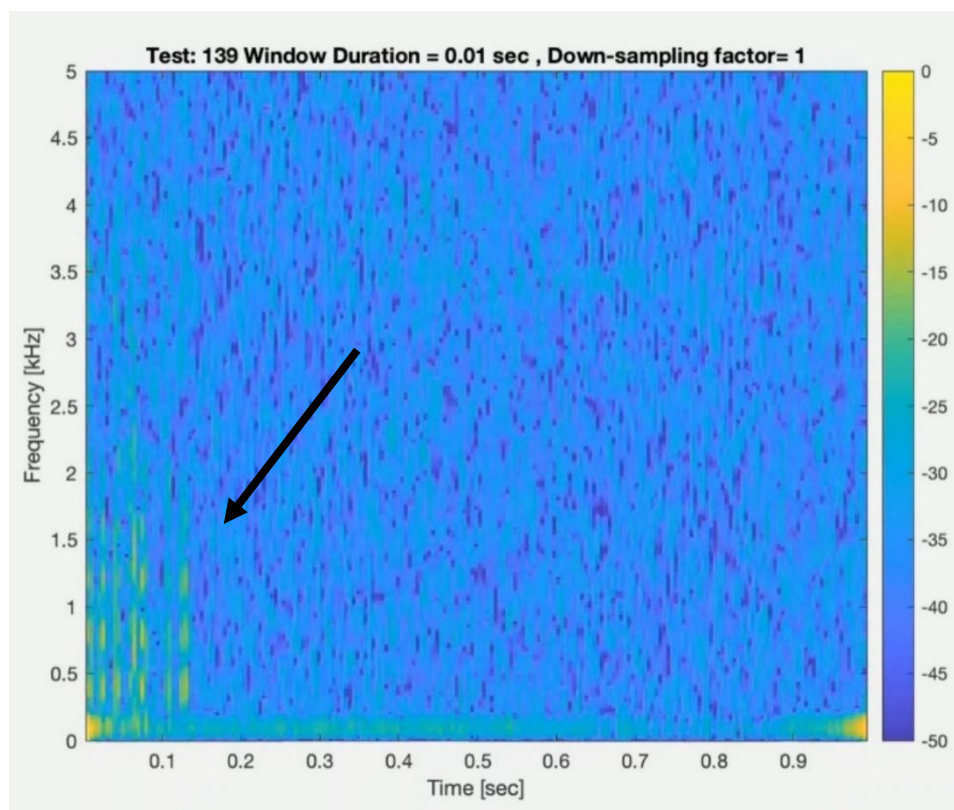


Figure 66: Visual representation of a possible larval munch

No recordings were obtained from the other 3 areas of known beetle activity selected for testing, as interference with the sensor obfuscated readings. While the exact cause of the interference is unknown, it may be due to the electrical wiring throughout the ship. There was minor interference around the bowsprit and in the conservation lab, represented by the colour change in the graphs between 3-3.5 kHz, but this did not obscure the recordings.

Although there were problems with the methodology used, this experimental work still served as a preliminary investigation, and the lessons learned can direct future investigations. The fact that potential larval sounds were detected with this device suggests the method has merit, which is further supported by the literature (Chesmore & Nellenbach, 2001; Chesmore & Schofield, 2010; Mankin, 2012; Mankin et al., 2011).

As a result of these investigations, a number of key next steps can be identified. Firstly, a clear reference recording of DWB larval activity is needed, which can be obtained from the culture established at ZSL, where the presence of larvae has now been confirmed. A reference recording of background noise common to the ship should also be taken and will help determine frequency thresholds. Next, different sensors (accelerometer, piezoelectric or ultrasonic) tailored to the specific larval frequency (based on the reference recording) and able to better filter background noise should be assessed. The one used for this preliminary investigation is usually used to detect vibrations from tanks and military vehicles over long distances (Balleri pers. comm, 2023). It is university equipment that could be freely borrowed for research purposes, and there were staff able to assist with its use, which is why it was used. Acoustic detection specialists should also be consulted in the next stages to provide expertise and guidance.

A monitoring network using sensors across the ship to detect larval activity and send alerts when activity is detected may be a suitable solution. A similar set-up was successfully trialled in Greece on urban trees (Rigakis et al., 2021), so the premise is not without precedent. When activity is detected, an alert can be sent

to the conservation team indicating which sensor detected the activity, and thereby, the approximate location of the active area.

5.3.1.3 Acoustic camera

Unfortunately, equipment failure on the day of testing and long-running repairs meant that it was not possible to gather any data. However, previous work (Busset et al., 2015; Hashemi et al., 2024; Rittenschober et al., 2024; Zimmermann & Studer, 2010) shows that it can be used to detect location and strength of acoustic emissions for a variety of different applications.

It is likely that the camera would be best at locating beetles based on their tapping. While not as useful as detecting larval activity, this information would still be useful, as identifying areas where adults are emerging (before they start falling from elsewhere) means larvae and pupae are likely present in that area. The camera may also be able to detect adult tapping in hard to reach areas. Additionally, minimal expertise is required for interpretation of results. However, as the frequencies detected can be specified, with a reference recording of larval activity, the camera may be able to detect larval activity, but this would definitely need to be tested. However, when compared to the other equipment used for acoustic detection in this project, acoustic cameras are extremely expensive, both to purchase and maintain (as demonstrated by the equipment failure). While it has some potential as a means of detecting areas of activity, it is not the most practical for NMRN to pursue.

5.3.1.4 Further discussion

These preliminary investigations into acoustic detection of larval activity have demonstrated that, with further development and testing, a suitable system for monitoring larval activity could be developed for the ship, and subsequently be used on other historic sites. Specialist expertise would be required to develop an acoustic monitoring system, but data and results could be interpreted by the conservation team with a small amount of training. It also demonstrated that a simple, easily implementable, low-cost method (stethoscope) may be suitable as an immediate means of detection. The use of acoustic detection also carries minimal health and safety risks to the conservation team.

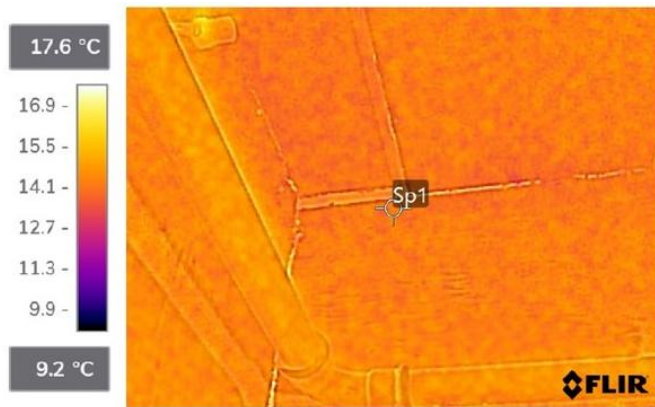
The investigations instigated with this project were expanded to an MSc thesis to trial more methods (Nguyen, forthcoming). Existing acoustic emission equipment (Hanwell Woodwatch- no longer produced) borrowed from English Heritage that had previously detected potential woodboring larval activity at Knole and a Laser Doppler Vibrometer (Cranfield University) were tested. The preliminary results for the vibrometer on the culture and ship look promising.

While most of the current acoustic work focuses on agricultural and timber pests, some work is currently being undertaken to adapt methods to the cultural heritage sector. Biebl & Wapler (2023) developed stationary and mobile equipment and software specifically to detect the smaller larvae of *A. punctatum* (Common Furniture Beetle) and *L. brunneus* (Powder Post Beetle) for use in historic buildings. Not only was the equipment and software successful at detecting larval activity in the laboratory, but they were also able to detect activity in several infested objects and a staircase (*Ibid.*). Investigations into use in cultural heritage thus far have primarily focused on smaller objects or the tests were only conducted on a small scale (Krajewski et al., 2020; Le Conte et al., 2014). The use of acoustic detection of woodboring pests is clearly possible, but more work on the upscaling of detection to large structures like HMS *Victory* and historic buildings is required.

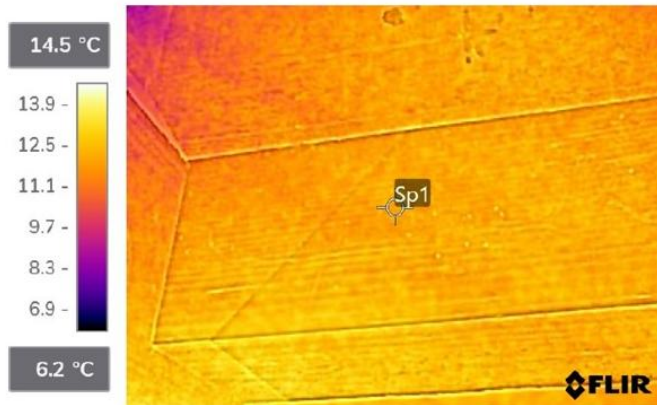
In agricultural contexts, there is rapid technological innovation and development to detect woodboring species, like the Red-palm weevil (RPW), on a large scale with significant background noise. Brandstetter & Hübner (2015) were able to detect characteristic larval noises despite significant background noise. Ashry et al. (2020) developed an optical-fibre-distributed-acoustic sensor that was able to detect 12-day-old RPW larvae in an infested tree. This area of research is still relatively new, but as technology advances and more research is conducted, it is becoming more prevalent and accessible, and hopefully more work on its applications to cultural heritage and its use on sites like HMS *Victory* will become more prevalent.

5.3.2 Thermography

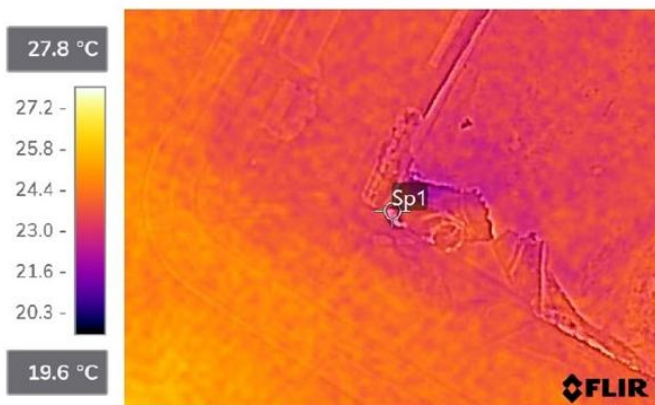
The images ([Fig. 67](#)) taken with the thermal camera around the ship and of wood from the developing culture showed that the camera was unable to penetrate the surface of the timber.



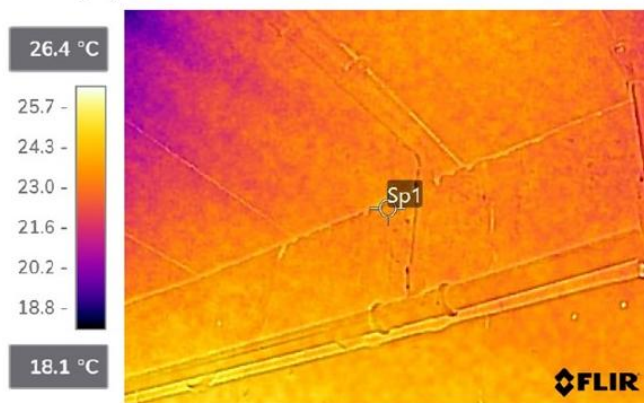
Bowsprit area (8/3/2023)



Infested pine in hold (8/3/2023)



Beetle and culture timber in lab (11/5/2023)



Bowsprit area (11/5/2023)

Figure 67: Thermal and corresponding regular images taken with the thermal camera. While there is a slight temperature difference with the exit holes on the timber surface, likely a result of a warmer pocket of air, the thermal images were unable to pick up any notable features. Even an exposed live beetle did not contrast much (it does have a different temperature, but the difference is subtle) with the surrounding area.

As images were taken of painted and unpainted timber with no discernible differences between the two, there is no indication that the results were influenced by the paint. There are little to no differences between the wood thought to be infested and the material around it. The slight increase of temperature within the exit holes is interesting, but not particularly useful. The fact that even an active living beetle did not create much contrast in the thermal images, along with the lack of contrast in the images from the ship suggest that this method is not worth pursuing by NMRN in future as a means of detecting areas of active infestation. Nor did it provide useful information regarding MC of the timbers. It should be noted that the images were only taken within the ship for access reasons. It may be possible that taking images of external timbers from outside the ship would provide more contrast, but there are many factors that may influence these images.

Thermography has been successfully used on the ship to map water ingress points and airflow (Davis, personal communication 2023), which, when compared with beetle hotspot locations may reveal common factors in areas activity. It will also be used to monitor temperatures of metal components embedded within the wood during microwave treatment tests (*Ibid.*). The method has its uses, but the detection of DWB within the ship's timbers is not one of them.

5.3.3 Radiography

5.3.3.1 Small-scale

The first small-scale images taken in January 2024 only had one potential larva/pupa that was distinguishable in one of the samples ([Fig. 68](#)). The images taken in May 2024 ([Fig. 69](#)), following the emergence period and providing more time for development, saw more distinguishable larvae. In one piece of wood ([Fig. 69](#)), approximately 10 potential larvae are visible.

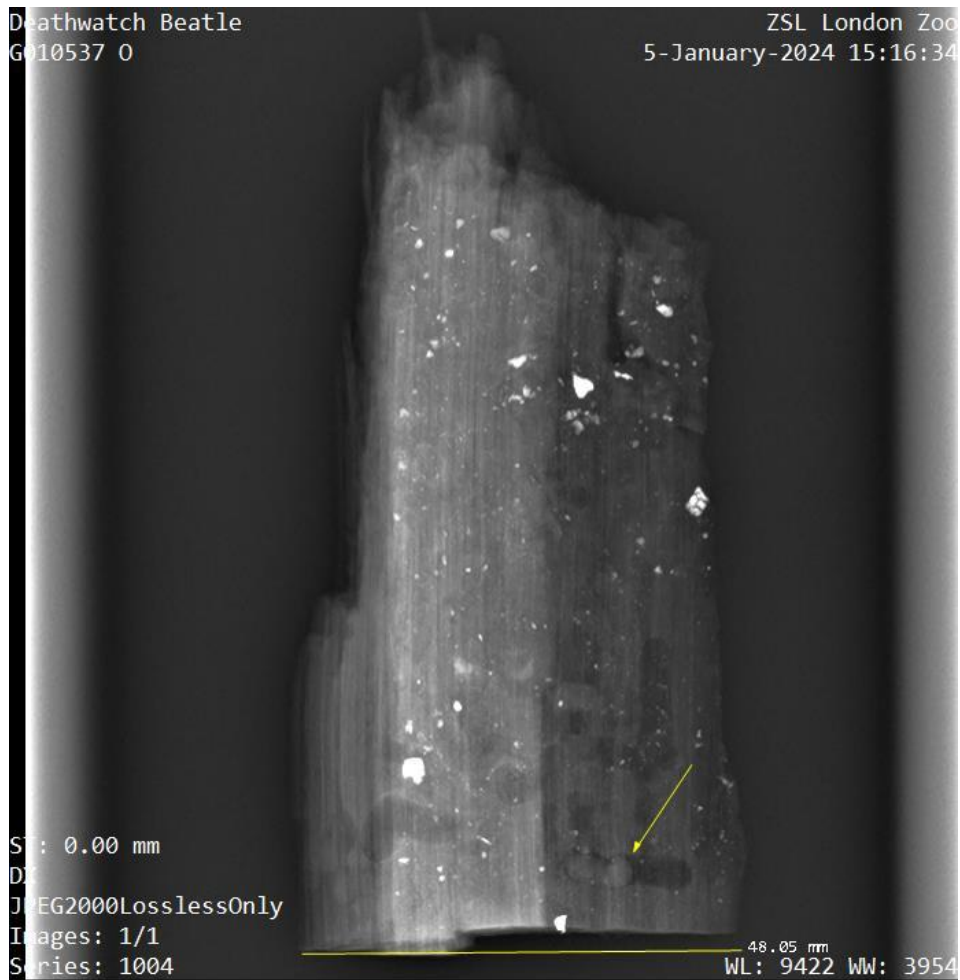


Figure 68: Possible larva (arrow) in wood from culture radiograph image taken on 5 Jan 2024. Image courtesy Dr Stefan Saverimuttu.

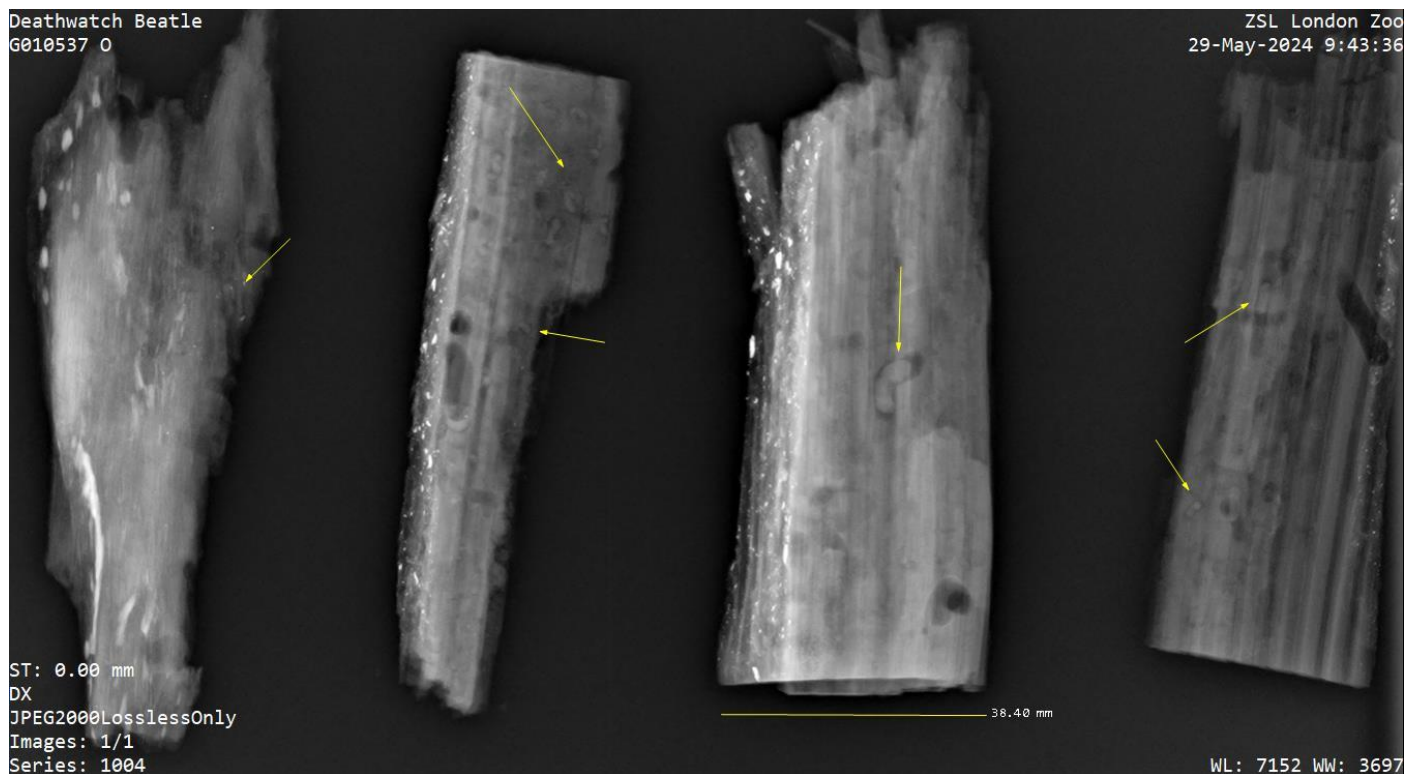


Figure 69: Radiographs of wood from culture with ~15 visible larvae of various sizes, locations indicated by arrows. The piece of wood with the measurement bar is the same as the one in Fig. 64 from a different angle. The second piece of wood from the left has ~10 larvae visible in this image. Image courtesy Dr Stefan Saverimuttu.

Radiography is clearly suitable for monitoring on a small-scale and can be used to monitor the development and movement of the larvae in the culture. However, it is worth noting that all the wood pieces where larvae were visible are <40mm at their widest points. No larvae were distinguishable in the wood fragment that was ~100mm thick.

5.3.3.2 Mid-scale

Initial examinations of the radiographs the day after capture (March 2022) revealed that there were no hidden fastenings that would inhibit sampling and clear evidence of tunnels, but no beetles or larvae were identified within the timber. It was not until the radiographs were re-examined more closely at a later date (June 2024) and supported by micro-CT images with positively identified larvae and beetles that any potential larvae or beetles were spotted. However, the superimposition of features of a 3D object presented in a 2D format prevented any certainty and the results are extremely subjective ([Fig. 70](#)). On this scale, radiography is still possible but is a less viable method for identifying areas of active infestation.

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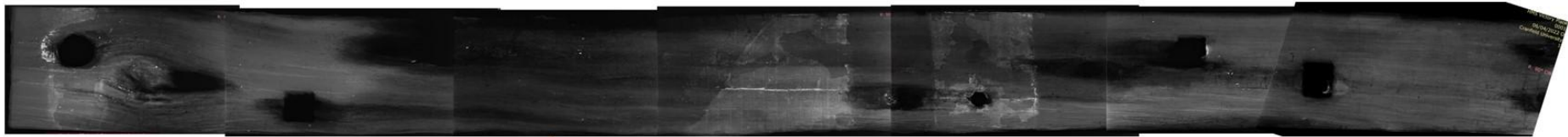
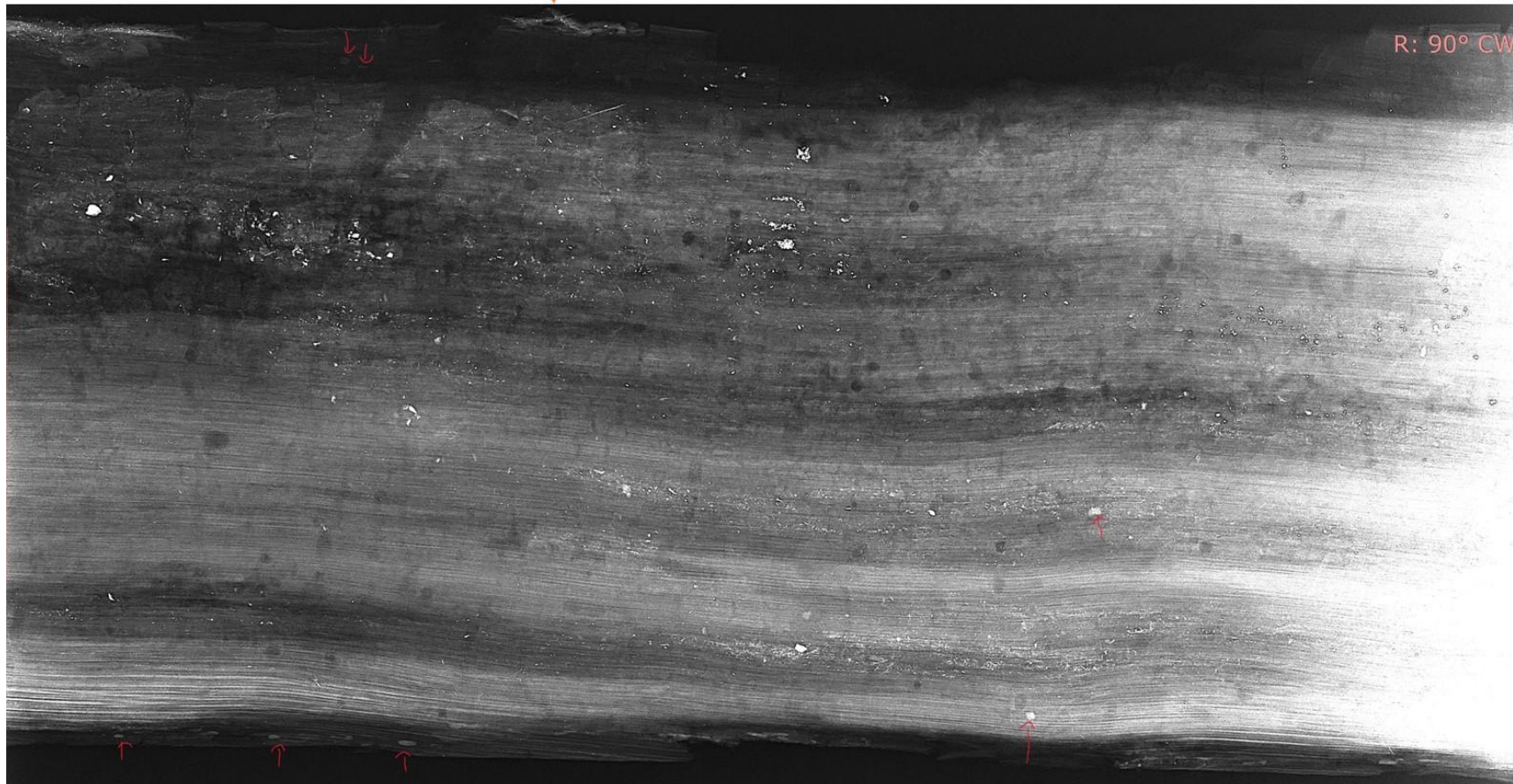


Figure 70: Radiograph images of plank taken in sections then stitched together. Magnified and brightened section indicated has possible larvae indicated with small red arrows. These were extremely difficult to see given their size and the scale of the image. Images courtesy Dr Mark Viner

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5.3.3.3 Large-scale

As already suggested by the mid-scale tests, when the size of the timbers increases, it becomes almost impossible to distinguish larvae within the timber, as they are too small. This was confirmed with the tests conducted by Dr Mark Viner ([Fig. 71-2](#)).

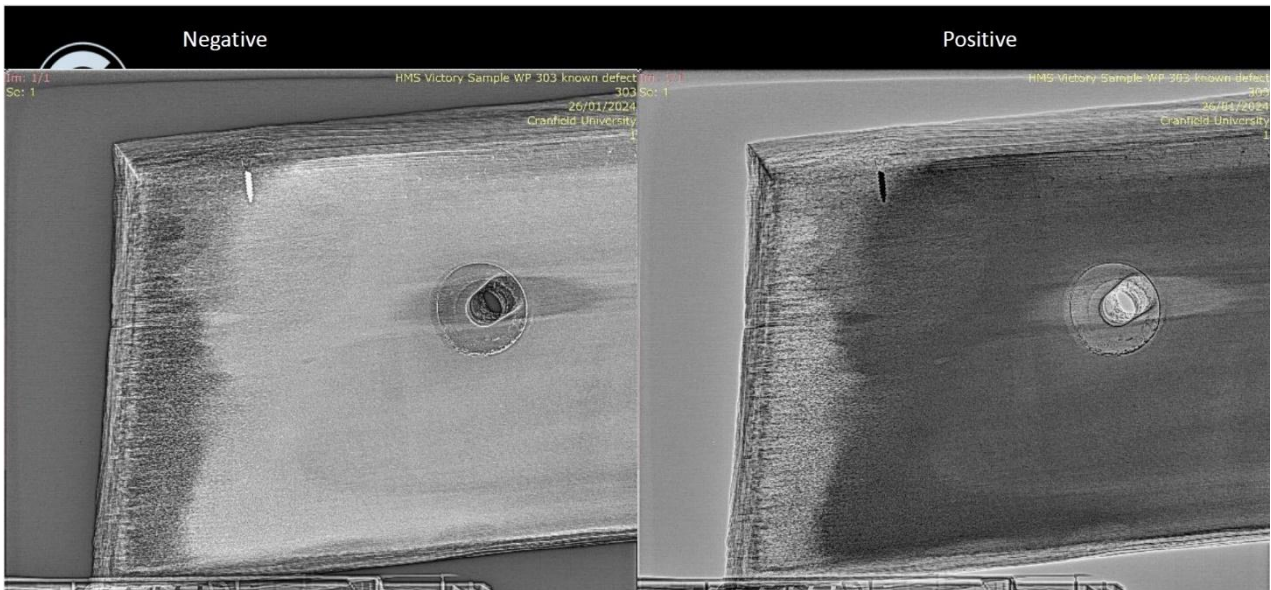


Figure 71: Radiograph images (negative and positive) of sample WP 303 taken in shipwright working area. Although the image reveals the extent of the rotten wood (darker grey in negative image), and metal fastenings, the scale is too large to reveal anything small unless it is denser than the surrounding wood. Image courtesy Dr Mark Viner

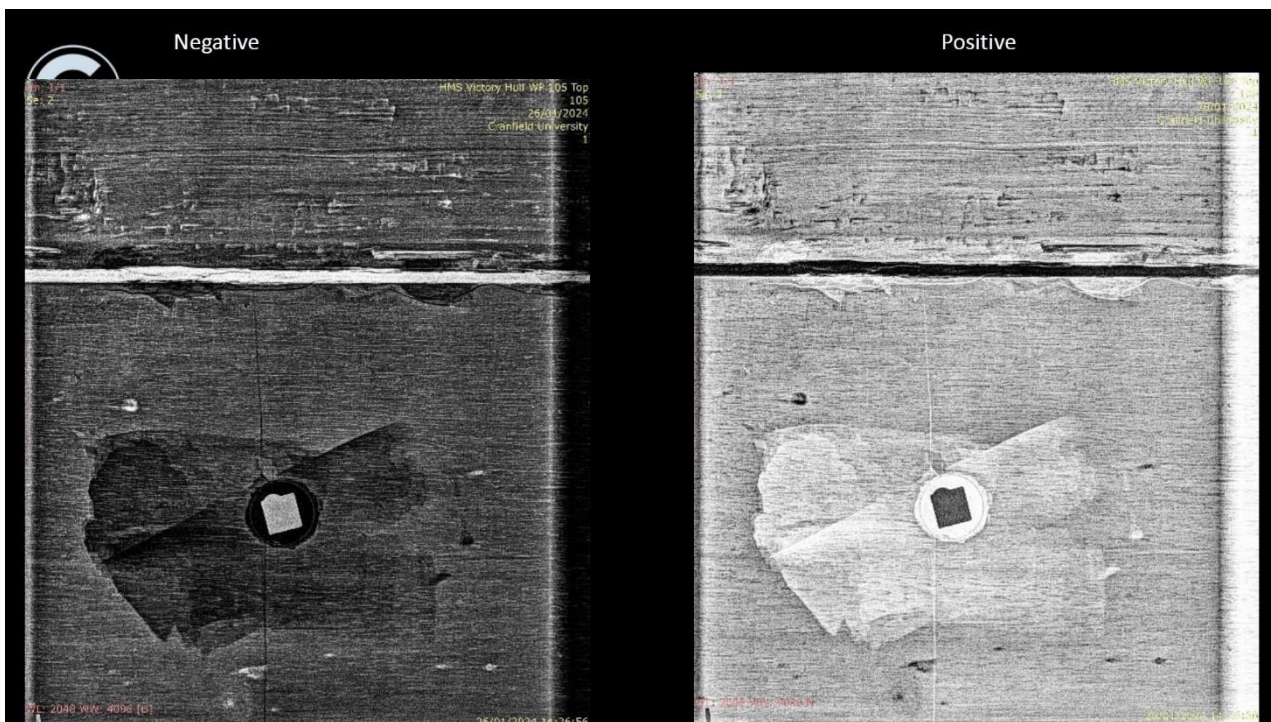


Figure 72: Radiograph images of Sample WP 105 taken on the side of the ship. There are further timbers behind the ones being imaged, imposing more features. Fastenings and density changes over large areas are visible, but little to no wood structure is discernible. Image courtesy Dr Mark Viner

5.3.3.4 Further discussion

These results demonstrate that radiography is a suitable method for determining active infestations on a small scale, but that the method does not scale up to the size of the ships timbers and is therefore unlikely to be useful for NMRN to pursue further.

As the culture develops and progresses, images will be taken every few months to track larval development and monitor larval movement through the wood fragments. In the 5 months between the first (January) and second (May) images, there was a significant increase in the number of visible larvae. The use of X-rays does raise concerns about exposing the larvae and beetles to radiation and whether that will affect the viability of the culture. But as invertebrates tend to be more resistant to X-ray exposure, a few seconds exposure every few months should not create any issues (Haff et al., 2020; Jiang et al., 2022; Koval, 1983). As mentioned previously, there are some caveats to consider with X-ray images due to the superimposition of features, but the dimensions of the wood being imaged and ensuring a minimal OFD by placing the wood directly on the detector should mitigate most of these issues.

These regular radiographic images should provide valuable information with regards to larval development, which historically has been extremely challenging to study. Although X-rays were used to examine DWB larvae within small pieces of wood in the past (Belmain, 1998; Fisher & Tasker, 1940), technology at the time meant that exposure times were long and relied on the development of X-ray film, a time-consuming process. Now, images can be seen immediately after capture and take no more than a few seconds at most. As this study focused on the feasibility of radiography to visualise larvae at different scales, the images captured were only taken from one or two directions. In future, images of each side of the wood should be taken. This would enable determination of the distance between larvae and the wood surface and may provide information about oviposition sites.

Although radiography is not suitable for detecting larvae within large ship timbers, it is still useful for visualising density changes within the wood as a result of fungal decay and for hidden fastenings or electricals. It could be used as a quick scanning method for small pieces of timber (below a certain size threshold) that are removed from the ship during the replanking process to see if there is any evidence of larvae within a timber, in which case, that timber would require treatment. Detecting density changes within the large timbers and mapping them across the ship may help conservators identify an area more at risk of infestation, as the results from [Ch 4](#) demonstrated a preference for lower-density wood. Equipment access remains an issue. Although portable X-ray equipment is well-established, it is expensive.

5.3.4 Other methods

5.3.4.1 Ultrasound

Both the surface in contact with the bag and the external surface of the wood were detected by the ultrasound, but the images were unclear and difficult to obtain. It is possible that more specialist ultrasound equipment designed for timber detection may have more success, but due the lack of expertise, it was decided not to continue down this path of investigation and instead focus on more promising and feasible methods.

5.4 Conclusions

The non-invasive detection of larval activity is something that is worth further investigation. The methods used in these preliminary investigations demonstrate that bioacoustics has the most potential in terms of detection of both larvae and adults, and a long-term monitoring system can feasibly be developed with further investigation. Although highly subjective, the use of stethoscopes, with some training, may provide an easily implementable interim method of detection. As a long-term acoustic monitoring method would require substantial further development, it may be more feasible to combine several proxies (i.e. water ingress, fungal growth and airflow) along with acoustic

detection (stethoscopes or something more sensitive) to hone in on areas of activity and risk (Davis pers. comm, 2024).

Radiography is suitable for detection of larvae on a small-scale only and is not suitable for the scale required on the ship. It will be used to monitor the development of the DWB culture at ZSL London Zoo.

Thermography for the detection of beetles and larvae is not suitable given the size of the timbers on the ship. However, its use for other purposes on the ship may reveal common factors (airflow, water ingress) between beetle hotspots. Investigations into the use of ultrasound as a means of detecting active areas were limited by the lack of expertise, but a small test done with medical ultrasound equipment suggested that the method was unlikely to reveal information on the scale required for the ship.

5.4.1 Live culture

In the early stages of the research for this thesis, it became apparent that a live culture of DWB would be extremely beneficial for the non-invasive detection testing but would also enable further understanding of DWB behaviour. The previous DWB culture used by Belmain (1998) that revealed valuable information about their lifecycle and oviposition preferences was unfortunately not maintained and died out (Belmain personal communication 2021). To prevent this from occurring again, it was decided that should a culture be established, it should be in an institution that could ensure its long-term care beyond the duration of the project and be in a central location that multiple institutions can make use of and contribute to.

Following a visit to ZSL London Zoo, noting that it had the facilities and expertise to host a culture, a proposal was put forward to the invertebrates' team and NMRN to establish the culture in the Tiny Giants exhibit space at the Regent's Park site. The original proposal document can be seen in [Appendix D](#), but what follows below highlights the main points.

The aim of establishing this culture was for it to become a long-term resource for study. In addition to its use for non-invasive testing, having the culture in a

public-facing position with information on Victory Live! The Big Repair would also serve as a point of public engagement, bringing heritage conservation and science to a much wider audience that might not usually come across such information. A live feed or listening stream could be linked to the museum website. There could be regular updates on tunnel changes, activity, and scientific findings through a blog. A live feed would also encourage members of the public to participate in the monitoring of the culture, through platforms such as Zooniverse (*Zooniverse*, 2024), allowing participants to contribute to the research of the species and thereby contributing to the conservation of *Victory*. It would also serve to emphasize how much there still is to learn about DWB behaviour and highlight the unique collaborations that can take place during the course of heritage science and conservation research.

Technology and scientific knowledge have improved significantly in the 24 years since the last studies were done, and substantially since initial studies in the early 20th century. Repeating early experiments and studies with more recent equipment and rigorous scientific standards, in addition to conducting further research, would solidify the knowledge and understanding of the DWB, and may reveal new information. IPM has become firmly entrenched in the conservation principles of most museums and heritage spaces since its introduction in the 1990s. As such, there has been a shift towards environmentally friendly and non-hazardous pest-eradication techniques and management of deeply entrenched infestations. A live culture would enable research into the use of natural predators of the DWB as a means of population management. It may also be possible to test other methods of control (Takanashi et al., 2019). Recordings of vibrations associated with the mating and feeding behaviour of the Colorado potato beetle have been found to disrupt beetle activities and reduce the damage to potato crops (Kakadiya & Patel, 2024). It would be interesting to see if a similar method would be successful for DWB.

Finally, the use of a native British woodboring beetle to develop non-invasive means of detection means that techniques and methods can be investigated

and tested on a non-threatened species before being used to detect critically endangered species, like the Frigate beetle, whose larvae are also woodborers, that the Zoo researches and cares for. The invertebrates' team has already started making use of stethoscopes for this purpose.

6 PUBLIC ENGAGEMENT WITH CONSERVATION PROTOTYPES

6.1 Introduction

The data and information gathered as part of Chapters [4-5](#) is of use to those engaged in HMS *Victory*'s conservation as a means of approximating damage and methods that can be developed for non-invasive, active monitoring. It is also applicable to other historic sites dealing with DWB and other woodboring beetle infestations. But, as highlighted in [Ch. 3 Section 3.3](#), it is essential to communicate conservation research more widely to those outside the profession. Demonstrating the value of cultural heritage and why it is important to conserve it encourages everyone to become stewards of that heritage. In the case of HMS *Victory*, it is valuable to the local community as a point of pride and heritage, and source of revenue and jobs (through historic dockyard and naval yard), but it is also valuable nationally and internationally as a survivor of Trafalgar and Nelson's dying place, the flagship of the First Sea Lord, and as the only surviving wooden ship of its age. While the public are often aware of the ship's intangible value, many are unaware of the tremendous effort it takes to look after the physical, tangible aspects of the ship.

This lack of awareness can have serious implications with regards to funding and resource allocation for heritage conservation, which in recent years has suffered greatly (Case Studies of Resilient Heritage Organisations, 2012; *Economic Value of the Heritage Sector*, 2023; Hardaker, 2024).

With the unprecedented opportunity presented by Victory Live! The Big Repair (started 2021) to engage the public with the 'special project' of conserving the ship, the conservation team also recognised the opportunity to share the wider research that is involved, of which this thesis forms a part. From its inception, this project intended to trial innovative methods of communicating the research findings to the public, explore responses to those efforts, and initiate further potential impact trajectories for the work. This thread was a key consideration

throughout the work conducted as part of Chapters 4-5 and culminates in this phase of the research.

Much of the focus in the storytelling on HMS *Victory* is on Nelson and Trafalgar. Although understandable, so many other aspects of its history are missed out. It was already unique by the time of Trafalgar, as, at the age of 40, it had long surpassed its expected lifespan (McGowan, 1999). This singular narrative has been a point of frustration for those involved in its care. Diversifying the narrative to include the DWB research adds to the story of HMS *Victory* and encourages other elements to come to the fore, highlighting how special and unique HMS *Victory* is with regards to how it has been cared for over the years.

Many of the pre-existing methods used for public engagement with conservation are one-off or temporary events, as demonstrated in [Ch. 3](#). Little of it is long-term, and many rely on the shock value of before-and-after images (McClure, 2013; Williams, 2013a: 173). What the examples and case studies highlight is that it is impossible to cover the full scope of conservation work that takes place, but by focusing on specific elements, further discussion and investigation can be prompted (Williams, 2013b).

Digital engagement with cultural heritage, both onsite and online, is becoming increasingly common and is an excellent and effective tool for adding emphasis and extra dimensions to heritage spaces for interpretation (Bertrand et al., 2021; Chitty, 2017; Galani & Kidd, 2019; Harvey, 2001; Kidd, 2019). However, little of it is focused on heritage conservation and the research that goes into maintaining collections (see [Ch. 3 section 3.3.3](#)). This is an area that is only just beginning to be explored (Tan Grande y Jugando, 2023; Wong, 2024).

6.1.1 Aims and objectives

The aim for this phase is to communicate conservation research by telling the story of DWB on HMS *Victory*, emphasizing the level of work involved in dealing with the infestation, as well as providing proof of concept for the museum for such experiences.

Existing methods were examined in [Ch. 3 Section 3.3](#), so the objectives for this section are to:

1. Raise awareness of the conservation issue (DWB) and the work involved
 - a. Develop 2 public engagement experience prototypes based on the data generated from investigations into tunnelling behaviour and non-invasive detection.
 - i. What methods of delivery best support storytelling about DWB conservation research? How can the DWB research data best be packaged for digital public engagement activities?
2. Shift public perception of HMS *Victory* to include conservation
 - a. Gather public reaction to the prototypes by user testing on visitors to the ship. How do users feel in response to the prototypes?
 - b. Do people understand the level of complexity involved in conservation? Do they find it inspiring/daunting/surprising? Does this change the way they view HMS *Victory*?

6.2 Materials and Methodology

6.2.1 Initial considerations

Initial discussions with the conservation and public programming teams highlighted several key points that became integral when developing the prototypes: much of the engagement around DWB was aimed at young children, and conservators time is limited (they do not want to be doing regular events or talks). There was a need to have something for teenage and older audiences (12+, the target audience).

These discussions and further observations led to the identification of several main threads:

1. Visitors need to be made aware of the problem.
2. The current conservation work should be highlighted, and previous attempts to treat the infestation acknowledged.

3. Research like this is essential to understand more about the issue in order to find a more effective solution.

These threads, along with the following considerations with regards to the implementation of the experiences, were kept in mind during the design and development process:

1. The prototypes have to be adaptable to the needs of the museum: due to the current conservation work, the visitor route on the ship is constantly changing, so they need to be moveable. This feature also would be helpful in case of unexpected incidents, like leaks.
2. Space is extremely limited and there are many 'choke' points on the visitor route (areas on the route that are narrow and difficult to manoeuvre causing visitors to clump together). The experiences should avoid these choke points.
3. The ship is not accessible to everyone. Accessibility in this instance refers to physical access to the ship: not everyone is able to visit the site in person, and the ship is not mobility aid user friendly. Having experiences that are linked to the ship but not directly tethered to it would allow those unable to visit the opportunity to experience a different aspect of the ship.
4. While WiFi and electricity are available on the ship, they are not consistent throughout. The WiFi speed limits the file sizes of the experiences as the larger the file, the more time and greater bandwidth are needed for loading.
5. The experiences have to be able to withstand fluctuations in temperature and relative humidity (RH) and be robust enough to withstand handling by visitors.
6. The prototypes should take an absolute maximum of 10 minutes to prevent fatigue (Bitgood, 2009: 98; Davey, 2005).

The use of digital experiences addresses many of the issues outlined above and point 4 could be mitigated by either choosing an appropriate location with sufficient WiFi signal strength, or by pre-downloading the experience onto

devices. With all this in mind, consideration turned to the data collected as part of the tunnelling and non-invasive detection investigations, and how it could be turned into 2 distinct, yet complementary, informative experiences to achieve these goals.

6.2.2 Prototype 1: Plank Interactive

6.2.2.1 Narrative Premise

The aim behind this prototype was to highlight the hidden damage caused by the DWB, by going from a macroscopic view to a microscopic one. Users should come away with a basic understanding of the nature of the damage caused and the difficulties in detecting it. Ideally, it should incite an appreciation for the challenges that conservators face. [Figure 73](#) shows the narrative structure behind this interactive:

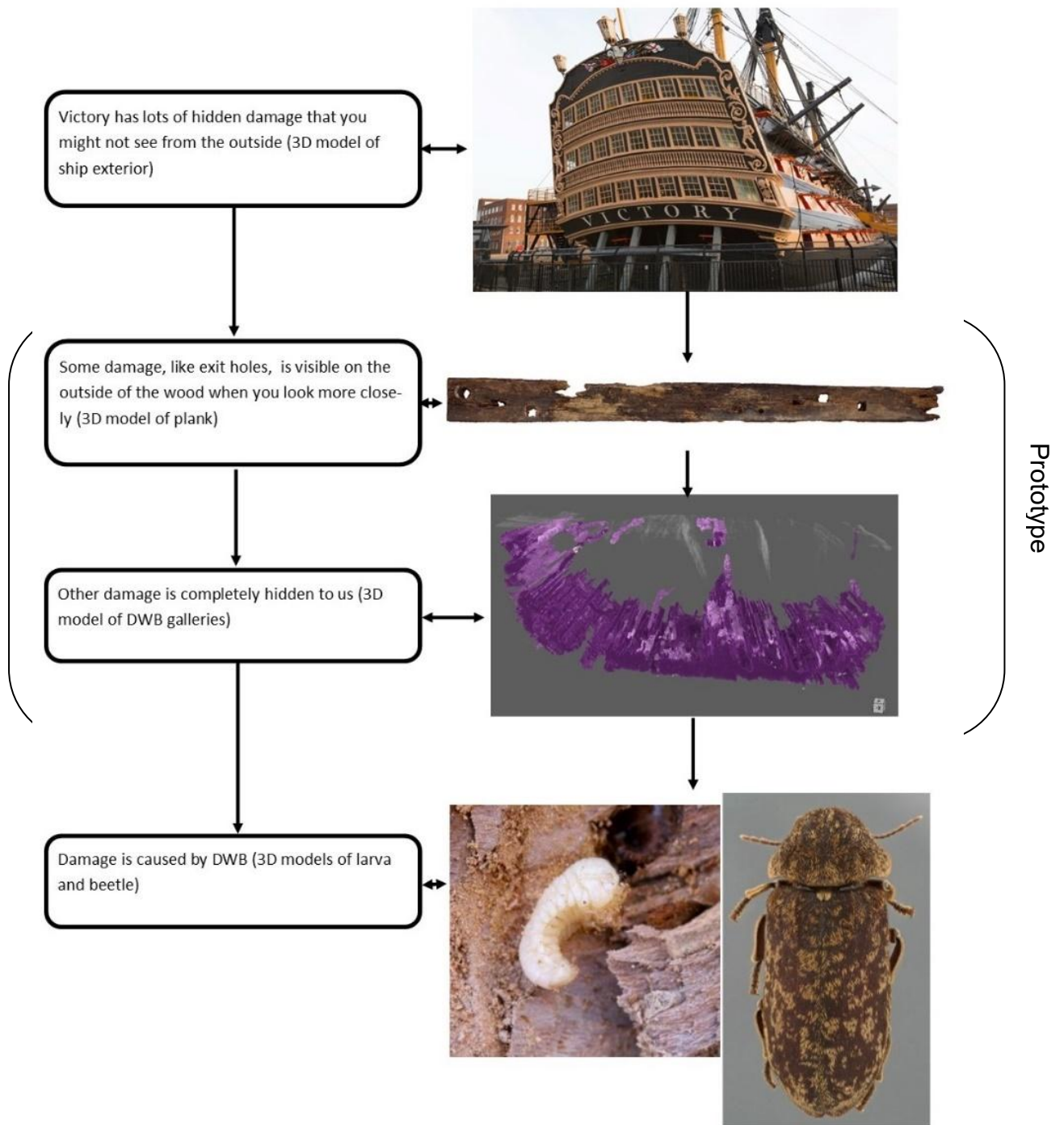


Figure 7.5: Flowchart demonstrating the narrative premise behind Prototype 1 (plank interactive)

For the prototype, the middle of the narrative was selected to be presented, as it demonstrates the basic concept, could be easily constructed, and could provide sufficient detail in a manageable file size for the available WiFi. It was designated the plank interactive prototype.

This prototype was designed to be a self-guided, self-led learning experience that would allow users to explore the damage at their own pace and level of interest.

6.2.2.2 Building the Prototype

The micro-CT segmented images from samples A8 and A9 were stitched together with the 3D stitching tool in Dragonfly ORS. The 3D models of the tunnels, beetles, and surrounding wood were extracted as a .stl mesh (export default) and converted to an .obj mesh file (more widely accepted file type) using MeshLab™ (free, open source software). A polygon mesh is a collection of edges, vertices and faces that defines the shape of a polyhedral object (Lorensen & Cline, 1987; Tobler & Maierhofer, 2006). The more detailed the mesh, the greater number of faces and the larger the file size (*Ibid.*). Samples A8 and A9 were chosen as they were adjacent, had already been segmented, had a distinctive tunnel map, and contained several beetles and larvae.

The meshes of the tunnels, beetles and wood were imported into Autodesk Maya™ (a 3D animation and rendering software available free for academic use) and grouped together. Each was assigned a surface material and coloured ([Fig. 74](#)).



Figure 74: Screenshot of the tunnel model hosted on SketchFab©. The numbers show the annotation points corresponding to beetle and larval locations. The beetles are indicated in green to contrast against the light brown of the tunnels. Larvae were highlighted in pink and the wood in a dark brown.

The colours of the wood and tunnels were selected to suggest the original context of the plank. Pink and green, while not true to life, were selected for the larvae and beetles to contrast against the browns and neutral grey background but can be altered as needed in future.

SketchFab®, a web-based 3D model viewing software used by institutions like the British Library and the British Museum to host models of objects in their collections, was selected as the host platform for the models. It is easy-to-use, is an industry-standard software, and models can be published privately and publicly. Views for models can range from several hundred to several hundred thousand (*3D Models by British Library*, 2024; *3D Models by The British Museum*, 2024). Uploaded model files are limited to <200MB with the Pro subscription.

The number of faces on the original meshes of the tunnels, wood and photogrammetry model of the plank had to be reduced using Autodesk Maya™ to fit under the 200MB limit. This unfortunately meant losing detail and resolution, but for the purposes of prototype testing was acceptable. This was most noticeable with the beetles and larvae. The models of the plank and tunnels were uploaded to SketchFab® and labelled accordingly ([HMS Victory Deck Plank](#) and [Deathwatch Beetle Tunnels from HMS Victory](#)).

The plank model was annotated ([Fig. 75](#)) to include information about the original location of the plank, age of the plank, and highlight the visible damage. The approximate location of the tunnel maps was annotated with a link to the 3D model of the tunnels, which, when clicked, would take you to the tunnel map model ([Fig. 76](#)).



Figure 76: Screenshot of the plank model hosted on SketchFab© with Annotation 2 expanded

Each material in the tunnel map model (from assigned materials in Autodesk Maya™) was edited in the SketchFab© editor. The wood was made almost completely transparent to give an idea of original shape and dimensions, but not interfere with the view of the internal structure. The tunnels were made slightly transparent to reveal larvae and beetles, and the larvae and beetles were fully opaque (Fig. 76). The larvae and beetles were annotated Beetle 1, Larva 1, etc. (14 total), along with either a fact about DWB, conservation research, or information concerning the larvae in the sample.

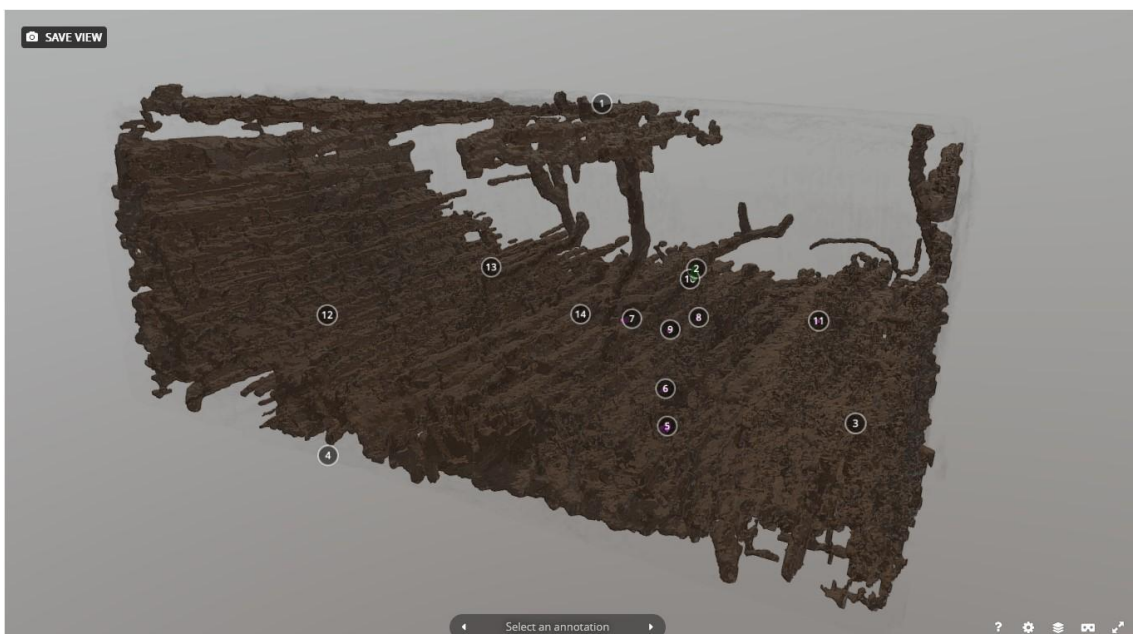


Figure 75: Tunnel model hosted on SketchFab©. The faint outline of the wood can just be seen, to provide an idea of the original shape of the wood without hindering the visuals of the tunnels and the beetles and larvae in the tunnels.

The models were published privately to SketchFab© so that only those with the link could access during the testing phase. The goal is to eventually make it available to everyone with internet access, allowing those unable to visit the ship a way to explore certain aspects from anywhere. They were grouped under Cultural Heritage & History 3D models, and Science & Technology 3D models. They were also tagged with the following: insects, beetle, entomology, photogrammetry, micro-CT, deathwatch, hmsvictory, deathwatchbeetle. The tags were chosen so that when the models are made public, any searches using those terms will bring up these models.

6.2.3 Prototype 2: Deathwatch Beetle Conservation Experience

6.2.3.1 Narrative Premise

The goal for the second prototype was to inform visitors of the work that conservators do to manage the DWB infestation and highlight the fact that novel research, like that done during this project, is an important component of the work involved. Users should come away with a basic understanding of what to look for in DWB infestations, and the measures that conservators can take at the current level of knowledge. Should the museum develop and implement these experiences in future, the information from each experience would support the other without repetition. Each will provide a unique experience to the visitor should they wish to do both or just one. The first prototype provides a less structured, self-learning experience, whereas this prototype will provide a more guided experience. [Figure 77](#) shows the narrative structure behind prototype 2.

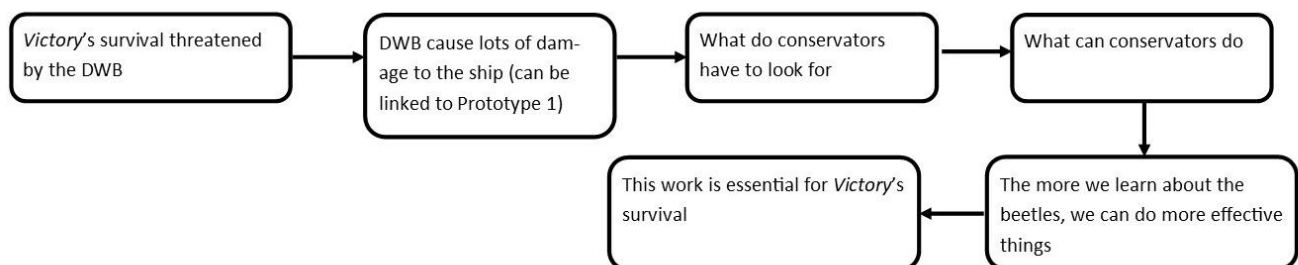


Figure 77: Narrative premise behind Prototype 2 (DWB experience) demonstrating how the narrative builds through the experience and the key messages behind the design.

Unlike prototype 1, it was felt that it was important to portray the entire narrative to demonstrate the information being imparted.

6.2.3.2 Building the prototype

As the structure of the narrative was similar to a guided tour, Augmented Reality (AR) was selected as the method for prototype delivery to provide a similar experience of a tour on the ship, without the need for a conservator or guide to be present.

CoSpaces Edu© was selected as the host software due to availability, ease of use and supported software, as well as the associated application for viewing and testing the experience. This application could be downloaded onto any smart phone or tablet computer.

An existing 3D female figure, altered to approximate the author, was selected as the 'guide', and given outfit colours that would contrast well with the ship's interior. A neutral background was used for the building process. The information for each scene was written in a speech bubble, with a recording of the text that automatically played at the beginning of each scene (both written and spoken language included to make the experience more accessible). The figure was animated with pre-set animations, depending on the information presented in the scene ([Fig. 78](#)). The coding for the experience was done with CoBlocks, the inbuilt system of CoSpaces with prebuilt blocks of code for specific actions and transitions. An information bubble appears at the end of the first scene with instructions on how to move to the next scene.

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Figure 78: Storyboard of opening four scenes of the Deathwatch Beetle Conservation Experience (prototype 2). The neutral background in these images were replaced by the ship during testing. The full storyboard can be seen in Appendix E

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6.2.4 User testing & data collection

User testing of the prototypes took place on the ship to provide essential context. However, the prototypes need not be limited to the ship in future and can easily be adapted for use off-site.

Two weekdays in mid-September 2023 were designated for user testing, with one day for each prototype. These dates were chosen to avoid school holidays, tourist season, and weekends so the majority of visitors would be adults, and numbers would allow for sufficient interaction without blocking the visitor route. Incentives were provided for participants from the museum shop's excess stock.

Questionnaires (see [Appendix E](#)) for each prototype were created to assess reactions to the prototypes and their suitability for use. They started with specific questions about the prototypes themselves, then broadened to more general questions about conservation and heritage science. The latter questions were the same for both prototypes to allow for direct comparison. The majority of the questions were yes/no/maybe questions followed by space to elaborate with a few prompts. These were designed to provide a quick initial response, which could then be expanded upon in the next part. The remaining questions were broader, and more open ended.

The questionnaires were designed to be completely anonymous. No identifying data was collected, as the goal was simply to get reactions and responses to the prototypes. Although it may have been informative to collect data like age, education level, or distanced travelled (provides insight into economic means) from a demographic point of view, this was not the premise behind this research but is worth considering for future.

The basic set-up for the testing period was as follows: a table with a sign was set up in the bowsprit area, and the museum's DWB puppet was strategically placed to attract attention ([Fig. 79](#)). The location was chosen as there was enough room for participants and other visitors to move about, and the WiFi signal was strongest. Additionally, it was early on the visitor route so participants were more engaged (Bitgood, 2009: 93-4), and they could use the

information learned throughout the rest of their visit. The testing period ran from 10.00 to 16.00 or until the limit of questionnaires was reached. It was decided that a minimum of 25 questionnaires, within the common range for prototype testing (~20-40), for each prototype would provide sufficient data to gauge reactions and viability, as well as identify patterns without responses becoming repetitive (Galani & Kidd, 2019; McDonald, 2011; Phichai et al., 2021).

Visitors were asked if they wished to participate and were given the opportunity



Figure 79: Prototype testing set up around the bowsprit area. The museum's DWB puppet was used to attract attention as a point of interest and was next to the incentives offered.

to read an information sheet that they could keep.

6.2.4.1 Prototype 1: Plank interactive

Wood samples A8 and A9 were placed on one side of the table to provide a physical interactive along with two computer tablets pre-loaded with the SketchFab© models. Some basic printed instructions were also provided, and the researcher sat at the table to provide additional help and guidance.

Participants were encouraged to interact with the models on the tablets and ask any questions to the researcher, before being asked to fill out a questionnaire, either verbally with the researcher asking the questions, or manually, reading the questions themselves. In total, 30 questionnaires were collected for this prototype. Participants typically spent 5-10 minutes to complete the process.

6.2.4.2 Prototype 2: Deathwatch Beetle conservation experience

The CoSpaces application was downloaded onto 6 phones the museum normally uses for Virtual Reality (VR) experiences. The researcher was assisted by Dr Jenny Kidd (supervisor) and a museum volunteer as the initial set-up process was more involved than that of Prototype 1 and the number of participants meant it was impossible for the researcher to do it on their own.

The experience was queued on the phones ([Fig. 80](#)) before being handed to the participants, who were given a quick overview and assistance with initiating, before being left unassisted to experience the prototype. The space was supervised by the research team to prevent blocks to the visitor route, and to provide aid when requested.



Figure 80: How the DWB trail figure appeared on the ship

Upon completion of the experience, participants were presented with the questionnaire. For this prototype, 31 surveys were completed. The prototype runs for about 4 minutes, so participants typically spent 9-10 minutes to complete the entire process.

6.2.5 Data Analysis

The data gathered from the questionnaires was analysed using a Grounded Theory (GT) approach, a method which “sets out to discover or construct theory from data, systematically obtained and analysed using comparative analysis” (Chun Tie et al., 2019: 1). Rather than developing and testing a hypothesis, GT is an inductive method where the data collected is systematically analysed to identify key threads, called codes, from which theories can be developed (Birks & Mills, 2011: 9-14).

The questionnaire data was transposed into a Microsoft Excel™ spreadsheet, and the responses to the open-ended questions were thematically coded based on common themes identified in the responses for each. The multiple choice data was then graphed to visualise the proportion of responses.

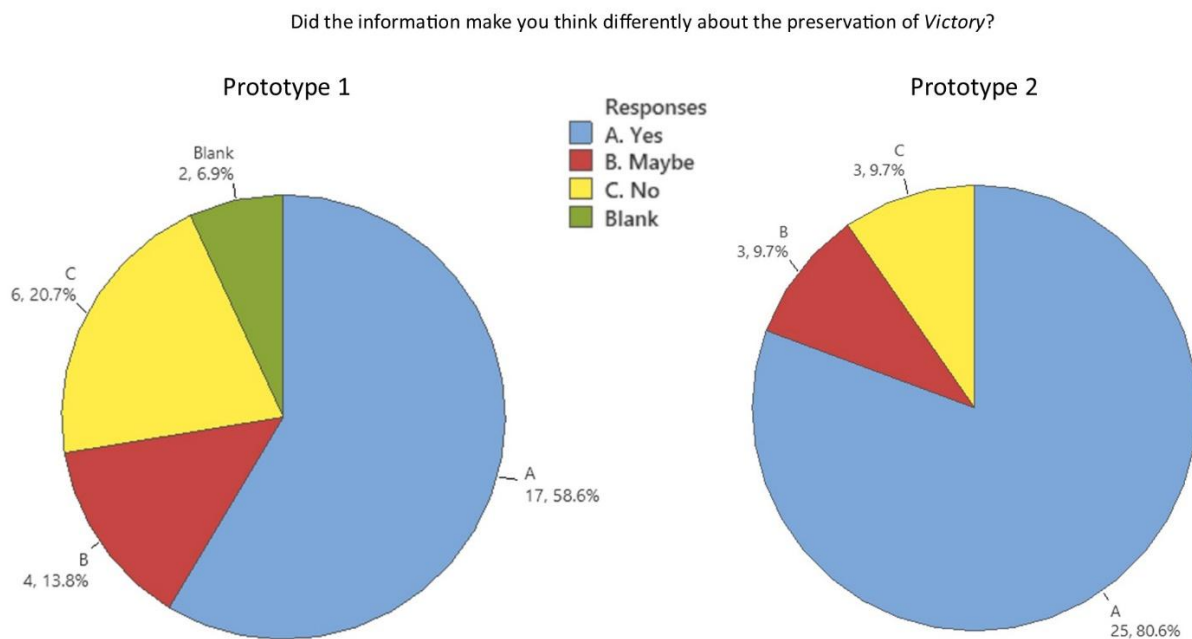
6.3 Results and preliminary discussions

The results from both prototypes are presented below. The first section will address results regarding engagement with conservation and communication of the DWB research. The subsequent section will look at the specific changes needed for the prototypes before further development as a result of the feedback given.

6.3.1 Engagement with conservation

6.3.1.1 Multiple Choice (i.e. yes/no/maybe)

The results of the questions assessing reactions to the preservation of *Victory* in response to the information presented in the prototypes were varied. [Figures 81-83](#) are pie charts providing an overview of the proportion of responses to the multiple choice questions. While these charts provided an overview of the proportion of responses to the multiple choice questions, they only present part of the question and can only be considered as a component of the wider results.



I *differently about the preservation of Victory?*. Unfortunately, not all participants realised there was a back side to the questionnaires, resulting in some unfilled questions.

At first glance, the pie charts in [Figure 81](#) suggest that Prototype 2 had greater success at changing the way visitors think about the preservation of *Victory*. The question does not allow for those that were already aware of the issue of DWB on the ship or were aware or interested in conservation already. Many of the participants who responded No or Maybe to the question went on to clarify in the open-ended part that they were already aware.

The management of pest infestations like the Deathwatch Beetle is one element of conservation and involves many aspects including research, investigation, and experimentation. Was the level of complexity involved something you expected?

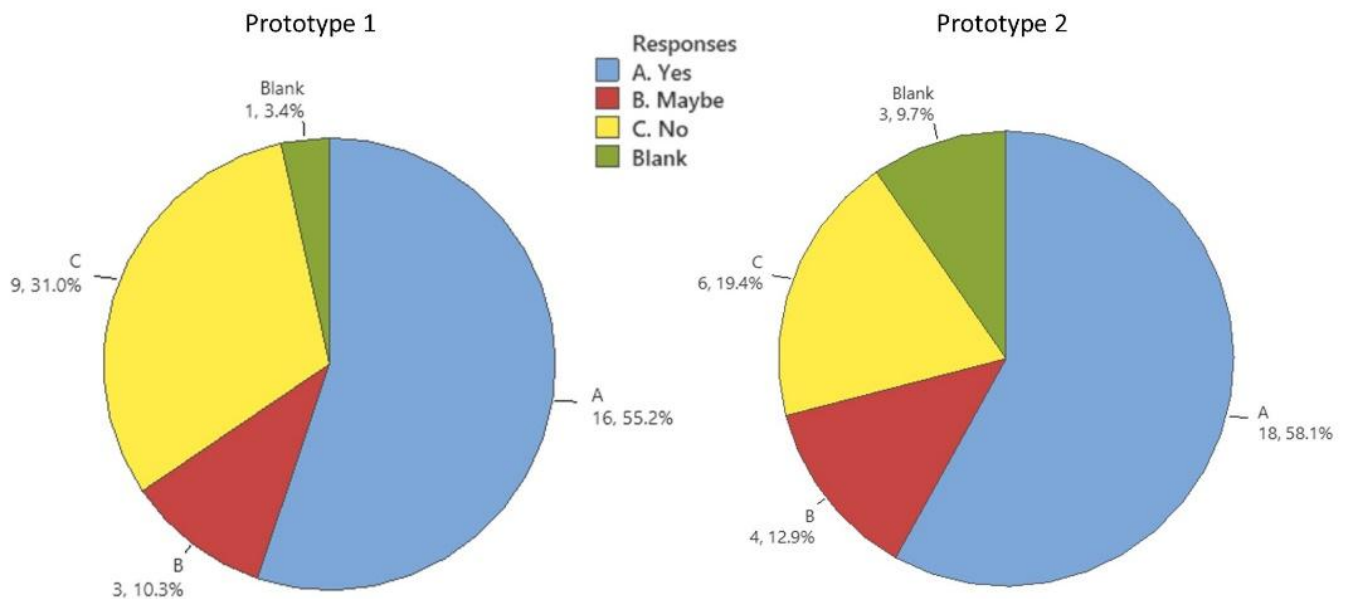


Figure 82: Pie chart results of multiple choice question regarding complexity of research.

In [Figure 82](#), the question is phrased in such a way that the No response is indicative of changing perspectives. The question was designed to assess whether participants were able to grasp the level of complexity involved with conservation and heritage science work. Those who answered Yes were not surprised by the level of complexity involved - while it may not have been something they expected, it was not surprising to them.

Does this inspire you to find out more about conservation and heritage science?

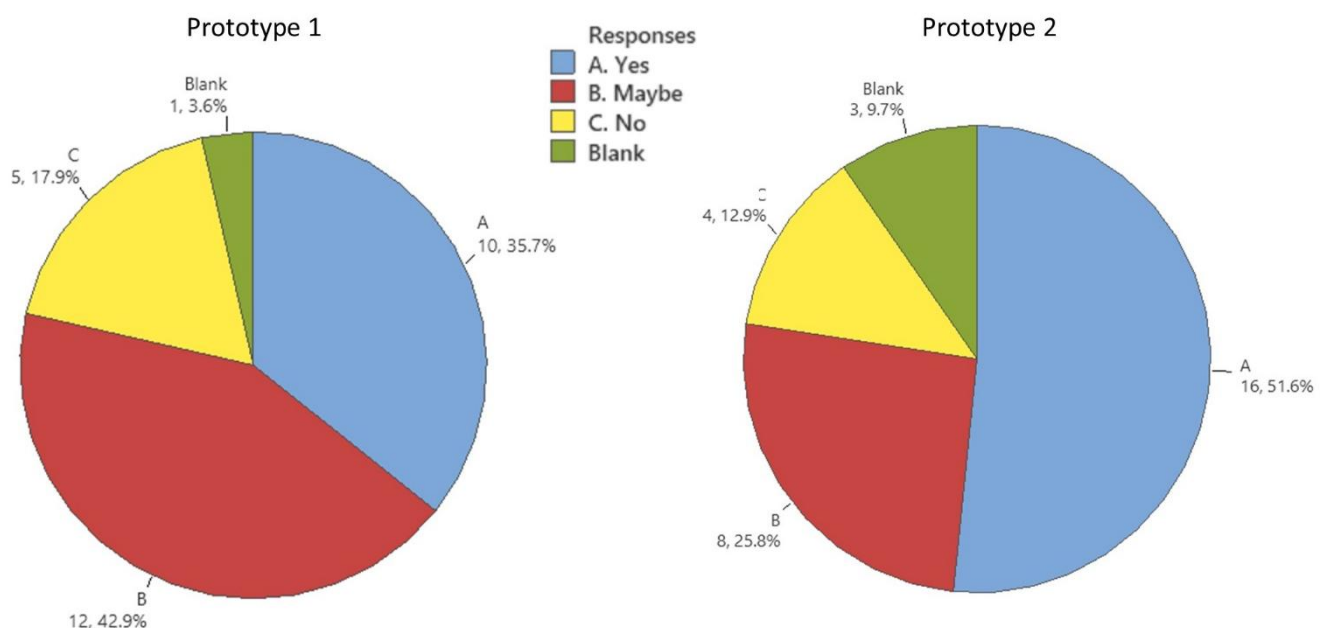


Figure 83: Pie chart results of multiple choice question regarding seeking further information on conservation and heritage science

The final pie charts in [Figure 83](#) suggest that Prototype 2 was more successful at inspiring participants to find out more about conservation and heritage science more generally. But again, many who answered Maybe or No went on to further clarify their response. Several mentioned that they were interested with regards to the context of *Victory*, while others said that they would keep an eye out for it at other sites, but it would not be something they actively sought out.

The final multiple choice question for Prototype 1 asked participants if the models hosted on SketchFab© should be accessible to anyone with an internet connection. Generally, people were keen for the models to be widely accessible (82.8%, 24 responses). Those who were uncertain (10.3% 3 responses) wanted to share the information but expressed concern that it should be an incentive for paying visitors, and those who firmly said no (6.9% 2 respondents) thought it should only be for paying visitors.

At this point in the presentation of results, it can be concluded that visitors are supportive of the information being more widely available, and that the presentation of the prototypes had an impact on participants views of the preservation of *Victory*.

6.3.1.2 Thematic Analysis

There were 7 themes identified from the open-ended responses:

1. Lack of awareness
2. Surprised by beetles
3. Level of damage/comments about wood
4. Lack of solution
5. Interest in Context (HMS *Victory*)
6. Possibilities for fundraising
7. Suggestions for new methods.

Each theme will be discussed in detail below.

6.3.1.2.1 Lack of awareness

One of the most common themes across both prototypes (36 responses) was a complete lack of awareness of the issue and conservation more generally. Respondents regularly said that they: *“Didn’t think about it as an issue”* (Prototype 1 Questionnaire 2), had *“Never come across it before”* (Prototype 1 Questionnaire 16), it was *“Totally new”* (Prototype 1 Questionnaire 13), and that it *“Alerted me to an issue I had not thought about before”* (Prototype 2 Questionnaire 10).

There were two comments that were more expansive, which more effectively capture the nature of the responses:

“Ignorance of conservation measures and all that is required for this vessel to be preserved” Prototype 2 Questionnaire 9

“It shows how much work goes into preservation” Prototype 2 Questionnaire 11

This theme demonstrates that most of the participants were ignorant of conservation and the work involved in preserving historic sites like HMS *Victory*. If the majority of participants were ignorant of conservation, then it is likely that most visitors to the ship are as well. The prototypes informed the participants about a novel aspect of the ship.

6.3.1.2.2 Surprised by beetles

The second most common theme across the prototype responses (33 responses over the 60 questionnaires) was surprise about the presence of the DWB on the ship. Here are a number of responses that demonstrate this theme:

“The fact that Deathwatch beetles are a thing.” Prototype 2 Questionnaire 5

“Not expecting Deathwatch beetles.” Prototype 1 Questionnaire 22

“The existence of Deathwatch beetles and how they threaten the HMS Victory.” Prototype 2 Questionnaire 7

“Had not considered there would be an issue with bugs. Had not considered any of the challenges in preserving a wooden structure for future generations.” Prototype 2 Questionnaire 15

“Unaware they were still causing damage to the ship.” Prototype 1 Questionnaire 21

“Never thought Deathwatch beetles as big an issue.” Prototype 2 Questionnaire 25

“That they are still extant on the ship after so much restoration.” Prototype 2 Questionnaire 8

These quotations demonstrate the variety in responses. Some, like the latter 3, suggest an existing knowledge of DWB generally (often by participants who mentioned experience with old building as an aside to the researcher), but others had never heard of the species.

Another interesting response within this theme stated: *“Pests yes, with regards to historical objects no”* (Prototype 1 Questionnaire 10). What makes this response interesting is the fact that the participant was aware of pests like the DWB but had never considered that they can infest historical objects and structures.

The responses under this theme show that for participants, the information presented in the prototypes was new and not something that had been brought to their attention before.

6.3.1.2.3 Level of damage/comments about wood

Participants were shocked by the level of damage caused by the beetles, which in the case of Prototype 1, was further emphasized by the presence of damaged wood samples on the table.

Only two respondents mentioned the damage caused by the beetles as a result of Prototype 2, with one saying, *“Scale of damage caused by the infestation and conservation measures still require research and implementation.”* (Prototype 2 Questionnaire 3). The other respondent expressed their amazement *“How*

something so small can cause such devastation!" (Prototype 2 Questionnaire 31). This is likely due to the fact that Prototype 2 focused more on what measures conservators take to manage the infestation and the wider research, whereas Prototype 1 was designed to highlight the hidden nature of the damage caused by the beetles.

The size of the beetles in the context of the extent of the damage appeared to be one of the most surprising factors, as a respondent from Prototype 1 also said *"I was surprised how much damage something so small can do without it being obvious."* (Questionnaire 6). Several respondents (9) commented that the experience with Prototype 1 was made *"much more impactful"* (Questionnaire 27) by the presence of the wood samples for handling.

The responses suggest that Prototype 1 was successful at communicating the hidden nature and scale of the damage to the participants. Although less direct comments were made in response to Prototype 2, the comments that were made as part of other responses suggest that sufficient understanding was imparted in the prototype for participants to comprehend why the beetles are a problem.

6.3.1.2.4 Lack of solution

This theme was a point of contrast between the two prototypes, as responses categorised under this theme were only from Prototype 1. This distinction is likely due to the difference in information presented by the prototypes. Prototype 2 focuses more on managing methods and future research rather than the damage, so the current lack of an effective solution did not appear in participant responses. Participants were really surprised *"by lack of suitable treatment"* (Questionnaire 24), *"That it is so hard to treat the wood"* (Questionnaire 9), and *"That there is no answer to get rid of them"* (Questionnaire 24).

This distinction between the responses to the prototype is something to consider for future. Visitors should not come away from their visit thinking that nothing can be done, as there are measures that can be taken. What needs to

be highlighted is that research is required to design more effective methods of management.

6.3.1.2.5 Context specific

As mentioned briefly in [Section 6.3.1.1](#) with regard to the multiple choice responses, at first glance, Prototype 2 appeared to be more successful at prompting further interest in conservation and heritage science. But those that answered No went on to clarify that they were *“interested specifically in Victory”* (Prototype 1 Questionnaire 29) and *“more interested in Victory context”* (Prototype 2 Questionnaire 28).

Those that answered Maybe further went on to say that they *“were not going to seek it out, but curious”* (Prototype 1 Questionnaire 14) and that they *“will keep an eye out when visiting sites like this, but won’t seek it out”* (Prototype 1 Questionnaire 27).

These responses demonstrate that the interest in conservation and heritage science is there, but that this is often context and spatially specific. People are not against learning about it, but they want it to be packaged and presented to them when they visit historic sites.

6.3.1.2.6 Possibilities for fundraising

Another distinct and surprising theme for Prototype 1 was the use of the models as a method for fundraising. Four different respondents made comments along the lines of *“can help with fundraising when seeing damage”* (Questionnaire 20), with one respondent going further and stating that the models can encourage *“other people can input, more collaborative”* (Questionnaire 12). This last statement is further demonstrated by the following theme.

6.3.1.2.7 New methods

The final theme, that was again unique to Prototype 1, was ground in suggestions of possible methods for dealing with and monitoring the infestation. One person suggested the use of *“sound/humming to disrupt activity”* (Questionnaire 12), and another suggested *“new scanning methods - HFR”* (High-Frequency Radar) (Questionnaire 21).

Although it was only 2 comments, the fact that there were two distinct responses suggests that more people may have suggestions, potentially contributing to a more collaborative conservation practice and solidifying the concept of shared stewardship of cultural heritage. Having inputs from a wider range of backgrounds and experiences might lead to novel solutions.

6.3.1.3 Initial conclusions

The first 4 themes listed demonstrate the participants' surprise about the presence of the problem, the scale of damage and the difficulties in treating the infestation, suggesting that the information presented was novel and interesting to them. It can be concluded that the prototypes were successful at raising awareness of the DWB infestation on *Victory* and conservation more generally to the visitors.

What was surprising were some of the unexpected commonalities appearing in responses, particularly in response to Prototype 1. The suggestions for future methods and potential for fundraising demonstrate that Prototype 1, being self-guided, prompted a collaborative response in some participants. They were more eager to put forward their own suggestions on how to deal with the infestation or point out how the prototype could be used for fundraising purposes. This was not the case with Prototype 2, which was a guided experience. However, participants from Prototype 2 showed a greater level of interest in seeking out more information on conservation.

That does not indicate that the other participants were not interested at all: it appears that people's interest in conservation is closely tied to their interest in specific sites and contexts, and that while many were interested in the subject, they did not want to actively seek it out.

These findings will be discussed more fully in the wider discussion section ([6.4](#)).

6.3.2 Functionality and usability of prototypes

There were several interesting responses to the questions asking for direct feedback regarding the functionality and usability of the prototypes. Although participants were understanding of the fact that these were prototypes rather

than finished products, several points regarding the usability were made that must be considered before any further development takes place.

6.3.2.1 Prototype 1: Plank Interactive

For Prototype 1, the most common piece of feedback was that there were “*too many numbers (annotations)*” (multiple respondents) in the model of tunnels.

Several respondents gave suggestions for improvements:

“Colour-code annotations to make clearer.” (Questionnaire 28)

“1 annotation for beetles, 1 for larvae.” (Questionnaire 10)

Reducing the number of annotations or creating ‘levels’ of annotations (where one annotation may lead to another that does not appear on the initial model) are two potential options for future iterations.

There were a few comments (3) on the size of the screen and the text. That is something that can be remedied by having a larger screen size. The size of the screen may also have contributed to the crowdedness of the annotations, making there appear more than there were.

Compromises had to be made with regard to file size when uploading to SketchFab®, meaning that details were lost, a fact commented on by two participants, who particularly expressed an interest in beetle details. Higher resolution models would be better, which means alternative hosting sources would be needed.

Another point for improvement was to do with the functionality. Navigating the model on a computer tablet was tricky, as the navigation bar occasionally disappeared and was difficult to recover. There was no obvious back button to reset the view. Some of these may be due to the fact that SketchFab® is designed for viewing 3D models on a computer rather than a tablet. But given preliminary investigations noted that people struggled to view the models with a computer and a mouse, this may be another case where an alternative means of hosting the model may be appropriate.

That does not mean that the SketchFab© hosted models do not have their place, as they can be made accessible to those unable to visit the ship. Having both an online version and a site-specific one would address the concerns some participants had about the profitable value and still have a version for wider outreach and potential fundraising. The presence of the wood samples on the table was something that participants responded strongly to (see [6.3.1.2.3](#)) and that can serve as an additional incentive for visitors to the site. [Figure 84](#) is a potential mock-up of how the experience might work for the ship in future:



Figure 84: Mock-up of plank interactive experience for future. Having a portable touchscreen and display case (the wood would be covered) would enable it to be moved around the ship to fit with the needs of the museum.

6.3.2.2 Prototype 2: DWB Conservation Experience

There were fewer (12 as opposed to 24) comments on improvements for Prototype 2.

Larger and greater number of images and larger text were requested, as was the option for headphones, both of which can be addressed easily. Another point that was mentioned was the limited movement and interaction. As a prototype, it was a static experience for participants. But one of the advantages of AR is the ability to interact and move. The use of trigger points around the ship had been an initial consideration, but due to the limited coding experience

of the researcher, space constraints, museum requirements, and personnel available for supervision during testing, it was not possible for the prototype trials. Tying the scenes to points of DWB interest is something that could be achieved in future iterations.

Several participants expressed concern about the digital nature of the experience and the struggles that less digitally literate visitors, in particular older individuals, that make up a significant proportion of visitors to the ship, might experience with the delivery method. Senior tickets made up 14% of visitors to *Victory* in 2023, however this does not include older adults who fall under the adult ticket category (Britton, 2024). But many also noted that younger people might prefer it, and that AR is a *“modern method to be embraced”* (Questionnaire 21). These comments, along with others about incorporating the information into the audio guides, suggest that it *“would be nice to have multiple options”* (Questionnaire 25). The audience for the prototype testing was deliberately broad (12+) to encourage a wide variety of participants (although several children under 12 still interacted alongside their parents). A more specific targeted audience may be something the museum would need to consider in future should they decide to continue development.

When participants were asked whether they would be comfortable downloading an app of the experience in future, there were mixed responses. Some suggested instead that a pre-loaded device, like those given out for testing, and similar to how the current audio guides are given out on site, might be a better solution. Others stated that they would be much more interested in downloading an app if it was part of a wider Portsmouth Historic Dockyard app with similar experiences for other vessels and other information.

The final change to the prototype before any further development would be to change the animated figure to a person or even a beetle. Several comments were made similar to *“would have been better with more visuals/animation of beetle rather than human weirdly waving hands.”* (Questionnaire 2). In the case of having a human guide, it would give the experience an even greater feel of a guided tour and is something that has been achieved at other historic sites ([Fig.](#)

85). Additionally, having a human guide may change the responses of those participants who would “also like a person” (Questionnaire 29).

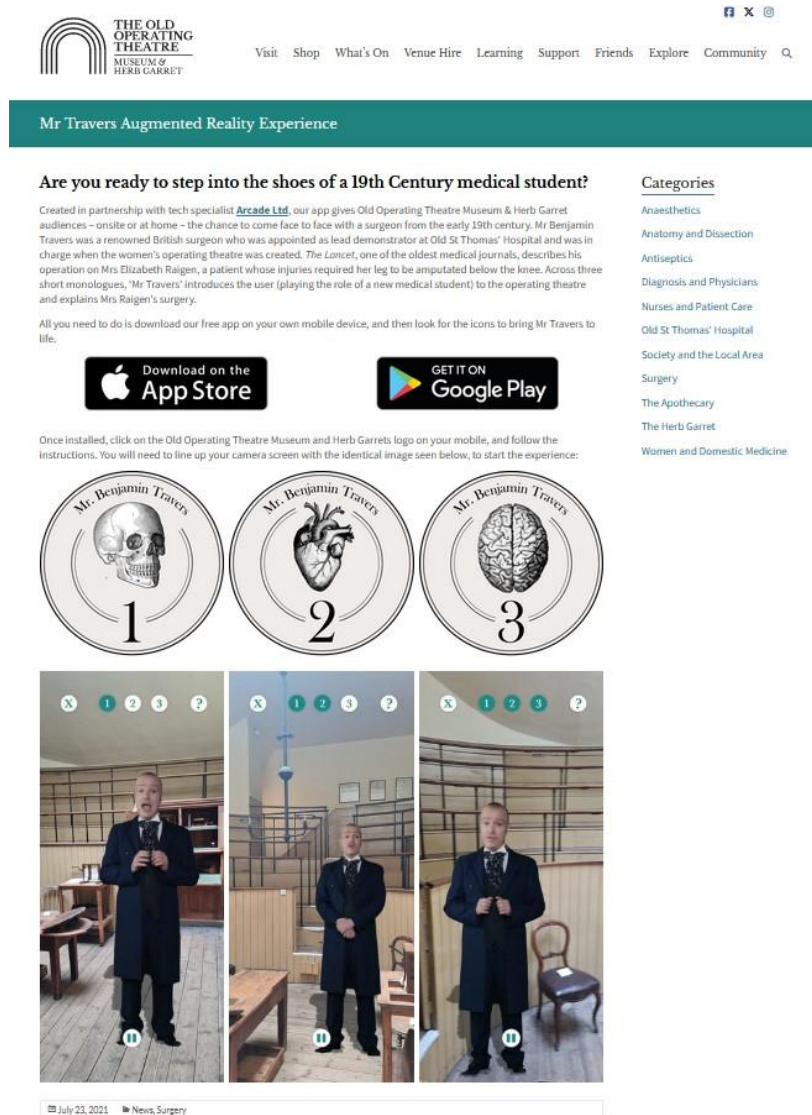


Figure 85: Webpage of the Old Operating Theatre Augmented Reality Experience, where an actor, dressed in historic costume as a 19th century surgeon, guides the visitor through an operation that took place in the space.

6.4 Wider discussion

The results with preliminary discussions of the user testing demonstrated that the prototypes were successful at raising awareness of the DWB infestation on *Victory* and conservation more generally, which often prompted suggestions or further reflection. There are two further quotes from participants that encompass the general response to the prototypes:

“Easy to take exhibitions for granted and don’t think about what goes on behind it.” Prototype 1 Questionnaire 20

“Detail of research and conservation still being required. Also the amount of knowledge needed for the general public to be made aware and understand.” Prototype 2 Questionnaire 3

The results also demonstrated that people’s interest in conservation is linked to their interest in specific sites and contexts. This section will discuss the results and observations more broadly with regards to the wider field of public engagement with conservation, as well as addressing aspects that did not fit within the results but are nevertheless important to discuss.

6.4.1 Interest in conservation

There was some concern raised during development about whether participants potential interest was as a result of the DWB narrative (people tend to be interested in creepy-crawlies) or the broader conservation aspect. But the results suggest that it is the broader conservation aspect when related to the *Victory* context. There is the caveat that the testing took place on the ship, so it is possible that participants were slightly biased. But it could also be argued that it was the best place to test, as the emotional connection, considered a key component for engagement and action (Khundam, 2020; McDonald, 2011; Perry et al., 2017), was already present. Presenting the information to an audience in a different context may yield different results and should be considered in future.

The literature investigating public engagement with conservation predominantly centres around case studies of specific sites and contexts ([Ch. 3 section 3.3](#)). While they demonstrate an interest in conservation in those contexts, which is further supported by the findings from this study, it can be difficult to gauge broader interest in conservation. The work done by Koutromanou (2015) in the Ashmolean Museum’s Conservation Galleries was the first comprehensive study into the wider interest in conservation that was not tied to a workshop or short-term exhibition or project. What is unique about the research and findings

from the DWB project is that it was a specific case study that directly asked whether or not the participants would be interested in learning more about conservation in future and whether their interest lay with HMS *Victory* or conservation more widely.

What the case studies in the literature do reveal is that community engagement is a key component of conservation engagement (Chitty, 2017; Drake, 2017). In these cases, community was considered local, but the definition can be broadened to include anyone with a vested interest in a site, whether they are local or not. Incorporating conservation narratives permanently into heritage experiences, through methods like the Ashmolean Galleries and these prototypes (which happened to be digital, but might not have been), enhances visitor experiences and will bring conservation to the fore, thereby ensuring a longer-lasting impact than do short-term projects and displays. This may help widen the community aspect and encourage further discussions and collaborations about heritage conservation, contributing to the concept of shared stewardship (Bertrand et al., 2021). Evidence of this can be seen in the aftermath of the cutting of the tree in the Sycamore Gap. The shock of the unexpected felling led to an outpouring of support and collaboration to rescue seeds and twigs of the historic tree (Bradshaw & Rannard, 2024). Messages, social media tributes and on-site memorials from the public were used by the National Trust, Northumberland National Park, Historic England and The Hadrian's Wall Partnership to identify themes to inform their thinking about what the legacy of Sycamore Gap should be (Mcdarby, 2024).

What is best exemplified by this event, but is present in all other case studies, including this research, is the personal connection people have to heritage and heritage sites (Saunders, 2014). This personal connection is what makes people care, brings them repeatedly back to the same sites (Donoghue, 2024), and maintains current and future interest (Maude, 2024; Stitt & Misuriello, 2024). Personal connections are formed through the sharing of different narratives. By not including conservation narratives, a potential connection point is missing.

6.4.2 Diversifying the narrative

The focus on one narrative, even if it contains multiple views and people, is incredibly limiting, and in the case of HMS *Victory*, reduces it to one small part of an amazingly rich history (Bugler, 1966; McGowan, 1999). The Battle of Trafalgar is a singular point in *Victory*'s life that realistically had little impact on the daily lives of British citizens (Ballantyne & Eastland, 2005), although it did secure the ship's long-lasting fame. The current conservation work is doing an excellent job at diversifying the narrative to include the work that goes into preserving *Victory*, but this must continue beyond the duration of the project.

Although, conservation and *Victory*'s wider history are too broad topics to address in any great detail in a short addition to the visitor experience, highlighting certain aspects, like the DWB, can prompt visitors to consider the wider aspects of the stories involved. This is essential in getting the public perception of museum objects (including *Victory*) to move away from static items to dynamic mementoes of the past that are constantly changing. The user testing of these prototypes demonstrated a perspective shift in how they viewed *Victory* just based on a small amount of novel information that was presented to participants and that interest in *Victory*'s wider story beyond Nelson is there. With the current rise in awareness of the finiteness of resources, it is an ideal time to highlight the fact that heritage is a very finite resource itself by having these discussions and incorporating these narratives.

Diversifying narratives is particularly key in increasing the resilience of heritage visitor attractions, which given the recent COVID-19 pandemic is an important consideration. The Association of Leading Visitor Attractions (ALVA) has identified 7 aspects of the most successful and resilient (consistently attract visitors) UK visitor attractions (Donoghue, 2024). Resilient organisations are:

1. Provocative in their storytelling
2. Disruptive
3. Risk-taking
4. Brand-stretching (be accommodating to contemporary issues)
5. Fostering unusual creative partnerships to allow for new perspectives

6. Audience developing

7. Audience diversifying

Of particular importance to this study are points 1 and 5-7. By incorporating conservation narratives, an organisation forces audiences to consider and acknowledge the work that enables them to enjoy and experience heritage, thereby developing the audience. Conservation and the science behind it are very collaborative, and conservators often consult each other and other specialists to provide the best possible care and enhance knowledge. During the course of this project, entomologists, engineers, zoologists, and veterinarians have been consulted. These partnerships are unlikely to have come about without the conservation of HMS *Victory*. Developing these relationships and communication allows for audience-diversifying opportunities, introducing conservation and heritage science to an audience that might not usually come across it. It could even be argued that NMRN, in communicating the DWB infestation to its audiences, is taking a risk and is disrupting the usual expectations of visiting a heritage site. Most heritage institutions are loathe to admit a pest infestation for fear of criticism and censure. But as a consequence of taking this risk and funding this research, the audience felt trusted and even willing to contribute their own ideas to aid in *Victory's* conservation. Simply by incorporating conservation narratives into their experience offerings, NMRN can work towards 6 of the 7 attributes.

Additionally, diversifying the narrative would assist in addressing the lack of diversity in museums, an increasing concern (Adams, 2019; Charr, 2022). Although conservation may not be the most provocative of subjects with regards to narrative diversification, it is still a good starting place, and its inclusion and promotion may aid in diversifying the conservation workforce, something that is sorely needed and is integral to the concept of shared stewardship.

Long-term studies of the impact of the permanent incorporation of conservation narratives would be required, but it is in the best interest of those working in the discipline to encourage this. HMS *Victory*, the Ashmolean Conservation Galleries, and the Fitzwilliam Museum exhibition *Mission Impossible?* (2006)

can serve as guides for how conservation narratives can be incorporated into existing spaces, both as a physical inclusion and an adaptive digital one.

6.4.3 Guided or self-guided

The prototypes presented two different options to visitors: a self-guided experience with the plank interactive and a guided experience with the AR. The results shown in [Fig. 81](#) suggest that the guided experience resulted in a greater number of participants responding with an interest in learning more about conservation and heritage science generally, as opposed to a specific interest in *Victory's* conservation. There was a noticeable difference in the number of participants seeking extra information from the researcher, which may have impacted responses. With the plank interactive (Prototype 1), participants were keen to chat to the researcher while interacting with the model. It was clear that there was a desire for guidance and interaction, further emphasized by those who commented on the questionnaires that while they enjoyed the prototype experience, they would like to be able to talk to a person. This is consistent with Galani and Kidd's findings: "With experiences that are not guided or scaffolded in the way that participants are used to, there is seemingly still a desire to locate an authoritative narrative or institutional line, a conditioning that seems very much encultured in our respondents." (2019: 10).

There was noticeably less interaction between the researcher and the participants during the testing of Prototype 2. While this may be due to the number of participants at any one time and the presence of assistants, it is likely due to the fact that the experience was more structured and guided, so there was less desire to seek reassurance. With hindsight, it might have been better for the researcher to not be present during the testing or be present only for technical assistance.

However, there were more collaborative responses as a result of Prototype 1 than there were with Prototype 2. Without the structured guidance, participants were more willing to contribute their own ideas and solution suggestions to the conversation. Not only does this input from visitors provide a wider pool of

experiences, expertise and knowledge from which solutions can be found, but in listening and acknowledging these inputs, visitors are involved in the conservation process and therefore become contributors and collaborators of heritage conservation, fulfilling the requirements of shared stewardship.

It is important to note that the process of getting the public involved in shared stewardship of heritage is a multi-step, non-linear process. The first step is raising awareness by incorporating conservation narratives into the regular heritage site experience. This is the stage that the process is currently at. At this point in time, it might be best to have more guided experiences alongside the self-led ones for those seeking reassurance, before gradually moving away from them once the conservation narrative is more thoroughly enmeshed in the heritage site experience. The presentation of information with minimal to no guidance is next, which then leads onto collaboration between conservation and the public. But having both guided and self-led options throughout the process allows for the possibility of collaboration early on.

6.4.4 Use of digital

The use of digital technologies does have some drawbacks that must be considered. The cost of equipment and maintenance can be prohibitively expensive. While the creation of basic prototype experiences can be done by anyone comfortable with technology using existing software, the further development of experiences in a more polished form is likely to require expertise outside of the museum.

It is important to remember that digital technology and resources are tools to help aid interpretation and add to the visitor experience. They are tools to complement, entice, excite, entertain, and invite but in no way replace the visitor experience (Donoghue, 2024). Many heritage sites in the past relied too heavily on the novelty of the technology rather than the content and the deliverable experience (Hildred et al., 2022). When used thoughtfully, these tools can bring many benefits. Visitors, in being encouraged to cross a digital threshold, can gain confidence to cross the physical threshold (Donoghue, 2024). Changes

can easily be made to an experience without having to change the physical infrastructure, and experiences like AR and VR can be incorporated into existing spaces without any structural impact. This is particularly key in the case of *Victory*, and the user testing of the prototypes demonstrated that digital assets could add greatly to the *Victory* experience without any physical changes. It is something that NMRN has highlighted as an underdeveloped aspect within the museum that requires more work (Sheldon et al., 2024).

It might be said that the current visitor experience on *Victory* feels somewhat old-fashioned and contrasts starkly when compared to the rest of the Dockyard experience, especially when considering the offerings at the *Mary Rose*. Only information panels and audio guides are available, and the vast majority of the information is centred around Nelson and Trafalgar. Whether this is an intentional choice as an homage to historic museums, or its status as a commissioned ship limits what can be done, it is beginning to feel out of place.

The use of digital approaches also means that experiences are not limited to the ship, making the information more accessible to those unable to visit the site. Although there is not much in the way of digital engagement with conservation in the literature thus far, the study conducted by Svodoba (2013) during the conservation of the Carolina Room in Colonial Williamsburg (USA) found that having both online resources and in-person experiences enabled a wider reach, while also still providing something unique to the museum for direct visitor interaction. A similar model may work well for NMRN and could be achieved with something like the mock-up for Prototype 1 (Fig. 80).

6.5 Conclusions

In recent years, conservation has been beset by major budget and staffing cuts (Case Studies of Resilient Heritage Organisations, 2012; *Economic Value of the Heritage Sector*, 2023; Hardaker, 2024) and yet conservators are somehow still expected to contribute the same quality and level of care in their work, assist with exhibitions, and more. One of the most significant contributors to this is the

lack of awareness of the profession, both within the heritage sector, particularly those in positions of resource allocation, and the wider public.

The goal for this work package was to raise awareness of a particular conservation issue (DWB) with the general public using data generated by the research. Two prototypes of public engagement experiences were created and user tested on visitors to HMS *Victory*.

Prototype 1 (plank interactive) was designed to highlight the hidden damage caused by the DWB by going from a macroscopic to microscopic view. The prototype version of the experience showed the annotated photogrammetry model of the plank with a link to a model of the tunnels from a small section that was generated from the micro-CT data, further supported by the wood samples from which the models were created. Prototype 2 (DWB conservation experience) informed participants of the work that conservators do to manage infestations and that research, like that of non-invasive detection, is a key component of this process. A basic AR experience of an animated 'conservator' guided the participants through the information. Questionnaires were presented to participants to gather feedback and gauge responses.

The questionnaires contained a mix of multiple choice and open-ended questions. The results of the former were charted, and the latter were analysed using a Grounded Theory method. Four of the seven themes identified from responses demonstrated the surprise of participants about the problem, suggesting that the information presented was novel and interesting. It can be concluded that the prototypes were successful at raising awareness of the DWB infestation on *Victory* and conservation more generally to the visitors.

Further development to the experiences is required to take them from the prototype stage to a more finished product, should the museum wish to implement them. With the changes outlined in [Section 6.3.2](#), the results show that these experiences would be positively received as additions to the visitor route. The in-built flexibility of the designs should enable these changes to be

made and for the museum to tailor the experiences to their needs with regards to access.

The results also demonstrated that interest in conservation is strongly tied to a specific interest in a site or context and that users want the information packaged and presented to them rather than seeking it out themselves. However, the self-guided (Prototype 1) and guided (Prototype 2) experiences showed a distinction in responses, with Prototype 1 showing more collaborative responses but Prototype 2 participants showing more general interest in finding out further about conservation in future. Finding a balance between guided experiences, which visitors are more likely to look for, and self-guided experiences, which prompt and encourage visitors to suggest possible solutions, is a key consideration towards permanent incorporation of conservation narratives into heritage sites.

This research has shown that digital experiences can be used to add conservation narratives to existing heritage sites with no impact to their structure, diversifying the presented narratives and enhancing the visitor experience. They can also greatly aid conservators in disseminating information about conservation without the need for a conservator present, something that most other methods of public engagement with conservation rely heavily on. Raising awareness of conservation is essential to getting people involved in the shared stewardship of cultural heritage, where everyone feels a responsibility to its survival. Although long-term impact studies into the effects of conservation information on public perception are needed, this research contributes a vital step in that direction by demonstrating a means of disseminating the information and the early research required for a long-term impact study.

What these prototypes and other case studies demonstrate is that there are myriad creative and engaging ways to communicate conservation information. DWB, and other pest species, work well as introductory subjects that engage audiences of all ages.

7 FINAL CONCLUSIONS

The aim for this research was to better understand DWB behaviour on HMS *Victory* to inform conservation decisions and to test methods of communicating the research findings to the public to raise awareness of the issue. The three components of the aim were DWB tunnelling, non-invasive detection, and public engagement with conservation. This overall aim has been achieved. Significant contributions to the understanding of the DWB species have been made. Methods for further development with regards to the detection and monitoring of larval activity were identified, as was a short-term method of detection with stethoscopes that can be immediately implemented. The research demonstrated a means through which conservation research can be utilised and packaged into digital public engagement experiences for visitors with in-built flexibility of design to enable the museum to adapt it to its needs, and that such experiences and narratives would be positively received by visitors. The inclusion of such narratives is key to building a concept of shared stewardship of cultural heritage.

7.1 Deathwatch Beetle tunnelling

The investigations into DWB tunnelling through the use of micro-CT on a deck plank from HMS *Victory* has identified discernible trends. Tunnels predominantly follow the longitudinal fibres, are concentrated in regions of lower-density, fungally decayed wood, and make use of early-wood vessels in the formation of the tunnels, as these offer less physical resistance to the larval mandibles. Tunnels that branch away from these areas are likely following fungal decay that was not visible at the scanned resolution. This theory was further supported by the presence of fungal hyphae in wood vessels of the sounder wood in samples examined under SEM. The presence of fungal hyphae in the SEM images of the wood and frass, and fine cracks radiating out from DWB tunnels in higher resolution micro-CT scans adds evidence of a relationship between the two, and hints at a symbiotic relationship with regards to attack patterns. While the exact nature of the relationship between DWB and fungal decay remains unknown, this research has provided further evidence for

the relationship and suggests further investigations into DWB frass, and different woods infested by DWB to examine commonalities.

There is a correlation between the internal damage caused by the DWB larvae and surface damage, and the number of exit holes on external surfaces can be used to approximate the percentage of timber lost using a logarithmic model. This evidence corroborates the initial findings of Southwell (2017) and Brock *et al* (2024). Although the model would benefit from more data gathered from other timbers damaged by DWB from other sites to enable greater accuracy, it can be used by the *Victory* conservation team to provide estimates of wood lost with potential for use on other historic sites dealing with DWB infestations. This is particularly relevant for *Victory* during the current conservation work re-planking the outside of the ship. Timbers, such as those making up the frames, that are not usually visible, are being exposed, and the team can input the number of exit holes on external surfaces into the model formula to estimate the amount of wood lost, which will aid in making an informed decision on replacing timbers.

The presence of larvae and beetles in the tunnel structures of the deck plank samples revealed by the micro-CT images has provided the first concrete evidence of previously theorised behaviours and contributed some unique observations. Re-use of tunnels by both beetles and larvae was evidenced by their presence in frass-filled tunnels. This re-use of frass-filled tunnels suggests consumption of frass. In the case of the adult beetles, this would be especially surprising as they have never been observed to feed. It also raises questions regarding the nutritional value of the frass. Clusters of beetles around cracks in the wood samples demonstrate the exploitation of wood features for access. This, along with the re-use of tunnels and exterior surface exit hole count, suggest that the beetles were able to utilise internal cavities for mating and oviposition. Beetles located in cavities adjacent to an exit hole but facing away from the external surface are likely using the pre-existing pupation chambers to lay their eggs in a protected environment, supporting previous observations of the use of cracks, crevices and old exit holes for egg laying (Fisher, 1938; Hickin, 1975; Kimmins, 1933). Unfortunately, no eggs were identified in the

images, as their small size and similarity to the frass pellets made them indistinguishable. But the number of individuals present in the scanned samples strongly suggest their presence, which then raises the possibility of oviposition within frass as a means of camouflage and protection, contradicting previous findings where extracts from frass were found to be repellent to ovipositing beetles (Belmain, 1998). It is important to note, however, that all previous observations of DWB oviposition were limited to surface observations of small wood samples. If mating can take place within cavity spaces, as suggested by the re-use of tunnels and use of wood features, then so can oviposition, meaning that not all possible oviposition behaviour has been observed.

Examination of DWB tunnels and frass under SEM revealed that, in addition to the fungal hyphae and possible spores or yeast cells (Fisher & Parkin, 1930), the interior surfaces of the tunnels were ridged incrementally. The consistent spacing and size suggest bite marks, thereby supporting the hydrostatic pressure method the larvae use to eat (Brock et al., 2024: 92).

This study focused on the DWB infestation on HMS *Victory*. However, with climate change and rising temperatures, there is a possibility that heritage pests, like the DWB, whose activity is linked to temperature (Creemers, 2015), may become more widespread, increasing the active periods and the amount of activity. This is particularly concerning with regards to DWB flight, as they have been demonstrated to fly above 17°C (Belmain, 1998). With a greater increase in the number of days in which this threshold is reached, the greater the likelihood they are able to spread. For NMRN, this has already become an issue, as DWB have been found in the historic buildings neighbouring *Victory* (Davis personal communication, 2023). When investigations were being conducted by Fisher and others in the 1920s-1940s, there were no recorded cases of DWB infestation in Scotland (Fisher, 1940a; Parkin, 1933). At the time of writing, at least one infestation has been recorded (Thompson Webb, 2024), proving that this is a legitimate concern.

There is still much to be learned about the Deathwatch Beetle, but this research has made a valuable contribution towards the existing knowledge and has identified suitable areas for future research.

7.2 Non-invasive detection

This thesis investigated possible methods of larval detection within timbers that would be suitable for use on HMS *Victory* and provided the initial groundwork for NMRN should they wish to investigate further. Following an extensive literature review, bioacoustics, thermography and radiography methods were trialled on the ship and in laboratory settings. From the tests conducted, thermography was demonstrated to be unsuitable. Radiography was suitable for larval detection on a small-scale, but unsuitable on the scale required for the ship. It will continue to be used to monitor the development of the live culture at London Zoo. It is able to detect changes in density resulting from fungal decay in large timbers and may be suitable for mapping density changes across the ship to identify areas more at risk of infestation.

A stethoscope and accelerometer were the primary bioacoustic detection methods tested. Although there was a degree of subjectivity involved in the use of stethoscopes, the research demonstrated that stethoscopes are a low cost, easy-to-use, and immediately implementable means of detecting areas of larval activity on the ship. Not only is this beneficial to the NMRN conservation team, but other heritage sites, particularly those with limited budgets and no dedicated conservation teams, can easily make use of such devices. It can also serve as a simple means for getting the public involved in an aspect of conservation work. The NMRN public programming team has started to make use of stethoscopes with school groups of young children to listen for DWB larvae on *Victory* (Hargreaves and Vidal personal communication, 2023).

The accelerometer was able to detect the adult beetle tapping on the ship and in the laboratory setting. Potential larval sounds were identified in the laboratory setting, but at the time of recording, the presence of larvae within the wood was unknown. However, the potential larval sounds and the ease with which the device was able to detect the tapping means that the method is worth pursuing

further, particularly given the confirmed presence of larvae in the colony which would be able to provide a reference recording. Other investigations using similar sensors have had success detecting other woodboring species in plantations, historic sites, and other places with significant background noise, further suggesting suitability of use (Ashry et al., 2020; Biebl & Wapler, 2023; Bilski et al., 2017; Brandstetter & Hübner, 2015; Chesmore & Schofield, 2010; Krajewski et al., 2020; Mankin et al., 2011).

This method also has the potential to develop a long-term active monitoring method for the museum. Having a network across the ship of these small, non-obtrusive sensors to detect vibrations resulting from larval activity would enable the conservation team to pinpoint active areas for interventive treatment. More development and testing, along with specialist acoustic expertise would be required for such a system. Such a system is not without precedent, although applications have thus far been limited to stored agricultural products (Mankin et al., 2021). The bioacoustic detection of larval activity, based on this research, was expanded to a Master's thesis (Ngyen, forthcoming) during the latter part of this project. Further methods of acoustic detection were trialled, with laser doppler vibrometry, a completely contact-free, non-invasive method, showing the most potential.

Finally, it must be noted that there are wider applications for non-invasive detection beyond heritage conservation. The methods were adapted from agricultural use for heritage conservation but can also be applied to wildlife conservation. The use of a native British woodboring beetle notorious for its cryptid nature to develop successful non-invasive means of detection means that techniques and methods can be investigated and tested on a non-threatened species before being used to detect endangered species.

As a relatively young field of research, acoustic detection of pests has much potential. This study has provided a contribution towards the field by identifying methods suitable for use on *Victory* and doing preliminary investigations to determine which methods are worth pursuing in future.

7.3 Public engagement with conservation

The final investigative chapter of this thesis examined public engagement with conservation, by taking the data resulting from Chapters 4-5 and creating prototypes of visitor engagement experiences, with the aim of communicating conservation research and the work conservators do to manage infestations. Many considerations and requirements from the conservation and public programming teams were incorporated into the development of the experiences, ensuring an in-built flexibility to the design to make future changes and adaptations as necessary.

Two prototypes of visitor engagement experiences were created. The first experience (plank interactive) was designed to highlight the hidden nature of the damage caused by the DWB through a self-guided experience from a macroscopic view of the ship to a microscopic level of the beetles and larvae within the tunnels they create. For the prototype of this experience, two of the 'levels' were built: an interactive, annotated 3D model of the deck plank that linked to another 3D model of the tunnels containing beetles and larvae. These were created using the photogrammetry model of the plank and the micro-CT scans of the tunnels. The second experience (DWB conservation experience) intended to inform participants of the work conservators do to manage infestations like that of the DWB on *Victory*, and how research forms an integral part of this process. The prototype was a basic AR experience, where an animated 'conservator' guided participants through the information, making use of images, graphs and recordings from investigations into the tunnelling and non-invasive detection. Questionnaires were presented to participants after their interactions with the prototypes to gauge responses and gather feedback.

The questionnaires, containing a mix of multiple choice and open-ended questions, were analysed using a Grounded Theory approach, identifying themes from the responses. Seven distinct themes were identified, four of which emphasized the surprise of the visitors in response to the material presented, suggesting that the experience was novel and interesting, and that the prototypes were successful at communicating the information and raising

awareness of the DWB infestation on *Victory* and conservation more generally. Although further development to the experiences is required should NMRN decide to implement them, the feedback demonstrated that these narratives and experiences would be positively received additions to the visitor route on HMS *Victory*. These prototypes can serve as models for how conservation narratives could be incorporated into other historic sites.

The responses to the questionnaires also demonstrated that participants' interest in conservation is strongly linked to their interest in a specific site or context, and that they prefer the information packaged and presented to them, as opposed to seeking it out themselves. However, there was a distinction in responses from the self-guided Prototype 1 (plank interactive) and the guided Prototype 2 (DWB conservation experience). Feedback from Prototype 1 was more collaborative, with participants suggesting new methods to try, whereas feedback from Prototype 2 showed a greater interest in conservation more widely. With the concept of shared stewardship as a guiding principle, encouraging collaboration is key, but without garnering the initial interest, there will not be much of it. Therefore, a balance must be struck between the more familiar and sought out guided experiences, and the more collaboration-inducing self-guidance when implementing conservation narratives into heritage sites.

This research has also demonstrated that digital experiences are a powerful tool to incorporate conservation narratives into heritage sites, an area of research only just beginning to be explored. Digital approaches can enhance visitor experiences without any structural impact or the need for a conservator to be present, meaning they can be used on permanent basis, as opposed to the short-term engagement activities that usually predominate public engagement with conservation (See [Ch 3 Section 3.3](#)). The incorporation of conservation narratives to heritage sites on a permanent basis is a key component of raising awareness of the discipline and shifting public perception of heritage from seeing it as static to dynamic, which are integral to the concept of shared stewardship. As the user testing of the prototypes demonstrated, this

does not require extensive amounts of information. Small, self-contained experiences were sufficient to shift participants perspectives on *Victory* and its preservation.

The impact of raising awareness of heritage conservation more widely has the potential to be substantial. The budget, salary and staffing cuts of recent years are partly caused by a lack of awareness of the profession, within and without the heritage sector, by those in positions of resource allocation. Conservators are an incredibly caring, passionate group of people with tremendous skills and knowledge that deserve to be recognised for the work that they do.

Although long-term impact studies into the effects of conservation information on public perception are needed, this research contributes a vital step in that direction by demonstrating a means of disseminating the information and the early research required for a long-term impact study.

Deathwatch Beetles are a fascinating species and a troublesome pest to historic timber buildings. Much about them remains to be learned, but this thesis has contributed valuable information to our understanding of them, means through which they can be detected in timber, and how novel conservation research can be communicated to visitors and the wider public, aiding conservation efforts on HMS *Victory* and other historical sites.

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APPENDICES

Appendix A Ethics Certificate



2 December 2021

Dear Ms Harvey,

Reference: CURES/14870/2021

Title: Investigating the infestations: Understanding and communicating Deathwatch beetle activity on HMS Victory

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/14870/2021, has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your research.

Regards,

CURES Team

Appendix B Glossary of Terms

B.1 Naval terms used by The National Museum of the Royal Navy

Adaptation	The modification of a vessel to suit a proposed new use. Additions to the vessels such as new machinery, commodities or functional elements to serve a new purpose can be considered adaptations.
Aft	A directional term aboard a vessel. Refers to 'towards the stern' or after part of the vessel
Amidships	Reference to the midsection of a vessel, either longitudinally or laterally. It is often shortened to 'midships when referring to the lateral midsection
Apron	A strengthening timber found behind the lower section of stem and above the foremost portion of the keel
Beakhead	A projection or platform forward of the forecastle
Bilge	The area of a vessel's lower hull on which it would have rested, generally, the outer ends of the floor
Bobstay	One of the timbers composing the knee of the head
Bow	The foremost portion of a vessel, opposite of the stern
Bowsprit	A large spar which projects from the bow of a vessel to act as a means to staying a fore-topmast and from which the jibs were set
Breast hook	A large horizontal knee situated at the bow of a vessel at the junction of the sides of the hull and the stem. The breast hook provides structural reinforcement to the junction of the sides of the hull to the stem
Bulwark	The sides of a vessel that stand above the upper deck
Cant frames	Angled frames that are located in the bow and stern of a vessel. The name derives from the obvious 'cant' that the frames are situated at
Capstan	A vertical cylindrical structure mounted on a spindle and bearing used for moving heavy loads, such as hoisting anchors or lifting yards. It was operated by turning levers and bars inserted into the main body of the capstan
Carlings	Square support timbers for deck planking, situated perpendicularly between the deck beams
Ceiling	Planking situated inboard of the frames, providing an interior protective layer inside the hold of a vessel
Chock	An angular wedge used to fill gaps between timbers or to separate them
Clamps	A thick ceiling strake or similar timber used to support deck beams
Conservation	Refers to all the processes of maintaining a vessel in order to sustain its significance
Crutch	A curved timber similar to a breast hook used as reinforcement in the

	lower portion of the stern and stem
Cutwater	The forward-most section of the vessel that parts the water
Dagger knee	A vertical knee set at an angle on the inside of the hull
Deadrise	A measurement of elevation of the floor above the horizontal plane. In practice this illustrates the difference between the height of the bilge and the height of the keel rabbet.
Deadwood	A section of timber or timbers situated in the stern (and sometimes bow) section of a vessel directly above the keel. Both sections of deadwood are firmly affixed to the keel to provide additional stability to the vessel
Deck	Horizontal platform on a vessel, likened to a floor in a house. Numerous terms exist for specific decks in reference to their location and function within a vessel
Deck beam (beam)	A transverse timber that provides lateral strength and deck support
Fabric	The material components of a vessel, including but not limited to, structural elements and fixtures
Floor	The lowest portion of transverse framing which extends across the keel onto both sides of the vessel
Forecastle	A short raised deck situated foremost in a vessel. Also refers to the quarters below the foredeck.
Foremast	Forward-most mast
Frame	A transverse timber that forms the basis for the shape of the hull. Frames create the basic 'skeleton' for which the ship is built upon. Conceptually frames can be regarded as the ribs of a vessel. A single frame can be made up of several timbers (see futtock). Planking and ceiling are attached directly to frames
Futtocks	A single timber in a frame. Several futtocks, combined with a floor, are used to make a frame
Garboard	The strake of planking immediately adjacent to the keel
Gundeck	The deck on a naval vessel that carried the guns. On large vessels there could be several gun decks. In this case the gundecks would be referred to in regards to their vertical placement (e.g. upper, middle, and lower gundecks)
Hanging knee	A knee that is situated on a vertical plane which reinforces the junction of a beam and the side of the hull
Hawse hole	A round hole in the bow of a vessel through which the anchor cable passed
Hawse hook	Typically the highest breast hook in the bow, situated above the upper foredeck
Headrails	Curved rails that which extended from the bow to the knee of the head
Hull	The watertight body of a vessel

Keel	The main longitudinal timber that forms the backbone of a vessel. In larger vessels, the keel is often composite and made of more than one timber.
Keelson	An internal longitudinal timber that mirrors the keel. The keelson was mounted on top of the floors centred along the keel.
Knee	An angular timber that reinforced the junction of two surfaces. Several different types of knees were used aboard a vessel.
Knee of the head (head knee)	A composite structure forward of the stempost that forms the cutwater at its lower end and supports headrails and figure head at its top end
Ledges	A short transverse beam that provides additional deck support
Lodging knee	A knee that is situated on a horizontal plane which reinforces the junction of two perpendicular beams, or the junction of the beam and the side of the hull
Maintenance	Continuous protective treatment and management of the fabric of a vessel
Mast	A vertical timber on which yards and rigging elements were located and operated
Mizzen mast	Aft most mast, smaller than the main and foremast
Main mast	Central and largest of the masts on a three-mast vessel
Planking	The outer strakes that form the side of the hull. Plank refers to the single line of strakes along the hull
Orlop deck	The lowest deck of a ship
Poopdeck	A shortened deck on the aft section of a vessel. The highest and aftermost deck of a vessel
Preservation	Keeping the fabric of a vessel in its current state and preventing further degradation
Quarterdeck	The section of the upper deck which is aft of the mainmast
Rabbet	A groove or notch made into a timber to allow the fitting of an additional timber in such a way to make a solid joint. Most often the term is used in reference to the grooves cut along the keel to allow the fitting of the garboard strake.
Reconstruction	Returning the fabric or part of a vessel to a previously known state utilising new materials
Replication	New construction of a vessel from scratch; the creation of a copy from new materials
Restoration	Returning the fabric or part of a vessel to its original or earlier state, by removing later additions or re-assembly of original pieces with as little new material as possible
Ribbands	Long flexible wooden strips used to temporarily describe/illustrate the lines of a vessel by tacking them to the frames during construction
Rider	An internal frame that was fastened on top of the ceiling for additional structural support

Rudder	The main steering device of a vessel. A structure of composite timbers situated directly aft of and connected to the stempost
Scarph	An overlapping joint used to connect two timbers together. Scarphs are common on a number of ship components including frames, planks, and keels, among others
Scupper	A channel cut into a vessel's side in order to drain water off the deck
Setting	The surroundings or location that a static vessel exists in currently, including its visual context
Significance	Refers to the sum of the cultural value of a vessel. Significance may relate to several different areas of value including aesthetic, historic, scientific, political, social, cultural, and spiritual
Spirketting	Thickened interior longitudinal planks situated directly above the waterways which provide additional structural reinforcement
Stanchion	A vertical supporting post
Standard (standing) knee	A knee that is mounted vertically on a deck, most commonly used to reinforce the junction between the deck and the side of the hull
Statement of Significance	A formal document which outlines the heritage value of a vessel
Stern	The aftermost end of the vessel
Sternpost	A vertical timber, located on the lateral plane, scarphed to the after end of the keel
Stempost (stem)	A vertical timber, centrally located on the lateral plane, scarphed to the forward end of the keel
Strakes	A continuous line of planking, running from stem to stern
Taffrail	The uppermost part of the stern or rail at the top of the stern
Treenails	A round or multi-sided piece of hardwood driven through planks and timber to connect them like a wooden nail
Tumblehome	The inward curvature of a vessel's upper sides as they rise from maximum breadth to the bulwarks. Tumblehome was an important design element of vessels as it greatly improved the stability of the vessel.
Upper Deck (main)	The topmost complete deck (running from stern to stern) of a vessel
Vessel	A boat or ship
Wales (harpins)	A thick strake of planking, situated along the side of the hull to reinforce and strengthen the vessel
Waterways	A timber along the edge of the deck which diverted water to the scuppers rather than allow it to seep between frames

Taken from *Victory Conservation Management Plan* (2016)

B.2 Wood Features and Anatomy

Bark	A non-technical term used to cover all the tissues outside the xylem cylinder. In older trees usually divisible into inner (living) and outer (dead)
Cambium	The actively dividing layer of cells that lies between and gives rise to, secondary xylem and phloem (vascular cambium)
Cell	A chamber or compartment at some time containing a protoplast. Cells form the structural units of plant tissues
Cell wall	The limiting membrane of a cell. In mature cells it consists of several superimposed walls as follows: primary, secondary, tertiary
Element	A general term used for an individual cell. Used in wood anatomy, particularly to distinguish between vessels and the individual cells of which they are composed – the vessel elements or vessel members
Epidermis	The outermost layer of cells on the primary plant body. Often with strongly thickened and cuticularized outer walls. Sometimes consisting of more than one layer of cells
Epithelium	The layer of secretory parenchymatous cells that surrounds an intercellular canal or cavity
Fibre	A general term of convenience in wood anatomy for any long, narrow cell of wood or bast other than vessels and parenchyma. Often further qualified as wood fibres or bast fibres. The former including both the tracheids of gymnosperms and the libriform wood fibres and fibre-tracheids of woody angiosperms. Also used loosely for wood elements in general
Fibril	A thread-like component of cell walls, visible under an optical or light microscope. This term, used without qualification to the microfibril as opposed to the ultrastructural microfibril
Growth layer	A layer of wood or bark produced apparently during one growing period. Frequently, especially in woods of the temperate zones, divisible into early and late wood or bark.
Heartwood	The inner layers of wood which, in the growing tree, have ceased to contain living cells and in which the reserve materials (e.g. starch) have been removed or converted into heartwood substances. It is generally darker in colour than sapwood, though not always clearly differentiated
Intercellular Canal	A tubular intercellular space of indeterminate length, generally serving as a repository for resin, gum, etc., secreted by the epithelium. May be (a) axial, or (b) radial (within a ray)
Lamella	In wood anatomy, a term of convenience for the compound layer between the secondary walls of adjacent cells, consisting of two primary cell walls and an intercellular layer of varying thickness
Lumen	The cell cavity
Parenchyma	Tissue composed of cells that are typically brick-shaped or isodiametric and have simple pits. Formed in wood from (a) fusiform cambial initials by later transverse divisions of the daughter cells

	(axial parenchyma), or (b) ray initials (ray or radial parenchyma). Primarily concerned with the storage and distribution of food materials. Termed wood parenchyma or xylem parenchyma if occurring in the xylem, and phloem parenchyma if in the phloem
Phloem	The principal food-conducting tissue of the vascular plants. It occurs both as primary and secondary tissue, and is usually, but not invariably, associated with xylem. In the stems of most gymnosperms and dicotyledons, the secondary phloem is separated from the secondary xylem by the cambium from which it is derived. The basic types of cells of which it is composed are sieve elements, parenchyma cells, fibres and sclereids
Pit	A recess in the secondary wall of a cell, together with its external closing membrane. They open internally to the lumen. Essential components are the pit cavity and the pit membrane. The following terms are used in describing pits: blind, bordered, cupressoid, fenestriform, half-bordered, linear, piceoid, pinoid, ramiform, simple, taxodioid, vestured, window-like
Pith	The central core of a stem, consisting chiefly of parenchyma or soft tissue
Pore	A term of convenience for the cross section of a vessel or of a vascular tracheid
Ray	A ribbon-like aggregate of cells extending radially in the xylem and phloem. Ray tissue can be heterogenous or homogenous. Aggregate rays are a group of small, narrow, xylem rays that appear to the naked eye or at low magnification as a single large ray. Primary rays originate in the primary tissue and are extended by cambial growth. Term also used for any ray that can be traced inwards to the pith. Secondary rays derive from the cambium but do not extend inwards as far as the pith. Uniseriate rays are one cell wide as seen in a tangential section
Resin canal	An intercellular canal containing resin
Ring, annual	In wood and bark, a growth layer of one year as seen in cross section
Ring boundary	The outer limit of a growth ring
Sapwood	The portion of the wood that in the living tree contains living cells and reserve materials (e.g. starch)
Sclereid	A strengthening element that is not markedly prosenchymatous, but which has thick, often lignified secondary walls and which commonly lacks a protoplast when mature. Vary in shape from polyhedral to somewhat elongated and are often branched. The type commonly found in wood and bark is the brachysclereid or stone cell. Such cells are often described as sclerotic
Trachea	Vessel
Tracheary elements	The principal water conducting elements of the xylem, mostly vessel members and tracheids. In primary xylem the tracheary elements may have only annular, spiral or reticulate thickenings and no pits
Tracheid	An imperforate wood cell with bordered pits to congeneric elements

Vessel	An axial series of cells that have coalesced to form an articulated tube-like structure of indeterminate length. The pits to congeneric elements are bordered
Wood	The principal strengthening and water-conducting tissue of stems and roots. Characterised by the presence of tracheary elements
Wood, diffuse-porous	Wood in which the pores are of fairly uniform or only gradually changing size and distribution throughout a growth ring
Wood, early	Also called spring wood.
Wood, late	Also called summer wood
Wood, ring-porous	Wood in which the pores of the early wood are distinctly larger than those of the late wood and form a well-defined zone or ring
Wood, semi-ring-porous	Wood in which the early wood is marked by a zone of (a) occasional large vessels, or (b) numerous small vessels
Xylem	Transport water
Taken from (Chalk et al., 1964)	

B.3 Beetle Anatomy and Morphology

Abdomen	Hindermost principal division of the body
Abdominal ventrites	Visible sclerite, or plate, covering the ventrum on the abdomen
Alutaceous	Covered with minute cracks
Antenna	A long, thin organ, usually a pair, found on the head of insects that are used to feel with
Apex, apical	In the coleoptera all the parts of the body are described in relation to an imaginary central point, between the thorax and elytra; the part nearest this is the base, the part furthest from it is the apex
Asperate	Rough or uneven
Basal	Forming the bottom layer of something
Chitin	Hard substance in the outer shell of insects
Ciliate	Furnished with cilia or fringes of hair
Compound eye	Eye that is made up of numerous separate visual receptors called ommatidia, each containing an lens and light-sensitive cells
Coxa	First, basal section of the leg
Crenulate	Furnished with a series of small blunt teeth
Dentate	Toothed
Diapause	Period when growth slows or stops as a result of a change in environmental conditions, e.g. a drop in temperature
Dorsal	Relating to the dorsum
Elytra	Singular: elytron. Hardened forewing modified to act as a protective wingcase for the hind wing in most beetles
Elytral epipleuron	Outer, downward-folding edge of an elytron
Elytral suture	Sean of rigid join between the elytra
Exoskeleton	The external skeleton
Femur	Third, and usually largest section of an insect's leg
Fusiform	Broadest in the middle, and gradually tapering front and behind
Humerus	Outer basal angle of the forewing, or elytron
Instar	Stage between moults of the larva; the first instar is the stage between the egg and first moult.
Labium	Lower 'lip' of an insect's mouth
Labrum	Upper 'lip' of an insect's mouth
Lateral	Pertaining to the side
Mandible	Paired biting jaws of an insect, often modified depending on the food favoured by the species They are also used in attacking and defensive behaviours

Margin	The outer edge
Maxilla	Paired structure below mandibles, used to hold and manipulate food during chewing
Mentum	Basal part of the labium
Oviposit	Lay eggs
Pheromone	Chemical substance secreted by an organism that influences the behaviour of other members of the species, e.g. used to attract a mate
Pores	Large, isolated punctures
Prosternal process	Ventral plate of the prothorax
Prothorax	The anterior of the three segments that make up the thorax, to which the first pair of legs is attached
Pubescent	Finished with fine hairs
Puncture	A small depression on the surface, usually round
Saproxyllic	Dependent on dead or decaying wood
Scarabaeiform larva	Somewhat resembling the larva of a beetle in the superfamily Scarabaeoidea, i.e. a thick-bodied, C-shaped larva with well-developed legs and head
Scutellum	The small triangular piece between the elytra, at base of suture
Setae	Outstanding bristles. Appear hairlike
Striae	An impressed line
Tarsomeres	An article of the tarsus. Beetle tarsi usually have one to five tarsomeres
Tarsus	Fifth segment of an insect's leg
Thorax	The middle part of the body, between the abdomen and the head
Trochanter	Second section of the leg, between the coxa and the femur
Tubercle	A small abrupt elevation of varying form
Vertex	Middle of head
Ventrum	In a beetle, its lower surface
Xylophagus	Eats woods

From Bouchard (2014) and Joy (1976)

Beetle Morphology

Coleoptera

Abdomen

Thorax

Head

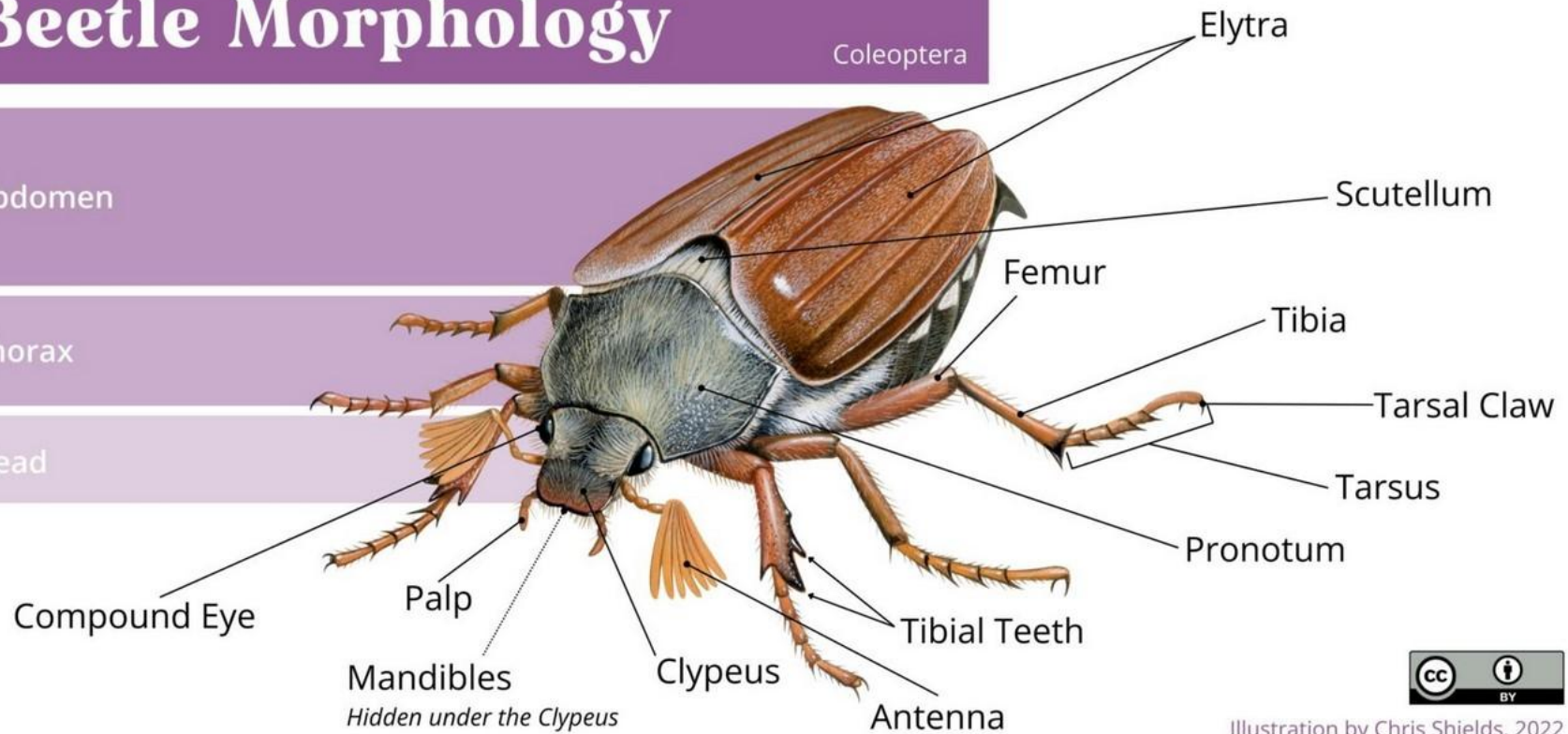


Illustration by Chris Shields, 2022

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Fig B1: Beetle morphology and anatomy diagram. Image from Shields (2022)

Appendix C Supplementary information for Chapter 4

C.1 Fungal Decay Comparisons (brown and white rot)



Fig C2(a) and (b): (a- left) Characteristic brown rot cubical fractures on timber from McCaig and Ridout 2012: 186. (b- right) Brown rot cubical fractures on sample A1A



Fig C3(a) and (b): (a- above) Characteristic white rot decay on timber. The timber is spongy and lightweight, and often 'stringy'. From Goodell et al 2020: 8. (b-below) White rot fungus on the plank prior to cutting

C.2 Deathwatch Beetle Exit Holes on plank



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C.3 Statistical Analysis and Residual Plots for Fig. 40

C.3.1 Statistical Analysis: % lost (original volume-wood vol versus Exit Hole count)

EXITHOLERELATIONSHIP

*Regression Analysis: % lost (original volume-wood vo versus Exit Hole)

The regression equation is

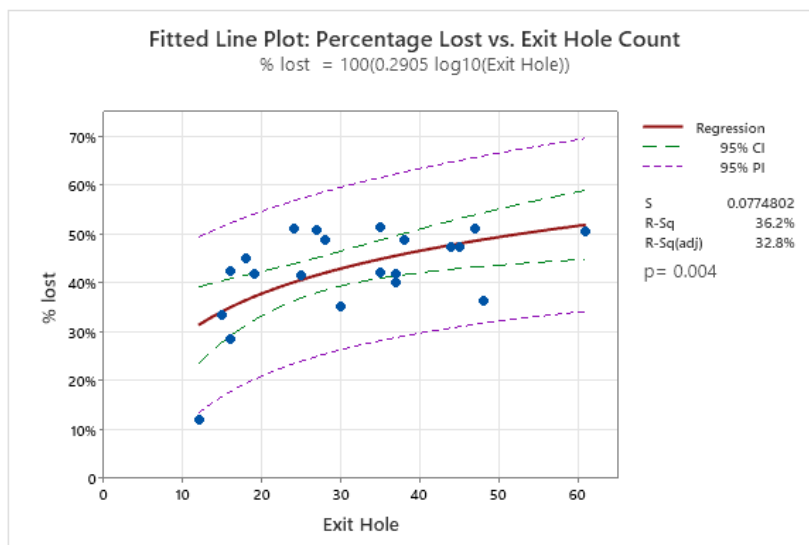
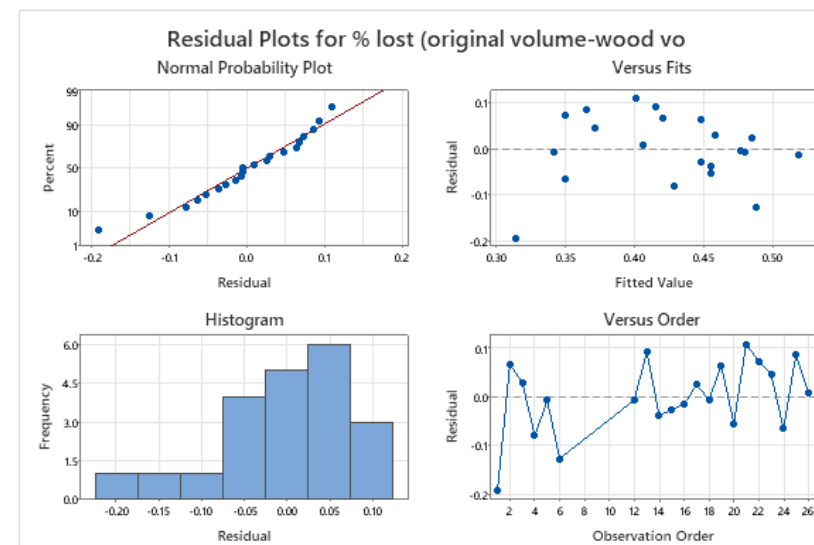
% lost (original volume-wood vo = 0.0000 + 0.2905 log10(Exit Hole)

Model Summary

S	R-sq	R-sq(adj)
0.0774802	36.15%	32.79%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.064584	0.0645836	10.76	0.004
Error	19	0.114061	0.0060032		
Total	20	0.178644			



Regression Analysis Residual Plots

T-Test

EXITHOLERELATIONSHIP

One-Sample T: Tunnel % of total Vol., % lost (original volume-wood vo, Exit Hole)

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean	95% CI for μ
Tunnel % of total Vol.	26	0.2471	0.0930	0.0182	(0.2095, 0.2846)
% lost (original volume-wood vo	24	0.4321	0.0974	0.0199	(0.3910, 0.4732)
Exit Hole	21	31.29	13.14	2.87	(25.31, 37.27)

μ : population mean of Tunnel % of total Vol., % lost (original volume-wood vo, Exit Hole

Test

Null hypothesis $H_0: \mu = 0$

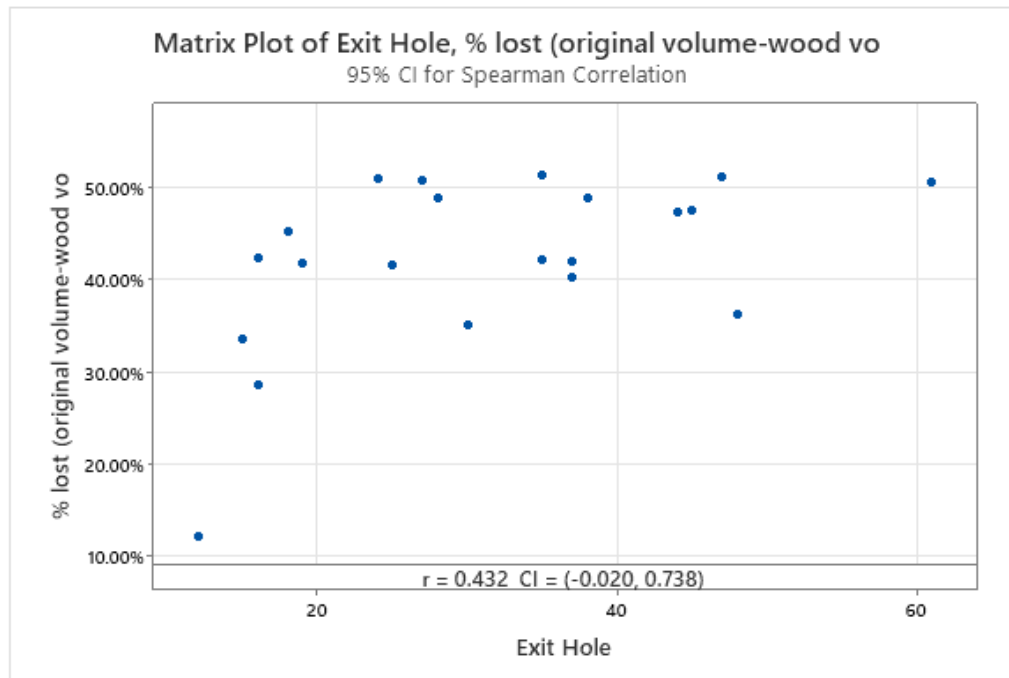
Alternative hypothesis $H_1: \mu \neq 0$

Sample	T-Value	P-Value
Tunnel % of total Vol.	13.54	0.000
% lost (original volume-wood vo	21.73	0.000
Exit Hole	10.91	0.000

Correlation

EXITHOLERELATIONSHIP

Correlation: Exit Hole, % lost (original volume-wood vo



Method

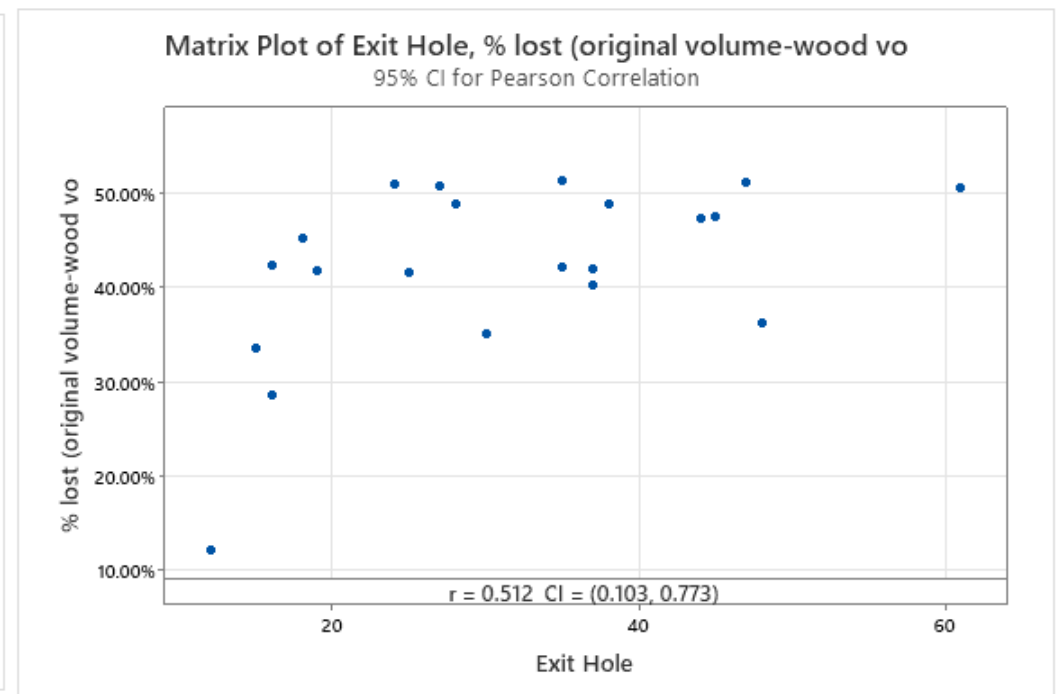
Correlation type Spearman
Number of rows used 21

Correlations

	Exit Hole
% lost (original volume-wood vo	0.432

EXITHOLERELATIONSHIP

Correlation: Exit Hole, % lost (original volume-wood vo



Method

Correlation type Pearson
Number of rows used 21

Correlations

	Exit Hole
% lost (original volume-wood vo	0.512

C.3.2 Statistical Analysis: Tunnel % of total Vol. versus Exit Hole

Regression Analysis

EXITHOLERELATIONSHIP

*Regression Analysis: Tunnel % of total Vol. versus Exit Hole

The regression equation is

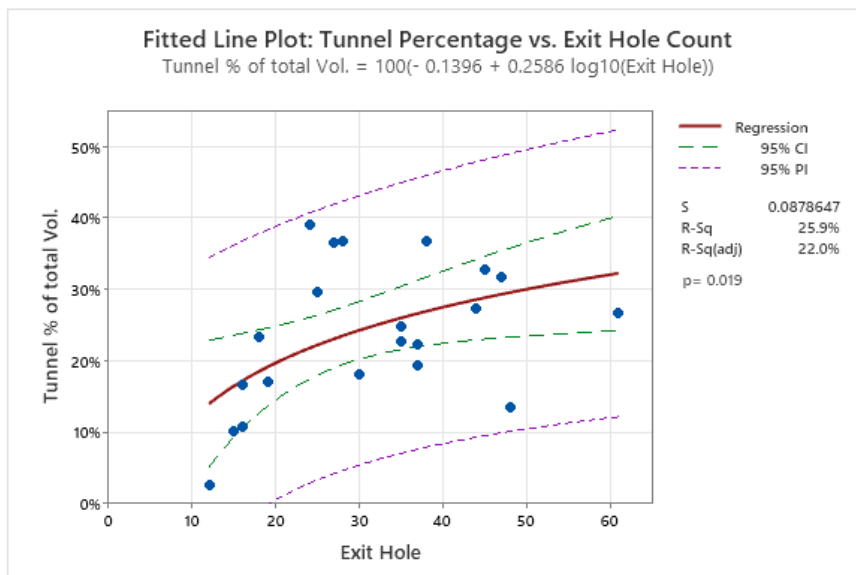
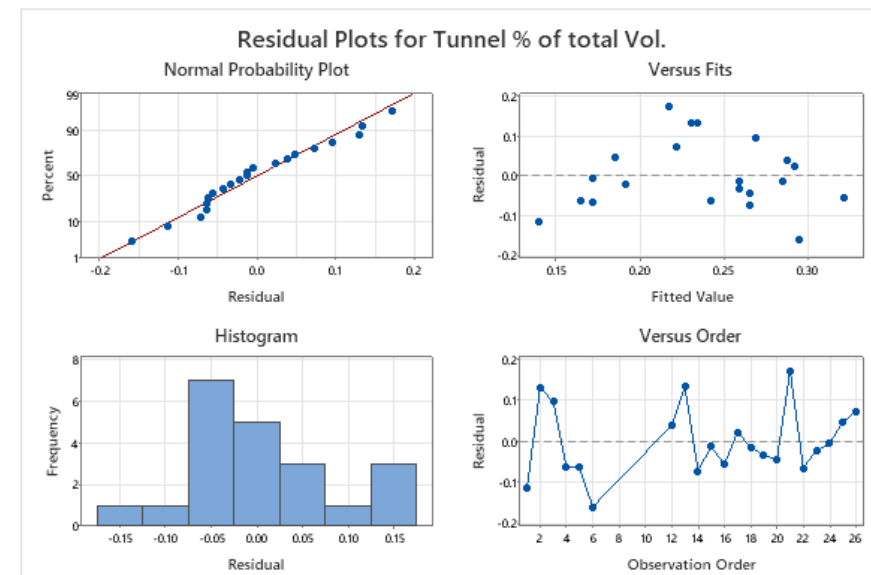
Tunnel % of total Vol. = - 0.1396 + 0.2586 log10(Exit Hole)

Model Summary

S	R-sq	R-sq(adj)
0.0878647	25.86%	21.95%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.051152	0.0511518	6.63	0.019
Error	19	0.146684	0.0077202		
Total	20	0.197836			



T-Test

EXITHOLERELATIONSHIP

One-Sample T: Tunnel % of total Vol., % lost (original volume-wood vo, Exit Hole)

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean	95% CI for μ
Tunnel % of total Vol.	26	0.2471	0.0930	0.0182	(0.2095, 0.2846)
% lost (original volume-wood vo	24	0.4321	0.0974	0.0199	(0.3910, 0.4732)
Exit Hole	21	31.29	13.14	2.87	(25.31, 37.27)

μ : population mean of Tunnel % of total Vol., % lost (original volume-wood vo, Exit Hole

Test

Null hypothesis $H_0: \mu = 0$

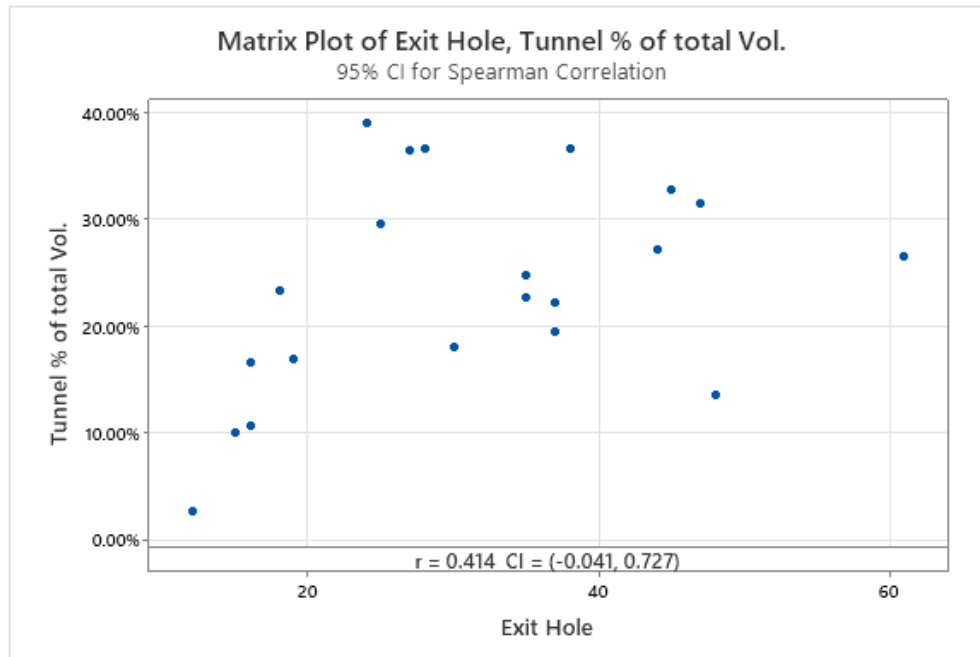
Alternative hypothesis $H_1: \mu \neq 0$

Sample	T-Value	P-Value
Tunnel % of total Vol.	13.54	0.000
% lost (original volume-wood vo	21.73	0.000
Exit Hole	10.91	0.000

Correlation

EXITHOLERELATIONSHIP

Correlation: Exit Hole, Tunnel % of total Vol.



Method

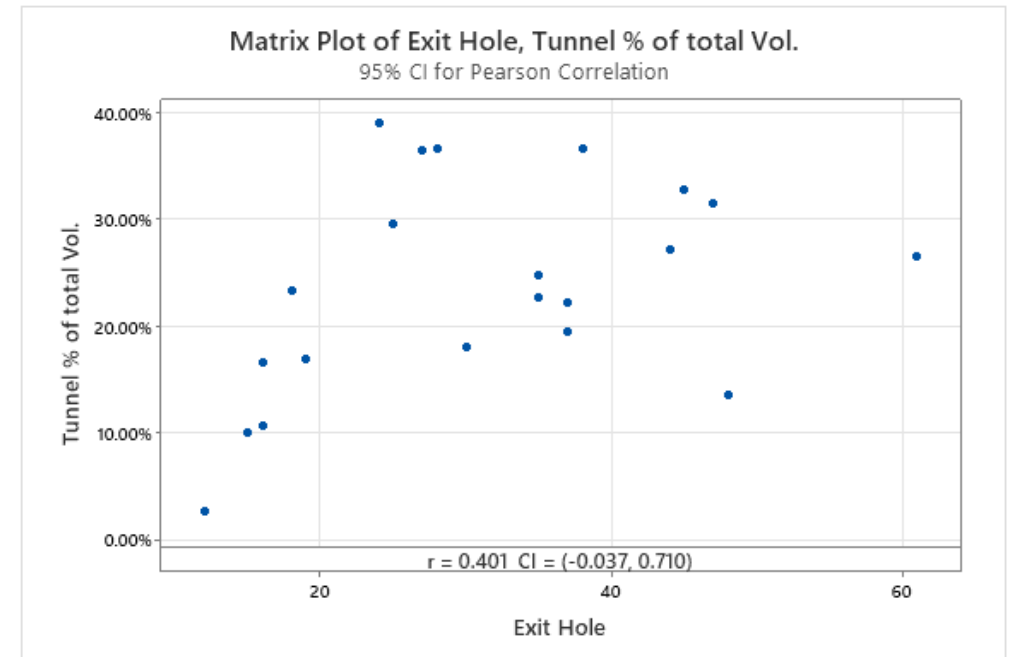
Correlation type Spearman
Number of rows used 21

Correlations

	Exit Hole
Tunnel % of total Vol.	0.414

EXITHOLERELATIONSHIP

Correlation: Exit Hole, Tunnel % of total Vol.



Method

Correlation type Pearson
Number of rows used 21

Correlations

	Exit Hole
Tunnel % of total Vol.	0.401

C.4 Spreadsheet of tunnel volume and calculations of amount lost

Sample	Exit Hole #	Estimated Original Volume (mm3)	Total Sample Vol (wood+tunnels mm3)	Wood Volume (mm3)	Approx. Tunnel Volume (mm3)	Tunnel % of total Vol.	Tunnel % of wood vol	% Lost (original vol-total sample vol)	% lost (original volume-wood vol)	Beetle #	Larvae #	Pupae #
F1A	12	668091.22	602821.80	586884.22	15937.59	3%	3%	10%	12%	2	1	0
F4C	49	568450.70								1	0	0
F6B	28	490476.14	396000.00	251000.00	145000.00	37%	58%	19%	49%	1	1	0
F7B	38	669270.87	597000.00	383000.00	214000.00	36%	56%	11%	43%	0	8	0
F8B	30	834559.40	661000.00	542000.00	119000.00	18%	22%	21%	35%	3	1	0
F9A	15	601659.66	444800.00	400000.00	44800.00	10%	11%	26%	34%	0	1	0
F10C	48	652360.92	481081.37	415781.37	65300.00	14%	16%	26%	36%	0	2	0
F13D			178785.05	115985.05	62800.00	35%	54%			2	2	0
CF1D			285200.00	195000.00	90200.00	32%	46%			0	6	0
CF2D		264864.81	229700.00	168000.00	61700.00	27%	37%	13%	37%	1	5	0
CF3D		378568.53	221800.00	165000.00	56800.00	26%	34%	41%	56%	1	2	0
CF5D		543642.88	323200.00	240000.00	83200.00	26%	35%	41%	56%	4	4	0
CF6B	45	441585.72	345000.00	232000.00	113000.00	33%	49%	22%	47%	1	1	0
CF11B	27	504650.60	390000.00	248000.00	142000.00	36%	57%	23%	51%	2	3	0
CF12B	37	615129.42	492000.00	357000.00	135000.00	27%	38%	20%	42%	2	2	0
CF13B	35	479044.94	368200.00	277000.00	91200.00	25%	33%	23%	42%	2	0	0
CA1C	61	701869.41	473544.58	347544.58	126000.00	27%	36%	33%	50%	2	2	0
CA2C	47	718184.13	513101.60	351050.80	162050.80	32%	46%	29%	51%	7	1	0
CA6B	44	781620.91	612000.00	412000.00	200000.00	33%	49%	22%	47%	7	0	0
CA7B	35	633131.21	398100.00	308000.00	90100.00	23%	29%	37%	51%	2	3	0
CA8B	37	714427.45	549000.00	427000.00	122000.00	22%	29%	23%	40%	4	2	0
CA11A	24	685531.32	551000.00	336000.00	215000.00	39%	64%	20%	51%	1	0	1

A4A	16	651337.28	424229.05	379000.00	45229.05	11%	12%	35%	42%	1	1	0
A6A	19	571196.84	426583.00	332183.00	94400.00	22%	28%	25%	42%	0	2	0
A8A	16	622979.60	533364.48	444520.57	88843.91	17%	20%	14%	29%	2	7	0
A9A	18	561537.85	401600.00	308000.00	93600.00	23%	30%	28%	45%	2	3	0
A10A	25	538527.89	445967.14	314260.48	131706.66	30%	42%	17%	42%	4	5	0

C.5 Spreadsheet of Beetle, Larvae, and Tunnel measurements (mm)

Sample	Individuals	Length1	Length2	AH Length	Mean Length	Width1	Width 2	AH Width	Mean Width	Tunnel ø1	Tunnel ø 2	AH Tunnel ø	Mean Tunnel ø
A6A	Larva1	5.80	5.77		5.78	2.43	2.09		2.26	2.91	2.97		2.94
-	Larva2	2.61	2.60		2.60	1.08	1.02		1.05	1.79	1.74		1.77
A4A	Larva1	2.05	2.15		2.10	1.07	1.06		1.06	1.97	1.74		1.86
-	Beetle1	3.75	3.97		3.86	1.21	1.55		1.38	1.84	1.76		1.80
A8A	Larva1	3.40	3.40		3.40	1.60	1.58		1.59	2.68	2.67		2.68
-	Larva2	2.09	2.16		2.13	0.88	0.89		0.89	1.60	1.33		1.46
-	Larva3	3.22	3.22		3.22	1.30	1.36		1.33	1.52	1.55		1.54
-	Larva4	1.86	1.86		1.86	0.60	0.62		0.61	0.98	0.89		0.93
-	Larva5	2.11	2.11		2.11	0.83	0.76		0.79	1.19	1.24		1.21
-	Larva6	2.11	2.11		2.11	0.67	0.59		0.63	1.02	1.03		1.03
-	Larva7	1.92	1.92		1.92	0.64	0.65		0.65	0.91	1.14		1.02
-	Beetle1(?)	-					-			3.40	-		3.40
-	Beetle2(?)	2.72	2.74		2.73	1.46	1.44		1.45	2.92	2.78		2.85
A9A	Larva1	3.99	4.09		4.04	2.34	2.07		2.21	2.25	3.64		2.95
-	Larva2	4.95	4.89		4.92	2.19	1.86		2.02	2.67	2.41		2.54
	Larva3		1.30		1.30		0.63		0.63		0.71		0.71
-	Beetle1	5.91	5.66		5.78	2.86	2.89		2.88	3.64	3.82		3.73
-	Beetle2	5.26	5.50		5.38	2.24	2.40		2.32	3.19	3.00		3.09
A10A	Larva1	5.07	4.98		5.03	2.52	2.26		2.39	3.11	3.68		3.40
-	Larva2	4.57	5.05		4.81	2.11	2.20		2.16	2.90	2.87		2.89
-	Larva3	3.36	3.54		3.45	2.18	2.02		2.10	3.43	3.20		3.32
-	Larva4	4.11	4.07		4.09	1.47	1.44		1.46	2.39	2.53		2.46
	Larva5		2.39		2.39		0.82		0.82		1.61		1.61
-	Beetle1	5.54	5.53		5.53	2.39	2.28		2.33	3.48	3.91		3.69
-	Beetle2	8.18	8.00		8.09	2.80	3.07		2.93	3.47	3.48		3.47

	Beetle3		5.16		5.16		2.36		2.36		3.41		3.41
	Beetle4		5.75		5.75		1.97		1.97		4.68		4.68
CA1C	Larva1	4.38	4.36		4.37	1.25	1.31		1.28	2.22	2.60		2.41
-	Larva2	2.32	2.52		2.42	1.23	1.37		1.30	1.14	-		1.14
-	Beetle1	5.77	5.84		5.81	2.74	2.78		2.76	3.32	3.42		3.37
	Beetle2		5.02		5.02		2.03		2.03				
CA2C	Larva1	5.41	5.32	5.12	5.28	2.39	2.38	2.40	2.39	3.38	3.53	3.28	3.40
-	Beetle1	5.68	5.50	5.81	5.66	2.58	2.60	2.47	2.55	3.39	3.56	2.47	3.14
-	Beetle2	6.45	6.31	6.51	6.42	3.01	2.91	3.27	3.06	3.88	4.02	3.83	3.91
-	Beetle3	6.65	6.91	6.72	6.76	2.72	3.11	3.00	2.94	4.05	4.98	4.51	4.52
-	Beetle4	5.87	6.06	5.86	5.93	2.35	2.55	2.56	2.49	2.93	2.99	3.16	3.03
-	Beetle5	5.16	5.41	6.01	5.53	2.20	2.76	3.23	2.73	3.05	3.14	3.37	3.19
-	Beetle6	6.34	6.20	6.26	6.27	2.46	2.40	2.58	2.48	3.30	3.19	3.57	3.35
	Beetle7		7.46	7.32	7.39		3.10	3.39	3.25		3.92	4.10	4.01
CA6B	Beetle1	5.11	5.22	5.48	5.27	2.26	2.40	2.24	2.30	3.14	3.22	2.61	2.99
-	Beetle2	5.04	5.51	5.05	5.20	2.67	2.49	2.60	2.59	3.27	3.52	3.96	3.58
-	Beetle3	5.62	5.20	5.17	5.33	2.38	4.44	2.47	3.10	3.55	3.73	3.57	3.62
-	Beetle4	5.94	5.74	6.50	6.06	2.42	2.29	2.69	2.46	3.58	2.43	2.46	2.83
-	Beetle5		-				-			3.48	-		3.48
-	Beetle6	5.46	5.57	5.52	5.52	2.31	2.61	2.48	2.46	3.05	3.13	3.13	3.10
	Beetle7		5.83	5.62	5.72		2.33	2.09	2.21		3.59	3.22	3.40
CA7B	Larva1	3.55	3.60	4.47	3.87	1.26	1.23	1.31	1.27	2.08	2.08	2.22	2.13
-	Larva2	4.35	4.31	4.39	4.35	1.77	1.82	1.97	1.85	2.56	2.32	2.78	2.55
-	Larva3	3.21	3.63	4.30	3.71	1.62	1.58	1.75	1.65	2.72	2.54	2.62	2.63
-	Beetle1	5.14	5.23	5.09	5.15	2.47	2.34	2.42	2.41	3.27	3.23	1.81	2.77
-	Beetle2	4.56	5.15	4.58	4.77	2.82	3.27	2.34	2.81	3.13	2.93	3.09	3.05
CA8B	Larva1	3.04	3.04		3.04	1.28	1.18		1.23	2.82	3.23		3.02

	Larva2		2.62		2.62		0.88		0.88		1.36		1.36
-	Beetle1									3.67			3.67
-	Beetle2	4.95	5.14		5.04	2.26	2.26		2.26	3.03	2.69		2.86
-	Beetle3	5.78	-		5.78	2.20	-		2.20	3.83	-		3.83
-	Beetle4	4.95	4.95		4.95	2.28	2.12		2.20	3.31	3.23		3.27
CA11A	Pupa(?)	6.46	6.62		6.54	2.57	2.50		2.54	3.79	4.06		3.93
-	Beetle1?						-				-		
CF1D	Larva1	2.58	3.47		3.03	1.21	1.39		1.30	1.80	1.72		1.76
-	Larva2	3.30	3.97		3.63	1.16	2.22		1.69	1.56	2.84		2.20
-	Larva3	1.89	3.12		2.50	0.91	1.09		1.00	1.33	1.57		1.45
-	Larva4	4.21	4.25		4.23	1.64	1.43		1.53	2.16	2.96		2.56
	Larva5		1.72		1.72		1.10		1.10		1.08		1.08
-	Larva6		2.99		2.99		1.36		1.36		2.65		2.65
CF2D	Larva1	5.50	5.56		5.53	2.03	2.18		2.10	3.00	3.12		3.06
-	Larva2	6.75	6.67		6.71	2.38	2.64		2.51	3.65	3.57		3.61
-	Larva3	3.41	3.77		3.59	1.47	1.70		1.58	2.04	2.47		2.26
	Larva4	2.76	2.85		2.80	1.51	1.90		1.71	3.52	4.21		3.86
-	Larva5		2.54		2.54		1.70		1.70		3.35		3.35
-	Beetle1		-				-				-		
CF3D	Larva1	3.61	3.56		3.58	1.44	1.39		1.41	1.81	2.36		2.08
-	Larva2	2.20	2.22		2.21	1.04	1.00		1.02	2.04	2.43		2.24
-	Beetle1		-				-				-		
CF5D	Larva1	5.78	5.64		5.71	2.24	2.24		2.24	3.16	3.16		3.16
-	Larva2	5.68	6.28		5.98	2.26	3.28		2.77	3.65	3.95		3.80
-	Larva3	3.01	2.91		2.96	1.43	1.45		1.44	2.84	2.32		2.58
	Larva4		1.82		1.82		0.71		0.71		0.89		0.89
-	Beetle1	6.69	6.84		6.76	2.83	2.81		2.82	4.46	4.15		4.30

	Beetle2	5.75	5.75		5.75	2.16	2.44		2.30	4.72	4.59		4.66
	Beetle3												
-	Beetle4		6.18		6.18		2.66		2.66		3.75		3.75
CF6B	Larva1	4.83	4.78		4.81	1.88	1.92		1.90	2.22	3.07		2.64
-	Beetle1	6.22	6.99		6.60	3.02	3.01		3.01	4.05	4.02		4.03
CF11B	Larva1	3.53	4.04		3.78	3.29	2.45		2.87	3.45	3.20		3.32
-	Larva2	2.93	3.39		3.16	1.55	1.53		1.54	2.13	2.63		2.38
	Larva3		2.56		2.56		0.86		0.86		1.17		1.17
-	Beetle1	5.32	5.90		5.61	2.46	2.88		2.67	4.20	4.22		4.21
-	Beetle2		-				-				-		
CF12B	Larva1	5.55	5.68		5.61	2.07	2.53		2.30	3.28	3.25		3.26
	Larva2		2.18		2.18		0.69		0.69		1.43		1.43
-	Beetle1	4.86	5.10		4.98	2.43	2.52		2.48	3.34	3.64		3.49
-	Beetle2	5.13	5.72		5.43	2.65	2.85		2.75	3.29	3.70		3.50
CF13B	Beetle1	5.92	5.87		5.89	3.08	2.79		2.94	2.83	3.17		3.00
-	Beetle2	5.83	5.79		5.81	2.44	2.44		2.44	3.21	3.24		3.23
F1A	Larva1	2.64	3.06		2.85	2.03	1.59		1.81	2.26	2.60		2.43
-	Beetle1	5.85	6.06		5.96	2.89	2.81		2.85	3.29	3.36		3.32
-	Beetle2		-				-			3.26	-		3.26
F4C	Beetle1						-			2.84	-		2.84
F6B	Larva1	2.35	2.50		2.42	1.03	1.60		1.32	3.03	3.11		3.07
-	Beetle1	4.61	4.50		4.56	1.98	2.09		2.03	2.77	3.11		2.94
F7B	Larva1	3.96	1.87		2.91	2.19	1.82		2.00	3.09	1.90		2.49
	Larva2	4.29	2.37		3.33	1.63	1.51		1.57	2.39	1.86		2.12
	Larva3		5.88		5.88		2.36		2.36		3.09		3.09
	Larva4		1.40		1.40		1.34		1.34		2.09		2.09
	Larva5		4.61		4.61		1.79		1.79		2.24		2.24

	Larva6		1.47		1.47		1.21		1.21		2.67		2.67
	Larva7		1.40		1.40		0.78		0.78		1.35		1.35
-	Larva8		1.87		1.87		0.74		0.74		1.79		1.79
F8B	Larva1	2.36	2.37		2.37	0.97	0.83		0.90	1.58	1.59		1.58
	Beetle1												
	Beetle2	5.52	5.72		5.62	2.61	2.27		2.44	3.60	3.61		3.61
	Beetle3	6.68	6.66		6.67	3.18	3.00		3.09	3.57	3.59		3.58
F9A	Larva1	3.18	3.20		3.19	1.14	1.05		1.10	2.09	2.05		2.07
F10C	Larva1(?)	2.44	2.41		2.42	1.72	2.47		2.10	2.80	-		2.80
-	Larva2	3.40	3.51		3.45	1.22	1.39		1.30	2.22	2.52		2.37
F13D	Larva1	5.82	5.94		5.88	1.87	2.28		2.07	3.31	2.87		3.09
-	Larva2	3.21	3.51		3.36	1.49	1.55		1.52	2.98	2.22		2.60
-	Beetle1		-				-				-		
-	Beetle2		-				-				-		
F8B	Beetle1	4.67	4.60		4.63	2.28	2.38		2.33		3.82		3.82

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Appendix D Supplementary information for Chapter 5

D.1 Original proposal for live Deathwatch Beetle culture

with contributions from Dr Victor Jefferys

Note: this proposal was written early 2022, near the beginning of the research. There are some not quite correct statements and differences to what was presented in the final thesis. However, at the time of writing, this is what was known to the author and this proposal is what was presented to ZSL, NMRN and Cranfield.

This is a proposal for the creation of a long-term, live deathwatch beetle (DWB-*Xestobium rufovillosum de Geer*) culture to be housed at the Zoological Society of London (ZSL). It will be started as part of the PhD project, “Investigating the infestations: understanding and communicating deathwatch beetles on HMS Victory”, jointly funded by Cranfield University and the National Museum of the Royal Navy (NMRN). The aim is for the culture to be continued beyond the scope of the PhD, both for use in ongoing research into DWB activity and behaviour, and to engage the public with issues in heritage conservation.

The Deathwatch Beetle (*Xestobium rufovillosum de Geer*)

Despite over a century of study, not much is known about the DWB, and it remains a serious concern as a pest that impacts the structural integrity of hardwood timber. The DWB is native to Britain, and infests decayed hardwoods, most notably oak and willow (Fisher 1937). Their existence has been noted as early as the 17th century (Allen, 1698; Hickin, 1975), and they have many associations with folklore, as their tapping behaviour was most commonly heard during the quiet death-watch before a person died (Allen, 1698).

Most of the knowledge about DWB comes from two periods of study: the late 1930s/early 1940s and the late 1990s. The former were done primarily by Ronald C. Fisher on behalf of the Forest Products Research Laboratory. To our knowledge, these were the first in-depth scientific explorations into the DWB. Although yielding potentially valuable information on the DWB lifecycle and

conditions needed for development, the results were not conclusive, and many questions remained unanswered (Fisher 1937, 1938, 1940, 1941).

The late 1990s saw a concerted effort to understand DWB in order to better deal with infestations in cathedrals and historic houses (Fidler, 2001). English Heritage joined the European Commission's Woodcare Project, partially funded with the cathedral grants scheme (*ibid.*). The studies done covered a wide range of aspects relating to DWB and historic buildings, including the lifecycle, role of fungi, and trapping (*ibid.*). The study investigating the DWB lifecycle and feeding habits made use of a DWB culture brought over from Germany, and found that the lifecycle can take anywhere between 1-13 years (Belmain et al. 2001). There have been occasional studies on DWB in other periods, but the majority focus on eradication. To develop more effective pest management strategies, a thorough understanding of the lifecycle and behaviour of an insect is essential. It is not enough to test different methods of eradication. Considering how widespread the beetles are, and the amount of structural, and therefore economic, damage they cause, there is remarkably little literature on the subject.

HMS *Victory* and pest management

HMS *Victory*, which has been dry docked in Portsmouth Harbour since 1922, has been dealing with an infestation of DWB first noted in 1932 (Bugler, 1966). Various cycles of insecticide treatment have been performed since the 1930s, but the poorly understood nature of the beetle and the sheer size, complexity and ongoing use of the ship has meant the treatments had little impact. Removing and replacing infested timbers has been performed when possible, but the location and nature of the ship prevents steps being taken to ensure new timbers do not become re-infested. It also means losing the historical fabric of the ship. Regardless of the date of the timber, it is evidence of the history and biography of the ship, and loss of this information is contrary to the ethics of conservation (Caple, 2006a, p. 200).

In more recent years, with the introduction of Integrated Pest Management (IPM) into the heritage sector (Pinniger, 1993), the emphasis has been on

managing the infestation rather than trying to eradicate it. NMRN, since taking over management and conservation of the ship in 2012, has a policy of retaining as much historical material as possible and only replaces timbers when it is structurally essential (Victory Conservation Management Plan, 2016). While an IPM plan has been implemented, the structural damage the DWB has the potential to cause means a greater understanding of the beetle population on *Victory* is required to better manage the infestation. The current conservation programme will take place over the next 15 years, the aim of which is to enable the survival of the ship with only routine maintenance for the next 50 years (Victory Conservation Management Plan 2016). This PhD aims to contribute to the early stages of this conservation programme and provide essential information on the behaviours of the beetle and how the infestation can be assessed through non-invasive means. Conservation is an essential part of the heritage sector, and its work yet is not an area widely known to the public, which can have serious impacts in obtaining funding for conservation work. The second part of the PhD project is to raise understanding and awareness of essential conservation work, the findings of DWB activity on *Victory* will be communicated to the public by creating early interactive prototypes.

The Deathwatch Beetle population on HMS *Victory*

The first part of the PhD aims to understand the DWB population on HMS *Victory* and its behaviour on the ship.

Deck Plank

A highly degraded deck plank was removed from the starboard edge of the middle gun deck. It has clearly been degraded by fungal activity and DWB.

A complete recording of the surface was done *in situ* and further recording (through photogrammetry and laser scanning) is currently being undertaken.

Once complete, the plank will be sectioned into cuboid samples and scanned with micro-computed tomography (μ CT) to reveal further valuable information about the tunnel structure and volume, and their relationship with flight holes, and wood structure (Brock et al., 2022).

Non-invasive Detection

Unlike a deck plank, which is easily accessed and replaced, most of the timber on the ship, however, is too large, too integral to the structure, and/or is of historical interest.

The next stage is to develop non-invasive means of detecting areas of active infestation on *in situ* timbers. This stage of the project is still in development and will only be a preliminary study to determine suitable methods for further investigation, but three methods have been selected thus far: bioacoustics, ultrasound, and ground penetrating radar (GPR). Other techniques being considered are thermography or fluorescent labelling.

Public Engagement and Interaction

The second half of the PhD project involves developing two digital prototypes to communicate the findings from the first half to members of the public. As it is early in the project, this is still being developed. But current plans are for an augmented reality (AR) conservation trail that presents findings and information about DWB activity on the ship and how the infestation is managed, and an app-based game based on the DWB lifecycle. The idea is to allow people to play through the life of a DWB from hatching to oviposition, using a tunnel map created from the μ CT data for larvae to crawl through. They would find a mate by tapping the screen and having to listen for a response.

Reasons for Culture

This Project: Non-invasive detection

The culture would be invaluable in the development of non-invasive methods for detecting DWB activity and refining these to make them viable in the context of HMS *Victory* and other historic buildings and objects. It would allow for testing on a smaller scale beforehand and provide valuable reference information. For example, having a reference recording for larval activity for bioacoustics sensing would make filtration of background noise easier, an important consideration given the active use of the ship and its location on an active naval

base. A preliminary study on the use of bioacoustics into DWB larvae detection was done as part of the Woodcare Project (van Staalduinen et al., 2001), but no further investigation or application has been done since then.

This Project: Public engagement and education

Having a live DWB culture would be invaluable for public engagement. A live feed or listening stream could be tied into the AR conservation trail, and videos and images of each stage of the lifecycle could be incorporated into the game, all with links to further information. There could be regular updates on tunnel changes, activity, and scientific findings through a blog. A live feed would also encourage members of the public to participate in the monitoring of the culture. It would also serve to emphasize how much there still is to learn about DWB behaviour despite them being native to Britain. As many aspects of this part of the project are still in early development, much of the details will be designed as the project progresses.

Other researchers (written by Dr Victor Jefferys)

There has been a general acceptance, based on both empirical observation and theory, that DWB larvae need wood to be previously decayed by fungi for them to utilise it as a food source, but neither the fact nor the reasons for this have been conclusively proven. Indeed, the interaction between fungal colonisation of wood and DWB activity has not been studied at any length, but it would be of considerable value both in terms of pest management and academic interest in interspecies relationships.

Having a DWB culture would allow investigation into a variety of aspects of fungal-beetle interactions, including whether or not the beetles need actively decaying or simply already decayed wood (through e.g. choice chamber experiments with egg-laying adults), what precisely it is that the DWB larvae consume in decayed wood and how they digest it, and whether the presence of DWB in wood alters patterns of fungal activity. Such knowledge could aid in early identification of wooden structures at risk of DWB, as furthering our

understanding of the beetles, which is vital to improve pest management strategies.

Potential for future studies

As mentioned in Section 1, the lifecycle of the DWB can take up to 13 years to complete. Having a managed culture where conditions can be controlled to speed up the lifecycle for research purposes would be incredibly helpful and might encourage further studies into the DWB.

There is an historical precedent for a DWB culture that revealed valuable information about the lifecycle (Belmain et al. 2001) and oviposition preferences of mated and unmated females (Belmain et al. 2002). Unfortunately, the culture was not maintained after the lead researcher changed institutions and it died out (Belmain personal communication 2021). Having a culture in a central location with suitable resources that multiple institutions can contribute to will help ensure long term survival.

Technology and scientific knowledge have improved significantly in the 20 years since the last studies were done, and substantially since the 1940s, and repeating experiments and further research into the DWB with more recent equipment and scientific standards may reveal new information. This is particularly applicable in the case of public engagement. The Woodcare Project began in 1995 and set up a beetle hotline for people to contact the project and discuss experiences with DWB (Ridout, 2001a). A total of 48 people called the hotline (*Ibid.*). Although this is not an insignificant number, there are more platforms and methods of engagement available to current researchers. Having the culture in a public facing position with information on the project, combined with the prototypes created by the project and social media, information on the DWB has the potential to reach far more people today than in 1995.

IPM has become firmly entrenched in the conservation principles of most museums and heritage spaces since its introduction in the 1990s. As such, there has been a shift towards environmentally friendly and non-hazardous pest-eradication techniques and management of deeply entrenched

infestations. A live culture would enable research into the use of natural predators, such as spiders and the *Korynetes* beetle, of the DWB as a means of population management.

With the Woodcare project and the current PhD, it is evident that the applications of DWB research from a live culture to cultural heritage are many. Cranfield University and NMRN have a track record of joint research, including a 3rd MSc project running this year that may also benefit from access to a DWB culture. There is a high likelihood that other projects may be developed by Cranfield University and the NMRN because of the culture. In conclusion, not only will a culture be incredibly helpful for this PhD, but a DWB culture has long-term value for future research and public engagement.

Finally, it must be noted that there may be wider applications beyond heritage conservation. The use of a native British wood-boring beetle notorious for its cryptid nature to develop non-invasive means of detection means that techniques and methods can be investigated and tested on a non-threatened species before being used to detect endangered species.

Why ZSL?

In anticipation of questions regarding the housing of the culture at ZSL as opposed to the funding bodies of the PhD, I have provided a brief explanation.

The main issue is that the culture needs facilities and care to ensure it is maintained and can be monitored. ZSL is equipped to do this, and it fits within the normal remit and activities, whereas it is outside both the scope and facilities of Cranfield University and the NMRN. The presence of specialist knowledge for the development and establishment of the culture is also invaluable. Having the culture in a central location with suitable resources and a vested interest in the long-term survival will enable the expansion of this PhD project as another point for public engagement but will enable future research into DWB activity and behaviour.

At NMRN, there are no suitable facilities nor expertise for an insect culture. Space is also at a premium. Galleries, offices, and facilities are fit into historic

buildings originally built for other purposes. The conservation team is small and do not the time to maintain a culture. Therefore, there would be no guarantee for the long-term maintenance and survival of the culture.

Although Cranfield University has more space, the facilities are not equipped for long-term maintenance and storage of the culture. The facilities are geared towards forensic entomology, as is staff expertise. Again, there would be no guarantee for the long-term survival and maintenance of the culture beyond the PhD.

Although the likelihood of beetles escaping the culture is low, the subsequent risk should they do so at NMRN is high. NMRN is in the historic dockyards in Portsmouth and is in historic buildings across the site. The risk to the historic buildings, and any museum collection within is substantial. A similar risk applies at Cranfield Forensic Institute (CFI). Although all the buildings on both campuses are modern, CFI holds a significant collection of historic wood for teaching purposes, much of which is irreplaceable, and unique or invaluable historic and archaeological artefacts are often brought on-site for research or analysis.

Establishment and Set-up

As lead researcher and instigator, I will lead establishment and set-up. I will serve as a point of contact between the ZSL and the NMRN during my PhD but will hand over the responsibility to a suitable person at the end of my PhD.

The initial wood for the setup is to come from the *Victory* archive. Offcuts of unknown provenance from the ship have been consolidated into the archive. At present, their use, and value is limited, as they are too small to be of diagnostic value and are of unknown date and provenance (beyond coming from *Victory*). Many of the fragments have evidence of past DWB activity and fungal decay. Samples from this selection should provide a plentiful supply of food for the beetles.

The insects will be collected from the ship during the emergence period of the adults (April-September) and placed into temporary storage containers with a

variety of decayed wood (at differing levels of decay). The containers will be transported to ZSL, and the wood (with eggs and beetles) will be transferred into the designated case for the culture. This process may require several trips over a prolonged period, but regular updates for stakeholders and the public will be given, thus enabling the culture to be in the public sphere from the beginning. As it is unclear how many attempts might be required for the beetles to breed, as many beetles as possible (based on previous collection data this should be several hundred ('Deathwatch Beetle Collection Records' 1930)) will be collected during the emergence period to increase chances of successful mating and oviposition.

Plan for display and information

This will be developed alongside the ZSL team, Cranfield University, the NMRN conservation, curatorial and public programming teams, but a rough potential idea can be seen in the following diagram:

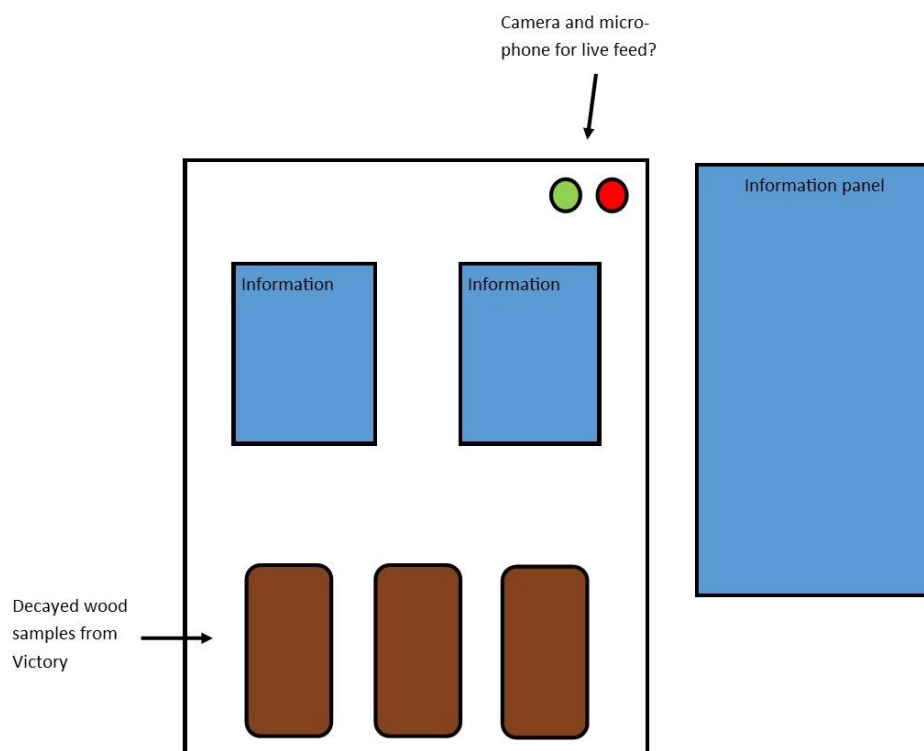


Fig D4: Mock potential layout of culture at ZSL

Mitigation to prevent escape

If the ideal conditions are in place and plenty of food provided through a regular supply of decayed wood, the beetles are unlikely to escape. It is only the larvae that feed, not the mobile adults. However, the adults only live a few months and prefer to lay eggs in decayed wood. In the unlikely event that an adult beetle escapes, they are unlikely to survive long enough to find suitable wood to lay eggs in.

However, there have been some instances where structural timbers with infestations have been immediately adjacent to lead roofs, and the adult beetles bored through the lead while exiting the pupation chamber (The Builder 1928 & Cathcart 1934 as cited in Belmain 1998).

In consideration of this, a glass container, properly sealed should be used. In the interest of research, access to the culture is necessary, but the access point needs to be completely sealed after each use.

The beetles have only been noted to fly above 18°C, although they are active (crawling) above 10°C (Belmain et al. 2001). Keeping the temperature below the flying threshold is one method of minimising risk of escape and spread.

If necessary, a channel of fluorescent powder around the edge of the culture can be created to track any beetles who wander.

There is the potential for the public to be involved in the monitoring of the culture for any escaped beetles. The use of a camera feed and a public-facing display would be an excellent method of engagement, particularly with younger audiences. 'Wanted' posters of adult deathwatch beetles could be used to encourage people to look out for the beetles, not just at the ZSL and the NMRN, but elsewhere as well.

Things to discuss

The points made in this section require further development and discussion with all stakeholders prior to the project commencement. They have been raised

here to prompt consideration and make those involved aware of the details that require finalisation.

Wood Maintenance

During the PhD project and initial use of the culture, I, as the primary researcher, will establish an initial supply of decayed wood from the NMRN to the ZSL, and add fresh wood to the culture annually. Before the end of the project, I will organise a source of supply and a responsible party for adding the supply.

Funding

The initial set up costs will include the following:

- Temporary storage containers (i.e. Tupperware)
 - o These are cheap and easily sourced
- Labour for beetle collection
- Transport from Portsmouth to ZSL
- Development and printing of information panels

Maintenance costs should be low, as the needs of the DWB are few. However, if a live-feed or something similar is set up, the question of who is responsible for equipment becomes a problem. The wider applications of the culture to heritage conservation may mean that grants can be applied for in organisations such as Historic England, or other heritage research bodies. Historic England (English Heritage at the time) has previously funded studies involving DWB, so there is a precedent. Towards the end of the PhD, such applications will be considered based on the initial findings from the culture and other researchers that have used the culture.

Other

As the DWB is native to Britain and is not a watched species (still considered common), there are no licenses required to keep the culture nor is further ethical approval required.

It may be necessary to create an agreement between stakeholders on use of the culture to ensure there are no competing studies occurring concurrently.

At present, there are no plans to do any testing on the beetles at the zoo. Procedures will be established prior to subsequent studies for obtaining permission and documentation for use of the culture. Any researcher wishing to do testing will collect a sample of beetles and conduct analysis elsewhere. The beetles only live a few months, so any taken away for study will not be reintroduced. It is hoped the population will be large enough to support this, but it may be possible to add additional beetles from the ship.

Conclusions

The aim of establishing this culture is for it to become a long-term resource for study. A live DWB culture at ZSL would be an integral component of the PhD project and provide valuable insight to testing non-invasive methods of detection. It will also serve as a point of public engagement, which will hopefully develop further beyond the scope of the project as a tool for education. Hopefully, this will be the first of many studies to make use of the culture to learn more about this native British species that we know so little about.

Appendix E Supplementary information for Chapter 6

E.1 Questionnaire Prototype 1

Plank Interactive

Thank you very much for participating in this research to inform people of some of the conservation work for HMS Victory. Your feedback will be instrumental for research of public engagement with conservation and will be used to develop the experience further!

Please note- no personal/identifying information will be collected. The questionnaire is completely anonymous.

1. Was the level/amount of knowledge presented in the experience suitable?
 - a. Yes, it was just right
 - b. Almost, but not quite (please elaborate)
 - c. No, there was too much information

Any suggested changes?

2. Were the models easy to interact with?
 - a. Yes, it was easy
 - b. Almost, but not quite (please elaborate)
 - c. No, it was too difficult

Any suggested changes?

3. Are there any changes you would make to any of the models (i.e. colour changes, more/less information, etc.)?

4. SketchFab is an online platform that hosts 3D models and can be accessed by anyone with connection to the internet. Do you believe that these models should be shared more widely?
- a. Yes, the models should be accessible to anyone
 - b. No, the models should only be accessible to visitors on the ship
 - c. Unsure

If you are comfortable, please elaborate:

4. Did the information make you think differently about the preservation of Victory?
- a. Yes
 - b. Maybe
 - c. No

Why? Is it something you've come across before? Had you ever thought about the challenges of preserving things like Victory?

5. Did any of the information presented surprise you? Please describe what surprised you the most (if any):

6. The management of pest infestations like the Deathwatch Beetle is one element of conservation and involves many aspects including research, investigation and experimentation. Was the level of complexity involved something you expected?
- a. Yes
 - b. Maybe
 - c. No

Please elaborate:

7. Does this inspire you to find out more about conservation and heritage science?

- a. Yes
- b. Maybe
- c. No

What did you find most inspiring?

Any other feedback:

*Originally spread between 2 pages, with plenty of space for elaboration.
Formatting adapted for appendix

E.2 Questionnaire Prototype 2

Deathwatch Beetle Conservation Experience

Thank you very much for participating in this research to inform people of some of the conservation work for HMS Victory. Your feedback will be instrumental for research of public engagement with conservation and will be used to develop the experience further!

Please note- no personal/identifying information will be collected. The questionnaire is completely anonymous.

1. Was the length and level of knowledge presented in the experience suitable?
 - a. Yes, it was just right
 - b. Almost, but not quite (please elaborate)
 - c. No, they were too long and/or too complicated

Any suggested changes?

2. Was the language used to present the information suitable?
 - a. Yes, it was just right
 - b. Almost, but not quite (please elaborate)
 - c. No, it was too complicated or too simple

Any suggested changes?

3. Did you feel that this was the best method to present this information?
Would you be comfortable downloading an app of the experience in future?

8. Did the information make you think differently about the preservation of Victory?
- a. Yes
 - b. Maybe
 - c. No

Why?

5. Did any of the information presented surprise you? Please describe what surprised you the most (if any):

6. The management of pest infestations like the Deathwatch Beetle is one element of conservation and involves many aspects including research, investigation, and experimentation. Was the level of complexity involved something you expected?
- a. Yes
 - b. Maybe
 - c. No

Please elaborate:

7. Does this inspire you to find out more about conservation and heritage science?
- a. Yes
 - b. Maybe
 - c. No

What did you find the most inspiring?

Any other feedback:

*Originally spread between 2 pages, with plenty of space for elaboration.
Formatting adapted for appendix

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E.3 Deathwatch Beetle Conservation Experience (Prototype 2) storyboard

