

CRANFIELD UNIVERSITY

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SELF-HEALING MECHANISM IN POLYMER COMPOSITE
MATERIALS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
PhD in Manufacturing

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Academic Year: 2019 - 2022

Supervisor: Dr Muhammad Ali Khan
Associate Supervisor: Dr Indrat Aria
September 2022

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ABSTRACT

The current self-healing mechanisms are still a long way from being fully implemented, and most published studies have only shown successful damage repair at the laboratory level. The complex nature of these mechanisms makes it difficult to implement them in real-life situations where the component or structure must continue to function. For complete healing, a molecular-level chemical reaction is required with the aid of external stimuli such as heating, light, and temperature change. Existing self-healing mechanisms are almost impossible to implement in critical applications such as 3D-printed products due to the requirements of external stimulations and reactions. The objective of this research is to investigate the strain release behaviour during crack growth of polymeric beams under elastic loads for self-healing. The mechanical behaviour of polymer components has been studied for many years, and their basic features are well understood. In this study, the elastic and plastic responses of 3D-printed beams made of Acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), and thermoplastic elastomers (TPE) were investigated under different bending loads. Two types of 3D-printed beams were designed to test their elastic and plastic responses under different bending loads. These responses were used to develop an innovative self-healing mechanism based on origami capsules that can be triggered by crack propagation due to strain release in a structure. The origami capsules, made of TPU in the form of a cross with four small beams either folded or elastically deformed, were embedded in a simple ABS beam. When crack propagation occurred in the ABS beam, the strain was released, causing the TPU capsule to unfold with the arms of the cross in the direction of the crack path. This increased the crack resistance of the ABS beam, which was validated in a delamination test of a double cantilever specimen under quasi-static load conditions. The results showed the potential of the proposed self-healing mechanism as a novel contribution to existing practises primarily based on external healing agents. The self-healing mechanism of TPU and TPE origami capsules has been demonstrated and reported for the first time. These materials achieved a good balance of mechanical strength and self-healing

ability. A thicker beam structure tends to yield higher strain energy than do low thickness values for the beam. Since the strain energy release is dependent on how much cracking has propagated, so the higher strain release from the DCB TPU star and roll contributes to the rate at which crack propagation extends.

Keywords: 3D Printing; Crack Propagation; ABS Simple Beam; TPU & TPE Origami Capsules; Embedded Structure; FDM; Self-Healing Mechanism; Double Cantilever Beam Test

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LIST OF ABBREVIATIONS

3D	Three-Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
DA	Diels-Alder
DCB	Double Cantilever Beam
FDM	Fused Deposition Modelling
OSH	Origami-Based Self-Healing
PLA	Polylactic Acid
PU	Polyurethane
SH	Self-Healing
STL	Stereolithography
TPE	Thermoplastic Elastomers
TPU	Thermoplastic Polyurethane
UTM	Universal Testing Machine

1 IDENTIFICATION AND SIGNIFICANCE OF THE RESEARCH PROBLEM

1.1 Research Background

Self-healing is the capacity of a material to repair damage to itself and restore lost qualities by using resources intrinsic to the system containing the materials. Inspired by the phenomena of self-healing in natural biomaterials, several self-healing polymers have been developed to repair internal or exterior damage. Through particular mechanisms, these polymers can heal or limit damage to systems containing them, extending their service life. The properties, and hence selection of a particularly self-healing mechanism of a polymers depends on how it is manufacturing.

Recent advances in 3D printing, rapid prototyping and direct digital manufacturing mean many polymer items are manufacturing using 3D printing which has advantages of reduced production time, being cost-effectiveness, environmentally friendly, and versatile. Conventional machining will remain, but possibly with decreasing relevance. However, very little work has been done so far on how self-healing mechanisms can be developed or incorporated in such printed materials. Investigation of the performance of polymers and their self-healing capabilities is now cutting a new channel in the academic domain. However, research could revolutionize the manufacturing of self-healing, smart 3D printed products. Therefore, theories and methods, for understanding damage in printed structures and how to cure it, is important.

The self-healing mechanism is a novel idea and will open a new generation of manufacturing of smart 3D printed products in which specially made origami inspired capsules are fused within the layers of a desired printed component. Traditionally, origami is a capsule where folding paper creates intricate three-dimensional forms. These origami capsules will be actuated as soon as damage, or a void, due to operational and environmental loads occurs within the layers of the printed product.

Self-healing will be provided by origami-based damage repair in the 3D printed products and hence will make their use safer and more reliable, especially in critical applications. Origami inspired capsule will be embedded in the structure while printing the required component by using fused deposition modelling. Presently, origami-based printing processes for self-healing 3D products is severely limited. However, this is changing as in-depth research is undertaken in support of the 3D printing industry.

1.2 Research Problem

The investigation of existing self-healing mechanisms is still very far from implementation and most of the published work has demonstrated the repair of damage has taken place only at the laboratory level. Their rheological nature makes them complex to implement for damage repair while the component or structure is performing its function. In most cases, bond level chemical reaction is required for complete healing of damage due to external disturbances such as heating. These requirements imposed by external disturbances and reactions make the existing laboratory self-healing mechanism almost impossible to implement, especially in 3D printed products almost impossible to implement industrially.

Any material damage causes a strain release or a reduction in the overall strain of a 3D printed structure or component. This strain in the structure/component is due to the residual or pre-stressed conditions established during the post print cooling process or due to external loads while the structure or component is in use. This research wants to use this inevitable phenomenon of strain release to actuate an artificial hormonal network made of origami inspired capsules. The origami capsule will contain extra stretchable material in a limited volume. These capsules could be printed and fused within the layers of the parent printed structure or component using a conventional fused deposition modelling-based 3D printer. The pre-stressed conditions or external loads will help them to remain inactive and restrain the added stretchable material. Once damage occurs or a crack is initiated near the capsule, the strain release due to this damage will relax

the capsules and the stretchable material will unfold and extend wherever the strain is less. This mechanical actuation will cover the void or damage due to a crack in the sub-surface and quickly repair the printed structure in a way that closely resembles the human hormonal system which becomes active as soon as a virus or bacterium enters the body.

1.3 Research Objectives

The aim of this thesis is to develop a self-healing mechanism based on origami capsules in 3D printed composite structures. To this end, the current research has the following objectives:

- I. Design and develop strain driven origami-inspired capsules.
- II. Investigate the workability of the designed capsules under different values of strain release.
- III. Characterize the mechanical strength and workability of a product (i.e., structure/ component) after healing.
- IV. Analyse the workability of the developed healing capsules with different material types and shapes.

1.4 Research Methodology

The research proposes a suitable research methodology according to the research problem summarised in Section 1.2. The research starts with a comprehensive literature review. The design conceptualisation methods depend on both the analytical approach (selecting the method that identifies the optimum cantilever beam and small capsule) and the experimental approach (developing a cantilever beam, capsules, and embedded capsules within the structure). The mechanical strength is identified using a bending test, where the bending load was applied to the beam. This scheme provided comprehensive mapping between the mechanical and material properties and the loading values measured and tested during the experiments.

The tests including observing the effects of the material and binder on two types of 3D printed beams and were designed to test their elastic and plastic responses

under different bending loads. These responses were used to develop an origami capsule-based novel self-healing mechanism triggered by crack propagation due to strain release in the structure.

The origami capsules were cross shaped, composed of four small beams that could be folded or elastically deformed and embedded in the main beam structure. Under the strain released due to crack propagation in the main beam, the small beams comprising the origami capsule unfolded in the direction of the path of the crack and hence increased the structure's resistance to crack propagation. This increase in the crack resistance was validated in a delamination test of a double cantilever specimen under quasi-static load conditions. Repeated results demonstrated the effect of self-healing on structural strength against crack growth. The results show the potential of a proposed self-healing mechanism as a novel contribution to existing practices, which are primarily based on external healing agents.

The effect of the printing parameters on the structural dynamic response and crack growth resistance is also investigated in the experiments. The experiments set out to investigate the properties of the samples, including bending moment and delamination tests. Two printing parameters (layer thickness and orientation) were analysed in the test. Three types of samples were printed at different temperatures. The crack propagation in the beam was measured and tested to determine the behaviour of self-healing under elastic and plastic loads.

1.5 Thesis Structure

This thesis is organised in nine chapters. Chapter Two provides a literature review of self-healing mechanisms for 3D printed polymeric structures. It addresses the research gap concerning crack growth under bending load and delamination tests. A theory of self-healing based on strain release phenomena for embedded structures is proposed in Chapter Three. Chapter Four presents the methodology for the experimental work for model validation. This chapter contains a description of both the experimental setup and procedure, as well as the materials and test conditions that obtained. Chapter Five presents the

technical aspects of acrylonitrile butadiene styrene (ABS) simple beam behaviour. The results of the experiments were then analysed and discussed. The results and discussion of the performance of the origami capsules under different loads are given in Chapter Six. The discussion of embedding the capsule inside the polymeric composite structure is provided in Chapter Seven. The analysis of the development of self-healing capability in embedded structures for crack growth is provided in Chapter Eight. Finally, Chapter Nine summarises the findings of the thesis. The overview of the structure is presented in Figure 1-1.

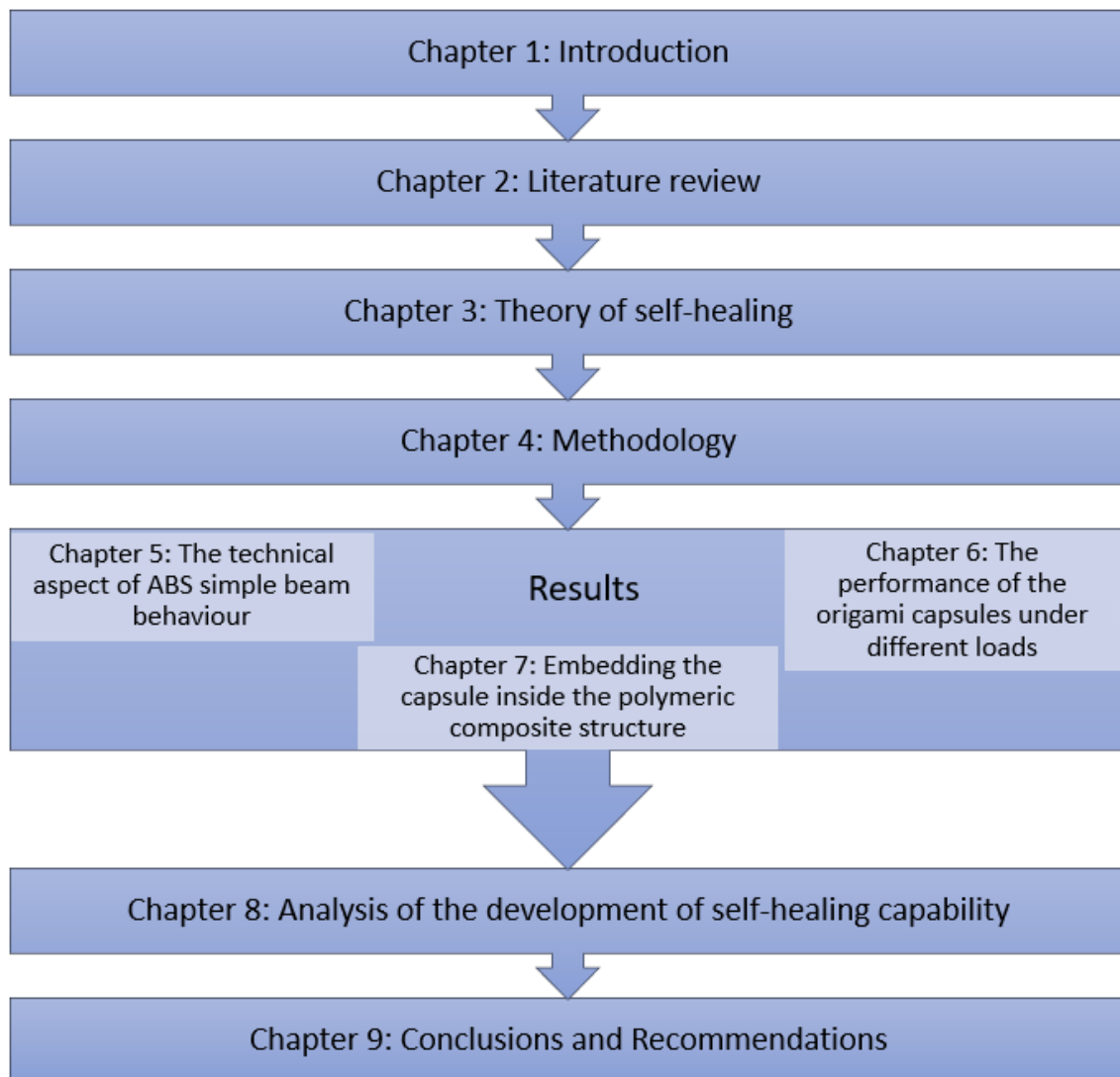


Figure 1-1 Block diagram of thesis structure

1.6 Conclusion

By laying out the aim and objectives of the research, this discussion has set the stage for the rest of the study. This chapter also identifies the rationale for conducting research into self-healing mechanisms of crack propagation under different load conditions. Moreover, the discussion provides an outline of the methodology used in the current study to attain its objectives. The next chapter looks at the relevant literature to help narrow the research topic.

2 LITERATURE REVIEW

2.1 Introduction

Self-healing materials with characteristics that allow them to heal themselves when damaged by mechanical, thermal, or other causes, and to restore their original sets of properties, include metals, polymers, ceramics, and composites [1]. Self-healing can be defined as a natural process or mechanism, which enables the material to recover from the damages caused by, e.g., external phenomena through a healing process that returns the material to its original set of properties [2]–[6]. While natural mechanisms such as autonomous repair of bone, are lacking in traditional self-healing materials, the last decade has seen tremendous progress in the development and design of such materials [1]. Materials such as polymers and composite can exhibit characteristics of self-healing. If these materials are damaged, possibly due to fatigue, during their utilization, that damage can repaired through self-healing mechanisms which not only heal that material but can also extend the working life of the materials by maintaining its strength [1]. These properties are considered important in materials, which are more prone to damage, and where repair is not possible during the execution time.

The self-healing process in terms of materials started in the early 1970s when exploration of space (i.e., the Apollo mission) became reality and the Shuttle was constructed of materials that included ammonium perchlorate-filled hydroxyl-terminated polybutadiene [7]. It was assumed at that time that materials could be damaged at the nanoscale and that would lead to larger microscopic cracks causing catastrophic loss of not only materials but also payloads. It became clear later that such damage could be self-healing.

First damage can be measured through mechanical stress-strain to quantify the damage and effect of self-healing methods [8]. This was known as a reversible self-healing crack, which was used later to assess basic characteristics of self-healing elements using, for example, the Maxwell and Voigt models [7]. Figure

2-1 below shows the first self-healing mechanism element which was further improved.

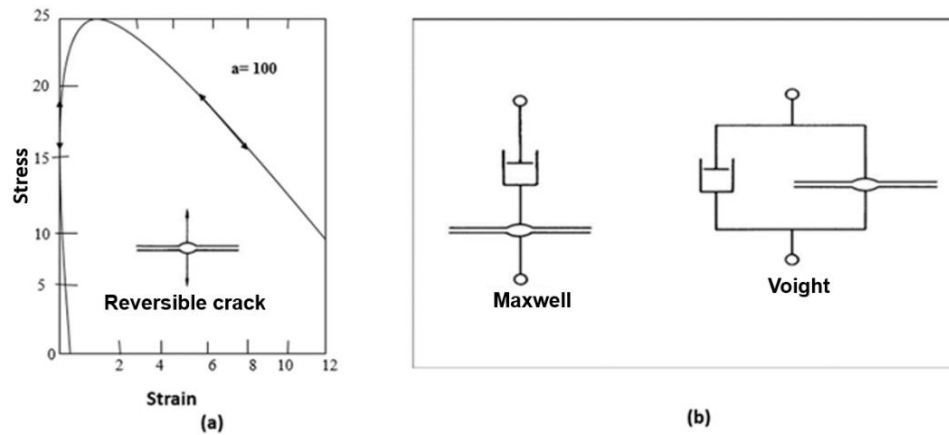


Figure 2-1 (a) The stress–strain response of a healing element is shown where the two parallel surfaces interact modelled by an anharmonic non-bonded potential function. (b) Viscoelastic elements composing the healing element, in series (Maxwell) and in parallel (Voigt) [7].

Since 1970, there have been a significant number of publications on self-healing mechanisms of different materials, especially thermoplastic and cross-linked systems. However, it was 2001 when the first article on the self-healing in polymer-based materials was published in Nature [7]. This triggered research into the use of self-healing polymer materials, inspired by the tremendous advantages of self-healing materials over traditional materials in engineering applications such as electrical, automotive, biomedical, aerospace, chemical, and civil [9].

Smart polymer materials have similarities to biological self-healing phenomena and have significantly improved the life of critical components [7], [10]. The development of these kinds of systems and materials is challenging but not impossible, and include self-healing paints and coatings, even bridges, buildings and cars [11]. Smart materials are often used in critical applications and components to make sure the products have durability, flexibility, and are lightweight. Such materials are required to self-heal after damage. For example, presently, if a scratch is found on the paintwork of a car, it requires either expensive corrective work in a repair shop or a significant and inconvenient repair

by the owner. In such a situation, a self-healing process that ensures the relevant material maintain its function is highly desirable, particularly if it retains its ability to reverse damage over a long time, and without delay. It would be doubly advantageous for the self-healing process to cure damage automatically without any peripheral intercession [4], [5], [12]–[14].

Most materials change their properties with age and gradually decay. Some materials take longer than others; wood rots when insects or micro-organisms eat it away; however, plastic can take hundreds of years to break or sooner with the help of fire or sunlight [9]. Some materials are very vulnerable and sensitive to breakage and sometimes very unexpectedly, such as when to applied force (e.g. stress and strain) generates internal fractures. Such materials pose the hardest challenges in terms of the self-healing process [15]. With regular maintenance and inspection, it is easy to spot such problems as rotting or rusting; however, there can be cracks in crucial components where they are hard to detect, such as inside hot engines that operate at high speeds with spinning blades. There are technologies and techniques, which can be used to detect such faults, e.g., the well-known non-destructive testing technique of ultrasound scanning, that makes it relatively easy to find defects within materials or components during routine inspections. However, when the component is in use, it is almost impossible to detect a potential failure.

The mechanics of these challenges have become more complex with recent advancements in the design and manufacturing of polymer-based components [10], [16]. For example, the mechanical behaviour of a component at microstructural level changes if it is manufactured using the additive method of manufacturing rather than a conventional method [17]. In the past, self-healing mechanisms were devised for components made of conventional methods materials, but additive manufacturing (AM) offers important opportunities to include into the object means for self-repair [18].

However, the design of polymers materials are considered highly self-healing and elasticity properties along with challenging task. Study from Zhao et al. found that

with the use of 4-tris as a tetratopic linker to crosslink a poly obtain a self-healing polymer with efficient outcomes upon stretching. It was also revealed that strain at break of material such as polymer recovered to original length after being stretched [19]. The damaged material was also healed at room temperature up to 93% within 1 hour. Zhao et al. suggested that polymer can be used in different applications like electronic sinks, biochips, matrixes in soft actuators and others.

Liu et al. study developed epoxy Vitrimers with the combination of versatile recyclability and high performance [20]. Liu and Colleagues conducted the experiment where two imine-containing hardeners synthesized from bio-based vanillin and petroleum-based material such as p-hydroxyl benzaldehyde. It was found that the material was good solvent resistance and cured epoxy resins, and chemical degradation products can be reused to prepare new epoxy resins. Both process and chemically recycled epoxy resins shows high mechanical and retention of thermal properties which means epoxy resin cured by petroleum-based materials.

Yuan and Colleagues also design strategy for self-healing epoxy coatings with blending a biobased DGEDP with TPU prepolymers. The results show significant healing properties; however, during healing restricted the epoxy network and chain entanglement [21]. Therefore, this study shows the rational strategy to develop self-healing process with controlled morphology in order to increase their functions with specific application.

Memon and Wei studied the welding and reprocessing of disulphide-containing thermoset epoxy resin exhibiting behaviour reminiscent of a thermoplastic. The study focuses on thermoset resins which is generally lack of the ability to be welded like thermoplastic because of their cross-link features. However, with the increased use of fibre-reinforced composites in a large structure (e.g., rail parts, wind blades, aircraft parts, etc.) can help to better repair damages and compliant with regulations of environmental and recycling [22].

Much research is required to develop effective self-healing mechanisms for polymer-based components made by additive manufacturing methods such as

3D printing [16]. 3D printing uses a layer-by-layer approach to build a part or complete product, typically small in size, in small quantities, and with complex tailor-made geometries [23], [24]. However, this layer-by-layer based microstructure makes the mechanics of fatigue and fracture more complex than for conventionally manufactured polymer components [24]. It poses questions such as how research can use the existing self-healing mechanisms for 3D printed components, and what new the methods and materials can research possibly introduce during the printing to increase the efficiency and effectiveness of the self-healing [25], [26].

In this research, a conceptual description of the self-healing phenomenon in polymeric structures is provided, as described in the existing literature. How the concept of self-healing occurs in nature is introduced in the middle section. Later, the requirements of self-healing in current polymeric structures and components are described in detail. The existing self-healing mechanisms for 3D printed polymeric structures are also given with an especial emphasis on their working principles and advantages. A critical discussion on the challenges and limitations of the existing working principles is provided at the end. A novel self-healing idea is briefly proposed, and its possible impacts addressed, and challenges highlighted in the concluding section.

2.2 Conceptual Description of Self-Healing Mechanism and Categories

Self-healing is considered to be the capability of a material to repair any damage and restore any of its characteristics that have been lost through the use of the resources contained naturally within the material or sourced from outside [27]–[29]. A polymer with a self-healing property requires the ability to turn physical energy into a chemical and/or physical reaction capable of repairing damage through a mechanism that is not available in conventional polymers [30]–[32]. Self-healing materials can be found with different inherent characteristics, which depend on the use to which they will be put. Self-healing can extend the lifecycle of synthetic materials and therefore has the potential for a large number of

different applications [33]. Additionally, self-healing materials are capable of restoring or healing themselves without external intervention [34] and are defined as an artificial group of materials that can repair damage on one or multiple occasions to prevent deterioration of the material, to increase its reliability and efficiency, and extend its lifespan [35], [36].

Figure 2-2 shows the self-healing mechanism in nature, the healing response of a hand injury without any external intervention. In nature, the ability to heal is an intrinsic mechanism for all multicellular organisms. This means every organism has the potential to occupy a role in the ecosystem. Figure 2-2 shows the healing process in nature where the body first stops the bleeding and then the required tissue grows over the wound over a longer timescale. This is also known as sequentially controlled phases which replace the dead tissue with scar tissue and repairs damaged organs [9], [15].



Figure 2-2 Self-healing mechanism found in nature [9].

Wool and O'Connor made a breakthrough in 1981, conceptualising self-healing as a mechanism that comprised five stages: surface rearrangement, surface approach, wetting, diffusion, and randomization, shown in Figure 2-3 [37]. These concepts were instrumental in providing insight into the complexities involved in the recovery of ruptured polymer interfaces and are linked with molecular inter-diffusion at temperatures above or at glass transition. The first stages after the occurrence of a damage event are the rearrangement of the surface and its return to original shape or condition. Healing takes place only if the broken interfaces get connected, which is why this process is considered to be essential. Crack

healing rate is important as surface topography (discontinuity and roughness) caused by the crack, changes with time, temperature, and pressure. Greater surface roughness results in greater contact area thereby resulting in higher diffusion and faster self-healing. This is an important consideration for surfaces pulled apart due to damage that may eradicate the surface layer, and which may end the self-healing process [37]. Also, the surface approach stage determines whether the healing process is in point or line mode [7]. Wetting of broken surfaces by one another or by a healing agent must be ensured before the healing process can commence. This ensures the material has a high initial chain mobility, which can also be enhanced by an increase in temperature or by addition of solvents. These promote diffusion resulting in the entanglement of polymer chains thereby promoting recovery of the mechanical properties of the healed materials. This random movement due to diffusion promotes entanglement of mobile polymer chains near the surface and thereafter their interpenetration into the unruptured matrix material. This stage represents an important step for the restoration of mechanical properties and in due course, these properties are either recovered or healed [37]–[39]. Failure of the original crack interfaces can be seen during the randomization stage [7], [29].

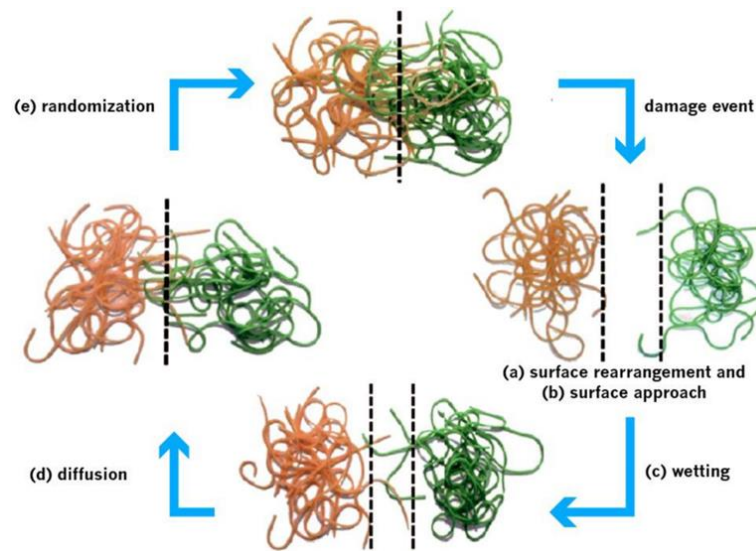


Figure 2-3 Five stages of the self-healing mechanism. (a) Re-arrangement of surface, (b) surface approach, (c) wetting, (d) diffusion, and (e) randomization [7], [29].

Self-healing mechanisms can be grouped into two categories: Non-autonomic and autonomic [40]. Non-autonomic self-healing is dependent on previous information regarding the type of damage likely to be experienced, as shown in Figure 2-4. It requires an outside trigger (such as the presence of light, heat, mechanical, or chemical) for cracks and damage in the polymer to be healed. The most common stimuli are heat and light since they can be quickly applied in service environments. Conversely, the autonomic self-healing mechanism requires no previous information, as shown in Figure 2-5 [29]. The self-healing procedure is initiated after the damage is experienced. The inherent chemical ability is automatically released, which facilitates the process of repairing/healing any damage or rupture caused to the material. This includes encapsulation and systems that are highly dynamic [40]–[42].

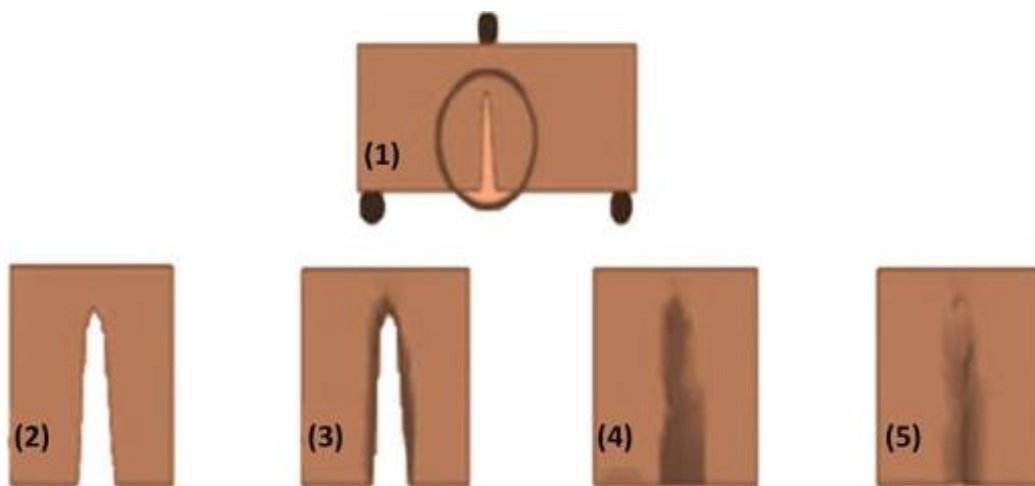


Figure 2-4 Shows the damages to the specimen due to crack formation. Figure 2-4 (2) indicates how the crack can be closed by the generation of the mobile phase. Figure 2-4 (3) illustrates the starting of the healing action by itself or through an external source. Figure 2-4 (4) suggests that the mobile phase is immobilized again, and Figure 2-4 (5) denotes complete restoration of the original properties [40].

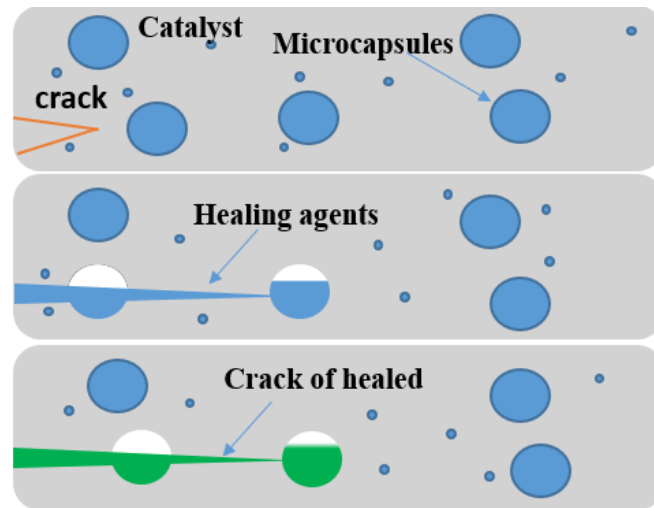


Figure 2-5 Autonomic self-healing: a micro-encapsulated healing agent is embedded with a catalyst (Grubb's) in a structural epoxy matrix capable of polymerizing the healing fluid [29].

2.3 Naturally Inspired Artificial Self-Healing

If a human suffers a scratch or cut, a scab will develop on the wound, thus allowing the healing process to proceed with no intervention from an outside source. Based on practices observed in nature, researchers have intensively studied how self-healing abilities can be incorporated into materials fabricated from synthetic polymers, primarily to extend their operational lifetime [10], [30], [43]–[45]. A self-healing polymer is intended to copy natural processes observed in animals and plants. Figure 2-6 depicts the artificial and biological routes to the healing of damaged and wounds. In biological systems, the inflammatory response starts with blood clotting followed by cell proliferation and matrix deposition, which may take several days, and finally the matrix remodelling, which sometimes takes several months. In the artificial system, the healing mechanism is triggered by a damage response, after which chemicals are rapidly transferred to the site of damage [7], [30], [43]–[45]. Chemical repair then occurs, extending over a period from several hours to days [27]. Any material that can automatically repair mechanical damage or do so with limited outside intervention, thus causing full or partial restoration of the material's mechanical characteristics, can be considered as a naturally inspired self-healing material [43].

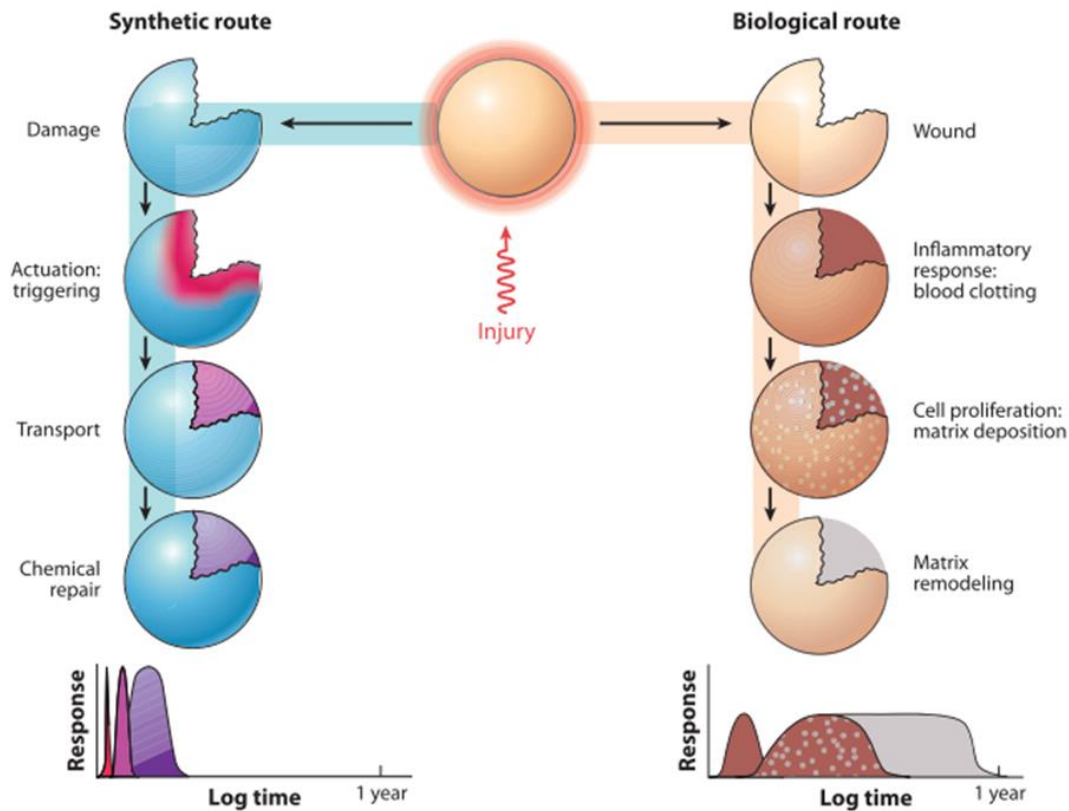


Figure 2-6 Demonstrates the different biological and artificial techniques involved in healing damaged and injuries [27].

Figure 2-6 shows the similarity in the self-healing technique of synthetic material (in this case the insulation) and biological systems. There are three main processes: (a) activation phase, (b) transportation phase, and (c) repair phase. Thus far, the majority of investigations in the field of self-healing have specifically concentrated on polymers and polymer composites, as these materials are widely utilized in commonplace or industrial applications. Materials based on polymers that have inherent self-healing properties offer a variety of advantages in addition to overcoming the frequently experienced issues related to polymers and their associated composite materials. For a material to be regarded as having self-healing properties, it must satisfy particular criteria. According to [29], [46], [47], out of the limited number of self-healing polymers, some necessitate healing agents (catalysts and monomers), while others are soft materials that necessitate a large solution (gel) or a plasticizer (rubber). Various studies have demonstrated that the lifespan of composite materials is generally constrained as a result of

fatigue or other factors that cause the material to fail due to damage experienced during use. 3D printing of self-healing gels, using cross-linking PHEMA with EDA to form dynamic imine bonds in the gel preparation, have been reported to have 98% recovery from mechanical damage [48]. 3D-printing of self-healing gels remains an easy way to selectively deposit protective coatings and manufacture smart and dynamic objects [49].

The concept of extrinsically simulated self-healing recovery of mechanical properties is also instrumental in imparting certain other functionalities; preparing smart materials with self-healing anti-corrosion coatings, self-healing electrically conductive coatings, thermo-sensitive composites, sensors, and self-lubricating and wear-resistant coatings [50]. This methodology involves the incorporation of capsules containing chemical agents with antimicrobial, anti-foaling, or biocides, with numerous types of functional coatings. Self-healing asphalt and concrete, for example, may be developed using embedded capsules containing asphalt binder or concrete binder, which can provide several significant futuristic options and benefits to the construction industry. The self-healing approach can be incorporated with other methodologies like shape memory and self-sensing materials to allow for autonomous recovery of structural composites in extremely hostile environments [50]–[52].

2.4 Self-Healing Requirements in Polymeric Structures and Components

The existing self-healing polymers are innovative, intelligent materials that are considered to be capable of repairing themselves and reinstating their properties with no requirement for outside sources or triggers. Usually, their healing ability relies on extrinsic healing agent encapsulations released after fractures or on intrinsic dynamic bonds, such as dynamic covalent bonds and physical bonds that develop autonomously after dissociations caused by fractures. Such polymers have been used in a wide range of applications thanks to their healing abilities, such as water membranes, lithium batteries, energy transducers, biomedical devices, flexible electronics, and soft robotics [29], [46], [47], [51],

[53]–[56]. However, despite the success of syntheses and applications, there is still a crucial challenge due to the lack self-healing polymers produced by 3D formation. This is seen as a bottleneck that separates artificial self-healing polymers from living materials (such as human organs) usually with practical microstructures and geometries.

The demand for an architecture of self-healing polymers is not adequately satisfied since the current 3D methods for producing self-healing polymers only include direct writing and moulding [56]–[58], which are either limited or time-consuming when developing complex 3D architectures[59], [60]. This report highlights the importance of photo-polymerization based AM for self-healing architecture such as free form. The studies also demonstrates that the rapid AM of single and more complex elastomer in multifaceted 3D geometries, in rates as fast as $12.5 \text{ mm}^3/\text{min}$, produced structures that were considered to heal and restore the original mechanical strength [61]. It was shown experimentally that self-healing 3D printing elastomers with a soft actuator, can restore their toughness within a range of 90% after a fracture. Such a self-healing photo-elastomer system is considered an efficient self-healing system mechanism and a promising source of revenue generation. The study of Yu and colleagues [61], presented molecularly designed photo-elastomer ink which has the potential for use in stereolithography based AM with a rapid healing mechanism. Using molecular balancing, the dual functions of self-healing and photo-polymerization were achieved using thiol-disulfide in the ink. The self-healing photo elastomer needs updating to be easily translatable to other systems such as photopolymerization-based AM systems that include self-propagation photopolymer waveguides, PolyJet printing, and two-photon lithography, as shown in Figure 2-7. Figure 2-7 (a-c) presents the AM of self-healing mechanism of elastomers having different 3D architectures and has the potential to open new methods and is not limited to demonstrated 3D soft actuators. Figure 2-7 (d-e) represents structural composite, and Figure 2-7 (f-h) flexible electronics, and may also include artificial organs, bionic sensors, biomedical implants, and robotics.

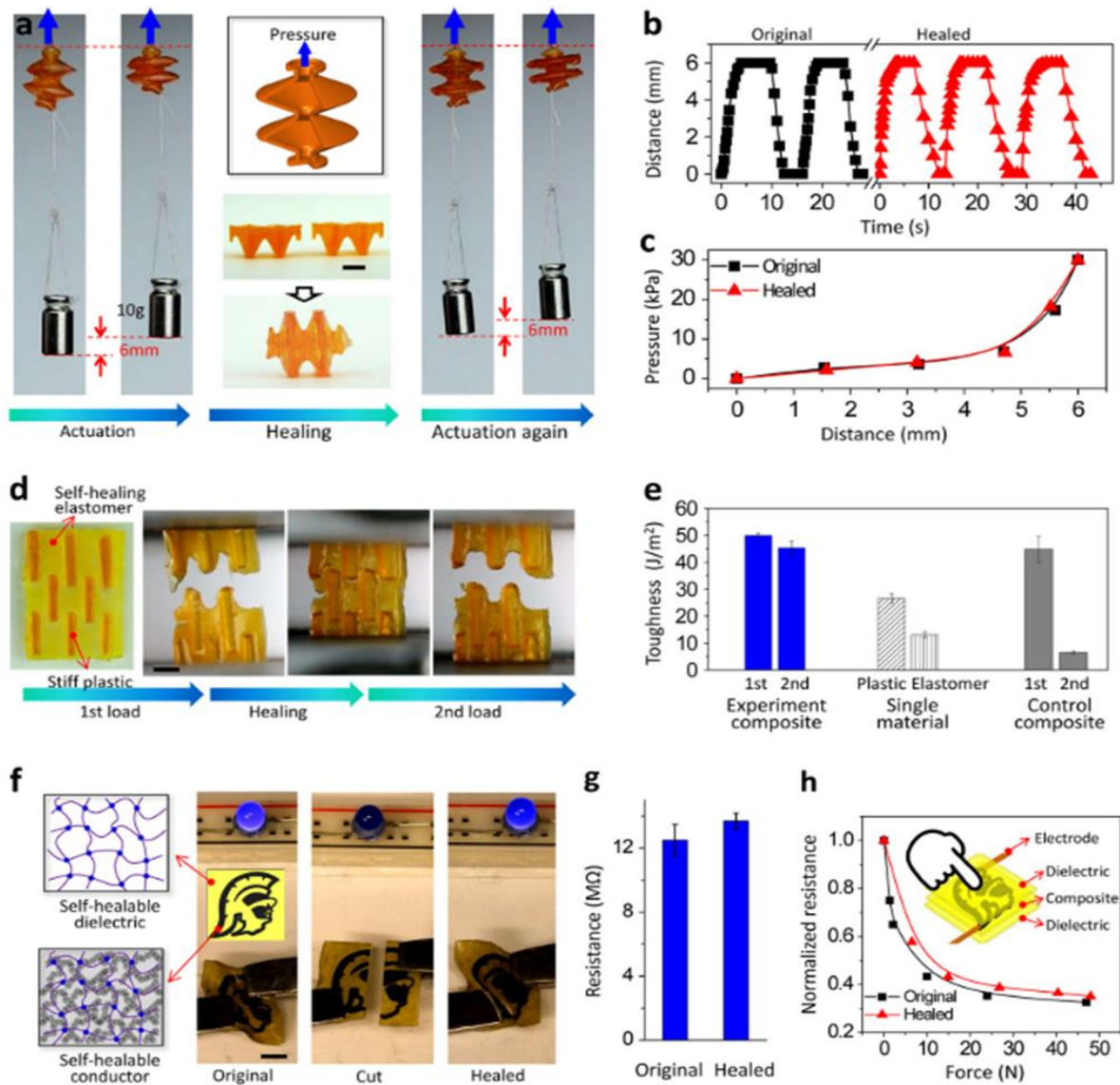


Figure 2-7 Applications of self-healing elastomers. Figure 2-7 (a–c): Self-healable 3D soft actuator. Figure 2-7 (a): Negative pressure actuation can enable the additively manufactured elastomer actuator to lift a 10 *g* weight by 6 *mm*. The inset shows the CAD model of the elastomer actuator. The actuator is then cut in half and brought into contact to heal for 2 *h* at 60 °C. The self-healed actuator can be actuated again by negative pressure to lift the 10 *g* weight by 6 *mm*. The scale bar represents 5 *mm*. Figure 2-7 (b): The cyclic lifting distance of the 10 *g* weight as a function of time of the original and self-healed actuators. Figure 2-7 (c): The relationships between the negative pressure values and the lifting distances of the original and self-healed actuators [61].

Figure 2-7 (d, e): Self-healable structural composite. Figure 2-7 (d): A notched stiff-soft composite is first uniaxially stretched until a rupture occurs and then brought into contact to heal for 2 h at 60 °C. The healed composite is then uniaxially stretched again until a rupture. The scale bar represents 3 mm. Figure 2-7 (e): The toughness of the original and healed experimental composites, single materials (pure plastic and pure elastomer), and the original and healed control composites. The toughness is defined as the enveloped area of the uniaxial nominal stress-strain curves until the rupture per unit sample area. Figure 2-7 (f–h): Self-healable electronics. Figure 2-7 (f): A specially constructed flexible pad, 10 mm square and 1 mm thick, with a self-healable elastomer phase and a self-healable conductor phase, was used to power an LED. Once cut and healed after 4 h at 60 °C, the self-healed pad could again power the LED and sustain bending. The scale bar represents 4 mm. Figure 2-7 (g): The resistance of the conductive path of the pad before and after self-healing. Figure 2-7 (h): The relationships between the normalized resistances and the applied force of the original and self-healed force sensors. The normalized resistance is calculated as the resistance normalized by the resistance for the force-free state. The inset shows the working paradigm of the force sensor [61].

The optimal means of extending the lifespan of a polymer is the self-healing mechanism, which reverses the process that ultimately causes the material to fail [43]. A perfect self-healing material is capable of sustaining its ability to sense and restore damage across the lifespan of its polymeric constituents, reinstating the material's performance with no negative effects. It is expected that such materials will offer enhanced reliability, safety, and durability in addition to a reduction in maintenance costs [10], [43].

In the past, studies of polymer damage restoration were with the intention replacing lost mass and recovering structural performance, the avascular approach was proposed as shown in Figure 2-8. This depicts a two-stage chemistry of masks using both rapid gelation to fill the gap and a polymer stage embracing the replacement of structural performance. At time t_0 , the impact

damage initiates a fluid release moving towards the damage. At time t_1 , the gel stage occurs by covalent cross-linking. At time t_2 , the polymer stage (yellow) follows with the use of a two-component initiation for monomer polymerization, resulting in the recovery of structural performance [62]. In the same study, through the control of vascular delivery and reaction kinetics over 20 minutes, damage exceeding 35 mm in diameter was targeted and within three hours, the mechanical function was restored. After impact damage recovery 62 % of the total energy absorbed was recovered compared to the initial impact tests [62], [63]. Renewable polymers may be possible in the future by supplying the chemical components of the original substratum polymer together with the flexible gel and polymer transfer.

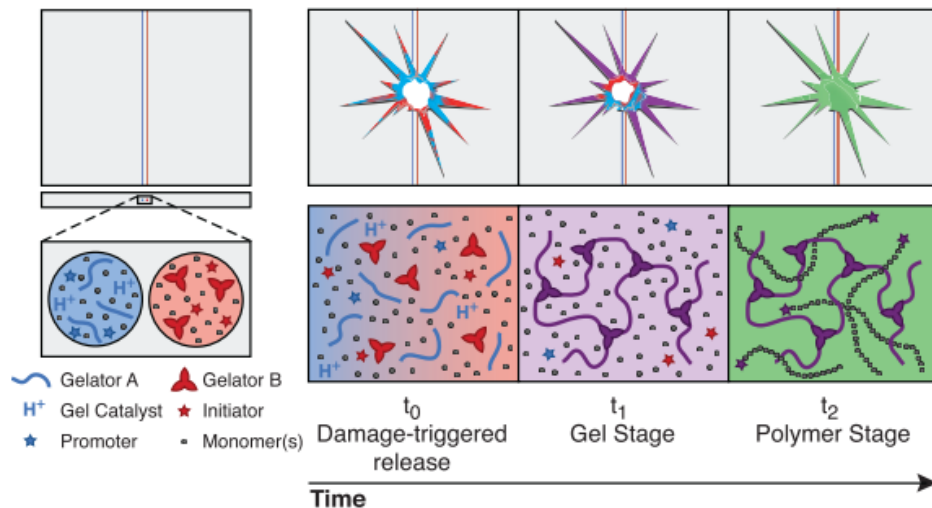


Figure 2-8 The avascular approach integrates reactive monomer solutions into a vascularized specimen [62].

2.5 Existing Self-Healing Mechanisms in 3D Printed Structures

2.5.1 3D Printing of Self-Healing Materials

The use of 3D printing has become increasingly ubiquitous across industries as the ability to generate user-defined 3D objects with a wide diversity of materials has developed [64], [65]. Evidence shows that 3D printing technologies can have a huge impact on the different sectors of business because it can move a business from traditional processes to new innovative procedures with a more

sustainable business model [65], [66]. However, sometimes, such a move can be proved riskier as well because there will be needed a significant amount of investments before moving toward innovative technologies or adopting the core business. Despite this fact, evidence also revealed that moving to 3D technology is considered less risky than any other innovative technologies because it allows firms to produce products or services based on customer demands with minimum costs as shown in Figure 2-9 [66].

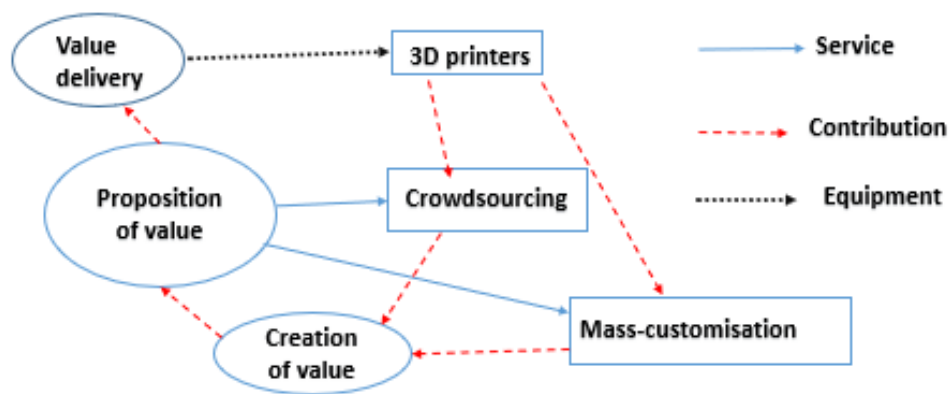


Figure 2-9 3D printing effective interlinking between different components of the business environment [66].

In the self-healing process allows reduction of operational costs and makes a self-healing mechanism more effective, as discussed earlier. The concept of self-healing mechanisms, 3D printing can make a significant difference and provide advantages. According to both the University of Southern California and University of Connecticut, materials with self-healing have added advantages in terms of rapid manufacturing process using 3D printing technologies [66], [67]. In 3D printing, the materials are manufactured using photo-polymerization-based 3D printing technique which use a process relying on light to solidifying a liquid resin; in which it is essential to maintain the right ratio between the different chemical groups to control the materials' characteristics. Yu and colleagues have discussed the process of 3D printing of self-healing materials such as 3D-printed rubber materials which can repair damage to themselves [68].

The process of 3D printing is both AM and rapid prototyping and involves the joining of materials to create objects based on data modelled in 3D, generally in multiple layers [69]. 3D printing consists of various AM techniques that allow rapid yet flexible fabrication of complex 3D structures with different characteristics from sub-micron to the multi-meter scale [70]. There has been extraordinary progress in the basic and applied knowledge related to the structure and treatment of 3D printing, and its characteristics, yet many gaps remain [49]. 3D printing is an emerging technology that can be used to produce complex geometries directly, which are otherwise next to impossible to manufacture. Instead of adopting the traditional manufacturing processes [71], including moulding, machining, and assembly, these steps are streamlined into a single process that greatly enhances design flexibility [72], [73].

3D printing technologies are capable of producing complicated functional or structural items through the addition of materials to reduce the crack while also achieving adequate geometric precision [74]. Self-healing for 3D printing had attracted attention in recent years, as it opens opportunities to build self-healing products even with commercially available printers for individual users [75]. Self-healing products (e.g., polymers) have the capacity and capability to recover and restore functionalities, in a manner identical to the natural ability of some living creatures to regrow and repair their tissues and grow limbs [76]. This provides a window of opportunity for extending the life span and minimizing the risks and failures associated with products [77].

Healing efficiency (η) can be calculated using a ratio of change in the property of products and materials of interest, as shown in Equation (2-1):

$$\eta = \frac{f_{healed} - f_{damaged}}{f_{virgin} - f_{damage}} \quad (2-1)$$

The f represents the property of interest; f_{healed} , $f_{damaged}$ and f_{virgin} , are the property of interest of healed sample, damaged sample, and virgin sample, respectively.

While interest in self-repairing systems is rapidly growing, and despite the success of the applications of self-healing, many challenges remain for the existing synthetic self-healing materials. There are different physical and chemical approaches, which reaches advanced awareness of synthetic self-healing materials, with a significant efficiency found with biological systems. The study by Yu and colleagues have found that many complications and challenges remain in this regard because during real life operations a multiplicity of different applications will produce numerous different types of damages [67]. For example, if cracks are not detected at the early stages, they become hard to fix it and it is difficult to restore the material's properties. Cracks can lead to complete failure of the materials and at that stage, it would be hard to intervene to make an effective repair. However, an initial or early-stage detection mechanism to fix problems could be a solution that lasted until manual or automatic intervention during a periodic inspection. The main materials known for their self-healing properties are polymers or elastomers, but there is a wide range of materials that could be used for self-healing processes, including cementitious materials, metals, and ceramics. To be practically useful the materials must have the potential to intrinsically correct damage, help to reduce overall cost, reduce failures, and extend working life [77].

The most critical hold-up can be attributed to deficiencies in 3D shaping [57], which makes self-healing polymers distinctive from biological materials with microstructures and functional geometries [49].

Many studies have discussed different polymers and mixtures for widely used printing technologies such as FDM, SLA, and SLS. Limitations on producing self-healing 3D printed components are mainly due to the need to understand each polymer's characteristics and limitations [78], [79]. Moreover, more control needs to be taken when setting up the printer before sending a file to the printer [80]. Besides, a dual extruder FDM, see Figure 2-10, may be necessarily to integrate self-healing polymers within the 3D printed components [81].

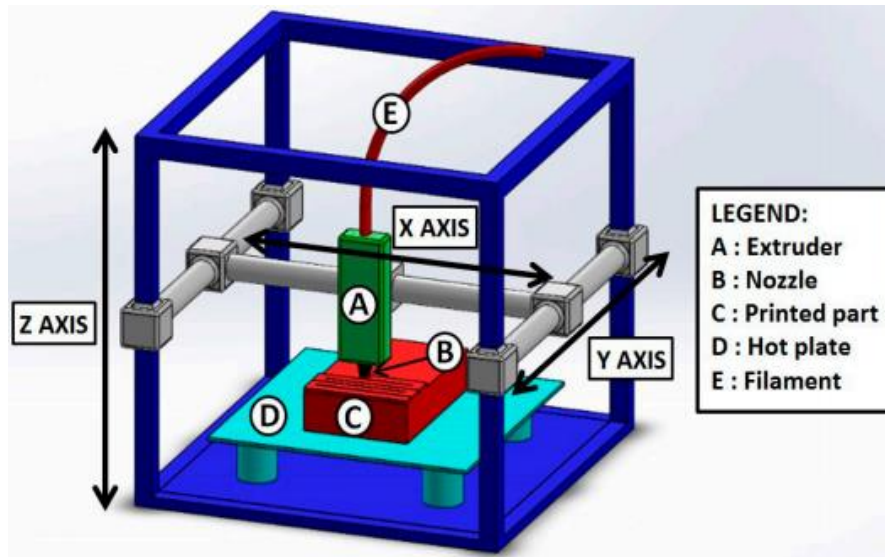


Figure 2-10 Typical fused deposition modelling (FDM) setup [74].

2.5.2 General Categories of Self-Healing Mechanisms Applicable to 3D Printed Structures

Self-healing mechanisms of polymer structures can be classified into two broad categories: Intrinsic and Extrinsic [10]. For the extrinsic approach, healing agents are sequenced through the main matrix, planted in microcapsules [29], [82]–[84] or a 3D vascular network of hollow fibres [79], [80] and channels [10], [53], [75], [81]. Though it should be noted that the quantity and amount of transmission of the healing precursor are somewhat restricted [10]. External microcapsules layers and vascular walls are subjected to stress, when crack growth takes place and ruptures and releases the healing agents that either react with each other or interact with the matrix to seal the crack [49]. Stiff polymer products can be incorporated, since molecular diffusion of the matrix is not a prerequisite [65], [82], and for other practical applications, extrinsic self-healing has opted to make use of hard polymer structures [76]. The correct option for a self-healing procedure will vary with nature and location of the likely damage, the chosen repair resin, the operational environment, the proximity size of damaged zone, and healing precursor container [75].

The intrinsic approach relies solely on the inherent capacity of the materials and comes into action through reversible covalent bonding [85]–[87] and

supramolecular interactions [30], [88]. To overcome the restrictions and concerns of the extrinsic approach several intrinsic healing systems are now available. These are tailored to provide multiple healing sites during macroscopic damage [76]. Figure 2-11 shows the dynamic strategy of damage acceptance and management [75], [84].

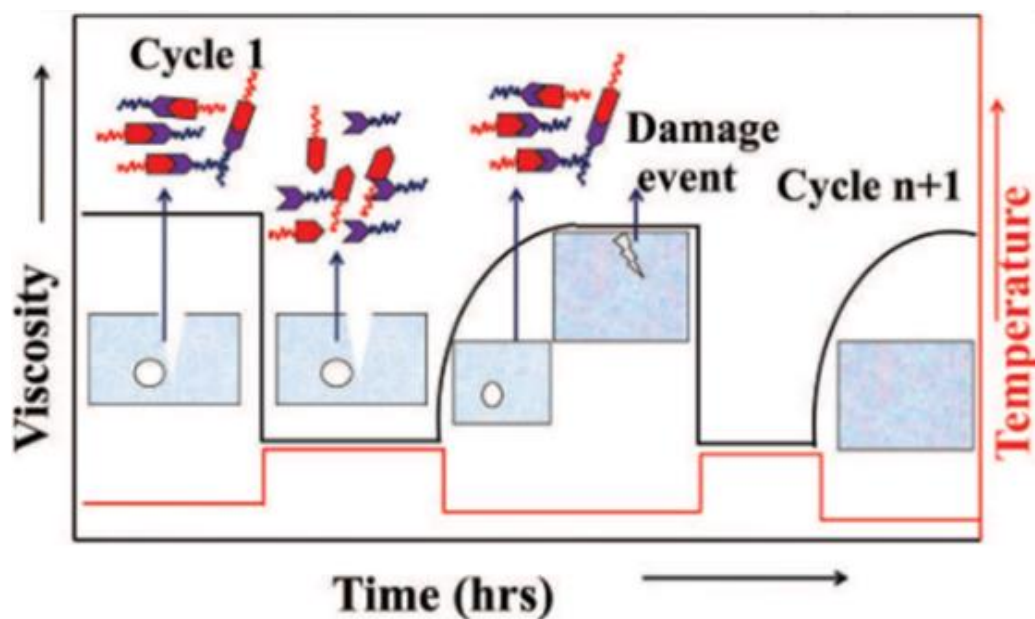


Figure 2-11 The concept of damage healing with the intrinsic approach [75].

An ongoing research study conducted on intrinsic self-healing of covalent polymers focusing on bond scission and reconnection has shown remarkable progress. Most prominent of these studies relate to the Diels-Alder (DA)-bond aided self-healing mechanism [83], [85], which has been modernized and improved because of the adoption of different perspectives. Some primary works targeted varied reversible chemistries, such as disulfide bonds, living silicon dynamic exchange of $C - C$ bonds [86], and reversible $C - ON$ bonds [56], [88]. These studies were important in the development of intrinsic self-healing reversible covalent bond materials, thereby making available a greater number of options for specific needs having stronger $C - C$ bonds and multi-functional $S - S$ bonds, as shown in Figure 2-12 [87], [89]. In addition to these, thiolene chemistry and pH-sensitive reversible acylhydrazone bond are still to be adopted in intrinsic self-healing of damage for the restoration of mechanical properties in

structural materials [88], [90], [91]. To provide customized solutions for practical purposes a much greater emphasis is needed on such topics as the reproducibility of healing results, minimizing dependence on external stimuli, providing self-healing to a particular engineering material and, to ensure complete satisfaction and confidence, preservation of the original material with structural flexibility and integrity during crack healing.

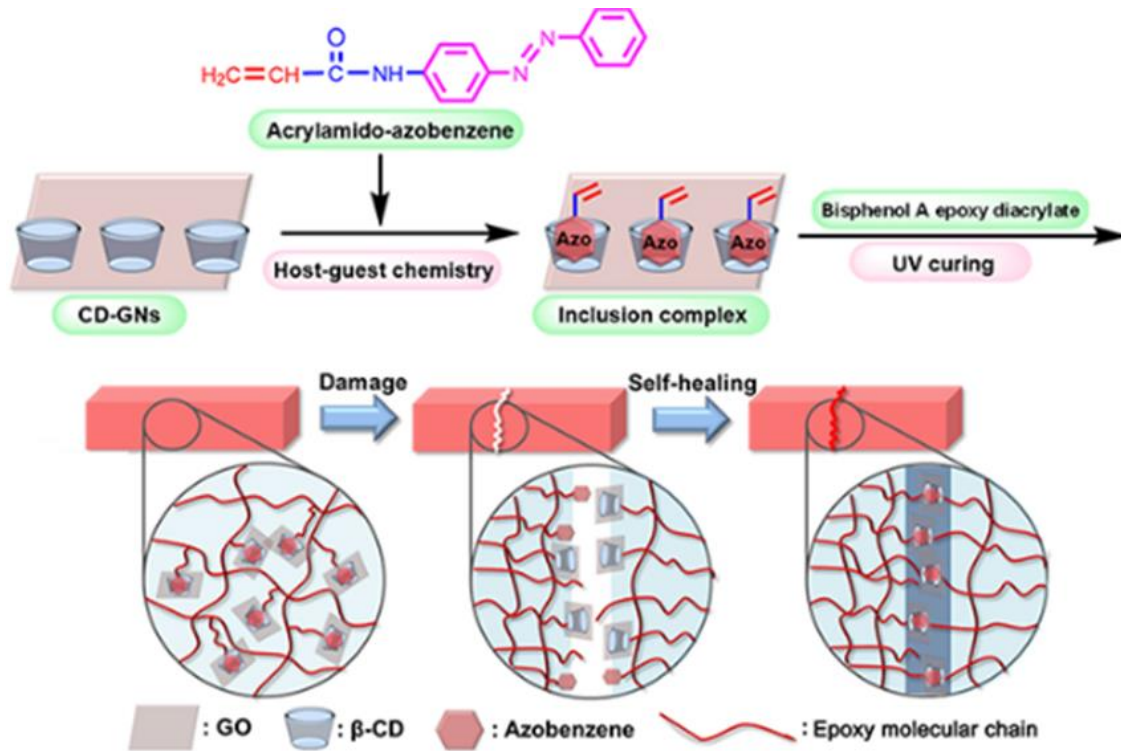


Figure 2-12 Schematic illustration of the self-healing mechanism of epoxy composite films [89].

2.5.3 Healing Mechanism for Different Material Classes

Different materials are used in 3D printing processes, including polymers, metals, and composites that have their self-healing mechanism. This means that 3D printing has an impact on how products are built, delivered, and designed. Moreover, the traditional economies of scale offered by traditional manufacturing are no longer so important.

The dependency of the required conditions as discussed is mainly on the nature and characteristics of materials. For metals, the desired mobility needs to be

induced by increasing the temperatures to more than 800 °C. To obtain healing effectively in various types of materials, different mechanisms each with its own strategy are taken into consideration. As such, the encapsulation process has been adopted for various materials in a general healing approach. Whereas reversible cross-link is designed for special cases related to polymers only [92], [93]. Table 2-1 shows mechanisms, materials and strategies for different options and classes of materials.

Comparatively less investigation has been made in terms of self-healing characteristics for metals [94]. As healing action in metals requires mobility and higher temperatures and this poses the greater challenge of incorporating higher temperatures into the design phase. Self-healing metals are categorized as nano-scale voids and macro-scale cracks [95], [96], depending on the dimensions of the healed damage [96], [97]. In contrast, concretes have an inherent ability to heal themselves, because of the distributed presence of hydrated and un-hydrated particles for the dissolution and carbonization of calcium hydroxide. These can heal smaller cracks and restrict crack width thereby restricting the damage at a later stage, which can also be healed. Besides, water acts as an agent for hydration and calcium hydroxide dissolution that crystallizes when reacted with carbon dioxide. Multiple types of research have been conducted on the natural ability of such materials to self-heal. To reduce the propagation of a crack, some cementitious composites have been designed with the addition of reinforcement of fibres.

Polymer materials with reduced melting points or in liquid condition are frequently utilized in the 3-D printing sector as a result of their minimal weight, minimal cost, and flexible processing abilities [30]. While the geometry of 3D printed polymer objects could be significantly complex, their insufficient mechanical robustness and functionality represent considerable obstacles in terms of broader applications [98].

Table 2-1 Healing mechanism for different materials, the symbol indicates the expected or demonstrated level of success (tick for applicable and cross for not applicable)

Mechanisms	Type of materials		Name of materials
	Polymers & polymer composites	Metals	
Encapsulation	✓		Polycarbonates, cement, ABS, poly(urea-formaldehyde) and polystyrene
Increase of temperature	✓	✓	Glass, aluminium
Expanding phases	✓	✓	powder or slurry
Separation phases	✓		Ionomers, epoxy
Reversible crosslinks	✓	✗	Diels-Alder reactions, polycyclopentadiene
Channel transport	✓		PLA (Polylactic Acid)
Biological processes		✗	Polyurethane (PU)
Electro-chemical process	✗	✓	Polycarbonates, polyethylene, plastic

2.5.4 Focused Efforts Made for Developing Self-Healing in 3D Printed Structures

This section discusses in detail the effort made for developing self-healing in 3D printed structure including working principles and advantages, with visual evidence.

2.5.4.1 Working principle

Nadgorny and colleagues researched the 3D printing of self-healing gels to understand recovery from mechanical damages [49]. The study presented the working principles of 3D printable, self-healing gels as shown in Figure 2-13, with the following stages.

- The first step comprises the synthesis and functionalization of PHEMA (Benzaldehyde-functionalized poly-2 hydroxyethyl methacrylate) with

pendant benzaldehyde group, next cross-linking with diamine takes place. A delicate rheological tuning of ink formulations and mapping of printable space is required to prepare printable inks [48].

- After the optimization, the study achieved a good outcome showing a balance between self-support capabilities and flow of 3D printed gel. Finally, the objects displayed self-healing and dynamic properties [99], [100].

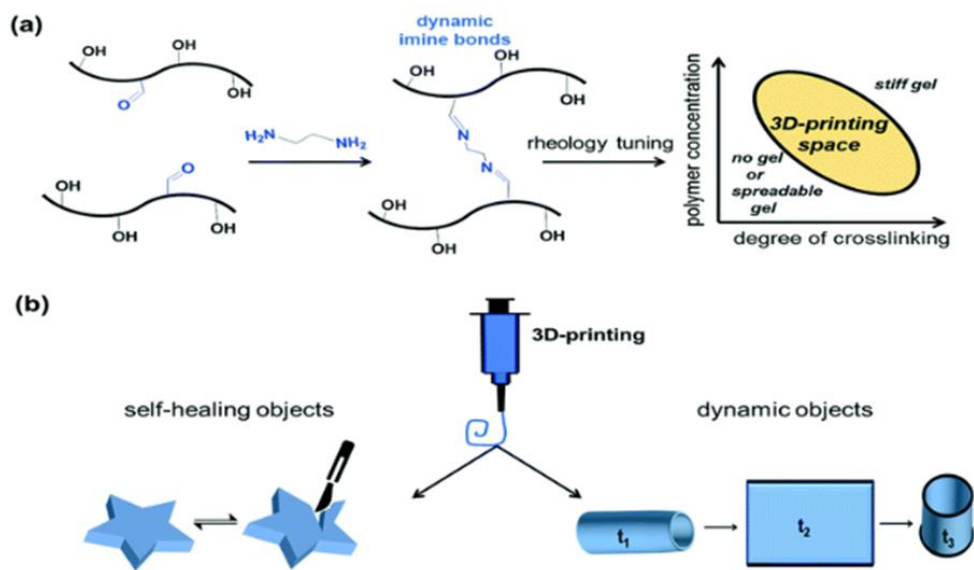


Figure 2-13 Schematic workflow for a 3D printable, self-healing working principle [49].

A self-healing 3D printed shoe pad was developed by Xin and Yu [64], using photo-polymerization-based 3D printing, a process that uses light to solidify the polymer into a particular shape as shown in Figure 2-14.



Figure 2-14 Severed 3D-printed shoe pad self-healing itself [67].

A team from the University of Southern California experimented on additive manufacturing of self-healing elastomers mechanism which can be used for 3D printing as well as 3D architecture and self-healing of fatal fractures [61], [67]. The mechanism relies on the molecular structures of photo-elastomer ink. Further, the experiment used projection micro-stereolithography systems with various 3D complex geometries printed at a fast rate, e.g., $0.6 \text{ mm} \times 15 \text{ mm} \times 15 \text{ mm}/\text{min} = 13.5 \text{ mm}^3/\text{min}$. The main purpose was to consider how rapidly a fracture healed, and the original structure and mechanical strengths restored. A model of the photo-elastomer in terms of the self-healing process was compared with a theoretical polymer-network-based model and with experimental results. The self-healing materials contained both conductive and dielectric phases and can be produced using a rapid photopolymerization capability available with various AM systems such as self-propagation photopolymer waveguide, PolyJet printing, stereolithographic, and two-photon lithography [101]. However, the proposed self-healing photo-elastomer system was considered a new and efficient self-healing mechanism and suitable for 3D printing [102].

The experiment used 3D printable self-healing elastomers with a soft actuator which can lift a weight ten times its own weight and with the feature of restoring toughness to over 90 % after fracture [103]. The materials were used without purification, included Vinyl-terminated polydimethylsiloxanes and dimethylsiloxane (MMDS), ethanol, sudan I (photo absorber), toluene, Iodobenzene diacetate (IBDA), phenyl-bis, and phosphine oxide diacrylate (HDDA). A computer-aided design (CAD) model was used for fabricating the multi-material structure and with image sequence which prescribed spanning in the vertical direction in the experiment as shown in the images in Figure 2-15 [61].

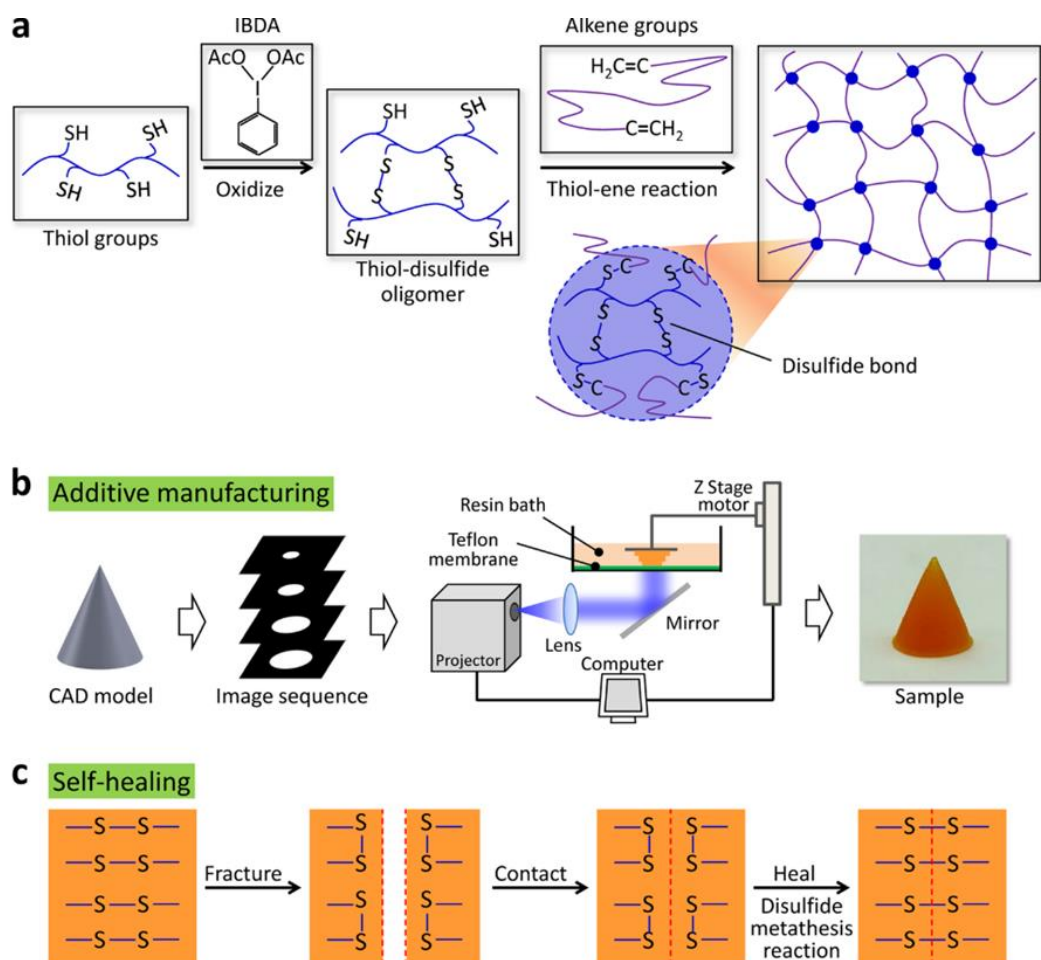


Figure 2-15 (a) The molecular design of the self-healing elastomer, where self-healing features and photo-polymerization were integrated with a self-healing elastomer based on the disulfide (R-S-S-R) and coexistence of thiol (R-S-H). Through harnessing the high-rate and high yield thiol-ene crosslinking reaction to achieve the photo-polymerization. (b) the CAD model using image sequences to perform additive manufacturing to achieve efficient samples through radical initiation. (c) the process further goes into self-healing by harnessing dynamic disulfide bonds through reactions (disulfide) to bridge the fractured interface as shown. The experiment was conducted with high efficient oxidant, iodobenzene diacetate (IBDA) [61].

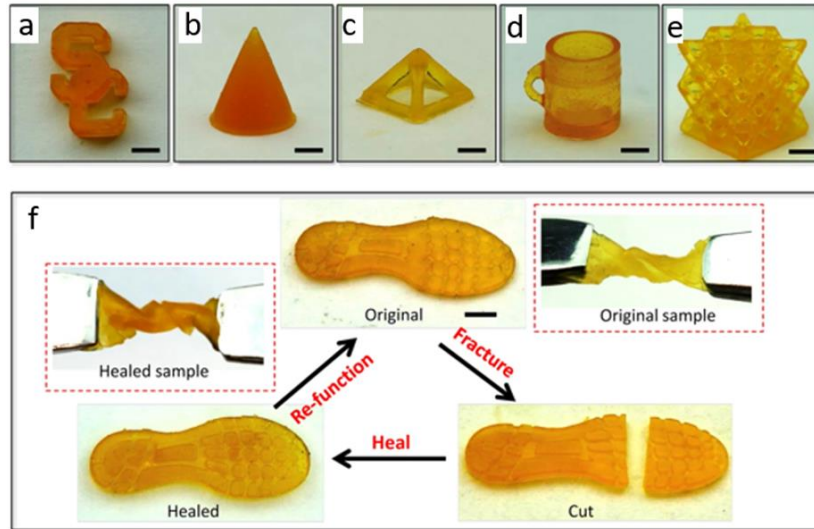


Figure 2-16 Manufacturing samples used to test self-healing mechanism with using shoe pad sample. (a) A logo of the South California University, (b) circular cone, c pyramid lattice, (d) cup, and (e) an octet truss lattice. (f) Self-healing of a shoes pad sample [61].

In this experiment, the molecular design of the self-healing elastomer was one which can be used in 3D printing [102], and other application as well.

An image sequence as shown above Figure 2-16 was sliced through the CAD model, with a fixed distance between each layer. The images were projected onto the resin bath, layer by layer to give the final shape its structure. The self-healing process was enabled by a disulfide bond and the fractured interface can be healed by the metathesis reaction of disulfide. The manufactured samples (i.e., 3D printed), circular cone, pyramid lattice, cup, and others are shown in the Figure 2-16. In terms of the self-healing process, the sample shoe pad could sustain a twist of 540 degrees. If the shoe pad was cut it, in 2 hours the healing process, at a temperature of 60 °C returned the pad to its original shape with properties similar to the original sample [61], [104]. It was claimed that using 3D printing help to make the product faster to manufacture and more durable.

2.5.4.2 Self-Healing Mechanism Advantages and Limitations

The self-healing mechanism as obtained in 3D printed structures has the advantages associated with 3D printing: reduced time to production, cost-

effectiveness, environmentally friendly, and versatile as almost anything that can be imagined can be produced [18]. Nevertheless, self-healing in a 3D printing structure can lead to strain release that subsequently initiates cracks that can propagate and damage the material [44], [49], [79], [105], [106]. However, the self-healing properties are capable of overcoming potential damage at the sub-surface level, thus allowing cracks to be healed rapidly with no impact on the workability of the component, thereby significantly reducing vulnerability. However, because of its high customizability and capability to print complex geometries, researchers commonly use 3D-printing [23]. Also, recent development in CAD software [10] and novel materials [107] further extend 3D printing capabilities, especially for self-healing mechanisms.

There are significant limitations that exist on both the self-healing mechanism, and the exploration of the study domain. Evidence shows that most of the investigations have been conducted on how different materials could be made more damage tolerant; less research has been conducted on how materials heal the damage within the perspective of 3D printing [18]. There are many materials such as polymers and polymer-based composite materials that can suffer from different types of cracks and which can lead to more severe or catastrophic damage: these are both external (e.g., environmental attacks, etc.) and internal (e.g., quality of materials, etc.) [102]. This omission is considered a gap in the research into self-healing as applicable to 3D printing. More research needs to be conducted in this area. The limitation in term of self-healing for 3D printing is cost, because more of the catalyst is required to achieve a higher degree of healing [108], [109].

2.6 Strain Release Behaviour During Crack Growth of Polymeric

An alternative approach to creating smart 3D printed products is to embed novel origami-inspired capsules into the layers of a printed component. For essential applications, in particular, such capsules could create an artificial hormone network that would make 3D printed products safer and considerably more dependable [110]–[112]. Standard fused deposition modelling can be utilised to

embed these capsules when printing the re-quired component, which would be a cost-effective solution for large-scale production. This is somewhat similar to the manner in which the human hormone system actuates when a virus or bacteria enters the body. The use of a strain removal-based actuation via origami-inspired capsules could radically transform the self-healing capacity within components or structures. Strain removal from an entire component could thus be initiated by any form of surface or subsurface damage. For strain removal to take place at a sub-surface level, the capsules could unfold and expand [113].

Some research has measured the strain release in the beam using a strain gauge and microcontroller [114]. Various experiments have also been conducted to measure strain using an electrical [115], [116], optical [117] or mechanical strain gauge [118]. The strain gauge was calibrated in a windmill structure [119]. Another experiment to measure strain was performed on a cantilever beam with a sensor. The vital factor in the structure was the applied force, and Taguchi-based optimization was used to determine the optimal parameters [120]. Systems for measuring strain and its impact have also been explored by using a resistance strain gauge [121]. The promising combination of readily available healing conditions (e.g., room temperature) and the useful mechanical properties of thermoplastic polyurethanes (TPU) has drawn a substantial amount of scholarly interest in TPU in the wider domain of self-healing polymers. While various reversible chemistries can facilitate healing, hydrogen bonding between urethane units at the broken interface is usually the most efficient way to engender interfacial healing [77]. However, the high reversible bond density can cause micro-crystals to form and inhibit macromolecular dynamics, which impedes healing.

The mechanical behaviour of ABS polymer components has been investigated for many years, and the basic features, such as stress–strain curves, are adequately known [122]. Such behaviour is measured elastically for very small strains and slightly larger strains when overcoming the intermolecular barriers to segmental rearrangements [123]. However, the complex properties of ABS polymer materials are temperature dependent, which has driven further

investigation to determine what relationships exist between strain, stress, and temperature [124].

Previous research into the mechanical properties of thermoplastic polyurethane (TPU) and thermoset acrylonitrile butadiene styrene (ABS) provides help in understanding the dynamics of such beams under load. Yuan et al. investigated the behaviour of a graded origami structure under quasi-static compression. A beam was fabricated using ABS material with flat brass sheets, 0.3 mm thick, implanted between the moulds, which were then compressed. Results indicated that the proposed origami structure showed plane stiffness and higher energy absorption to external loads [125]. However, the work lacked analysis in terms of geometric optimisation and behaviour under impact load. Hernandez et al. presented a kinematic study of origami structures for both elastic and plastic polymeric beams. After assessing various design structures, it was found that the kinematic variables of the structural model could fully explain the configuration of elastic origami structures within the beam [126]. However, the model developed by the re-searcher is far more complete and needs fewer variables for efficient FEA. Li and You re-searched open section origami beams to demonstrate energy absorption. Their research focused on designing a beam which included origami geometries, and which retained its cross-sectional height better than conventional beams when subject to large externally imposed bending deformations. Despite numerical simulation, the model did not develop origami geometries able to cope with symmetrical vertical loads; also, the energy absorption model needed to be validated [123]. Nevertheless, origami-based encapsulation has shown promising results [75], but tests of mechanical strength and healing properties tend to have been carried out on soft and weak materials [127].

The encapsulation of folded material, such as TPU in rigid and static structures, can induce self-healing properties in a structure, assisting it in overcoming extreme fatigue conditions, material degradation, and failure due to micro-cracks [128], [129]. Moreover, by activating the self-healing process, the material

becomes safer and more durable, saves the time and cost of replacing particular items, and reduces inefficiencies incurred due to damage [102].

The four-point flexure response of the ABS beam has been researched by Dhaliwal and Dundar and showed high impact resistance and toughness. Their work examined the strain rate using the generalised Incremental Stress-State Model. Though the compressive elastic modulus of ABS is found to be much higher than its tensile elastic modulus, the Von-Mises is yielded at a much lower force [130]. This means that at higher deformations, the ABS beam may not produce the predicted theoretical results. Therefore, it is necessary to continue to research self-healing techniques of polymers using origami structures [131].

Lee [132], [133] conducted an experiment using a large elastic bending machine to investigate the elastic energy behaviour of curved–creased origami to assess material bending behaviour. As the first step, an origami design model was developed to use different folds to produce the patterns necessary to make the 3D form required to meet a prescribed buckling criterion. The model was then used to simulate the shape of the origami capsule required, after which the results could be experimentally validated. The study by Lee [132] showed that skewed curved–creased laminated surfaces could help in assembling compliant and energy-absorbing structures, but the study itself did not provide any direct evidence for using this mechanism for self-healing [134], [135]. However, once the results were validated, it allowed a healing process using origami capsules to be simulated.

2.7 Challenges and Limitations (Identification of the Current Knowledge Gap).

Self-healing systems cover a wide area of interdisciplinary practice and are carried out using various techniques. Despite the benefits of using self-healing materials there remain challenges and limitations to the use of this mechanism. The key challenges to the self-healing mechanism is that the healing agent has a high reaction rate, which causes issues such as incomplete curing of the epoxy [44]. Unlike previously discussed mechanisms, there are no methods presently

available that can assess or evaluate self-healing systems because measuring healing must accurately measure parameters, including thermal changes, corresponding to the impact, e.g., in milli-seconds [49]. Knowledge of the basic mechanism and theory of damage healing remains the main challenge for the scientific community because healing chemistries have rapid kinetics, greater stability, and greater reactivity [77], [110], [136].

The integration of the concept of self-healing into aero structures has been critical, albeit difficult, to develop because of mechanical and thermal loadings. Sensor architecture to provide information about the healing process can be used to track components for structural health. While 3D printed sensors have several advantages, conventional sensor production methods continue to be an economical means of industrial production.

Further, much research is needed to address the challenge of transforming laboratory samples of healing mechanisms to practical applications [55]. Of the many studies on 3D-printing that have focused on concerns regarding strain release in crack initiation or damage, few have explored self-healing. Also, the majority of published material has shown damage cure only at the laboratory level [52], [80], [89], and the rheological attributes of certain structures or components mean that it is difficult to cure damage during their actual functioning [49]. The chemical reaction at the bond level is generally needed to achieve total healing with external interruptions like heating [105]. Such reactions and requirements render it virtually impossible for the current self-healing mechanisms to be implemented, particularly in the case of printed 3D products, while they are being used in crucial applications [113]. The vast majority of on-going research on self-healing materials will allow us to develop a new paradigm of this mechanism and overcome most challenges, and also lead to tailor-made self-healing materials for various applications. Future research needs to focus more on the practical implication of self-healing mechanisms and how effectively they could be used with 3D printing.

2.8 Potential Impacts of Smart Self-Healing 3D Printed Structures

2.8.1 Academic Impact

3D printing has been incorporated into the educational curriculum appearing in instances ranging from printed molecule models to plastic gear applications. Students can now print their 3D design models and are thereby assisted in their learning process, allowing them to see their designs in a physical form, assisting their conceptual understanding [33]. Whilst this entire subject has been researched extensively, the challenge of synthesizing a stiff material with intrinsic self-healing capabilities remains a significant challenge. The fundamentals of damage mechanics are based on energy release during crack initiation and propagation. The main actuation of the proposed self-healing capsules is based on strain energy release within the sub-surface.

It is important for Engineering, e.g., Civil, Mechanical, and Structural, curricula to be up-to-date and improved to include more focus on building the capacity to adapt to a changing global environment [137]. Products offer major potential for more sustainable buildings in the future. Therefore, there is a need to raise awareness that construction materials possess a huge variety of properties for beneficial use and that general-purpose approaches are dead ends from a global sustainability perspective [138]. In developing regions, in particular, economies should take advantage of curricula that better train for the next generation of civil engineers, because new technology can be applied at a point from which major developments can emerge so that the benefits can be readily accumulated.

2.8.2 Commercial Impact

The cost of 3D printing is going down. It is less resource intensive and requires less man-hours. 3D printing allows immense control, which can lead to more precise parts and low wastage. The design of a material incorporating a variety of functions remains highly complex [139]. Knowledge of smart self-healing materials is limited by the lack of work testifying to the effect on the mechanical properties of healing-enabling constituents such as vascular networks and

microcapsules. Consequently, much research effort is necessary to resolve the various technical problems before laboratory samples can be transformed into practice. This challenge could be overcome using unique capsule structures or via the integration of the shape memory concept into self-healing capsules to create a self-healing substance that offers multiple healing cycles. The implementation of such strategies will promote cost reduction and longer product life.

2.8.3 Social and Environmental Impact

Quieter / Room setups of 3D printing facilities. Low Noise pollution. Filters available for control of emissions leading to low levels of environmental pollution in general [105]. The research contend that manufacturing is a crucial factor in resolving the complicated social and environmental problems existing today and that the overriding ethical and social challenge for producers is to assume the fundamental obligations required for effective corporate citizenship. In this vein, the various ethical and social challenges include [140]:

- The achievement of a sharing economy. This is the anticipated objective of an increasingly competitive economy in which resources are maximized via the process in which the surplus capacity of services and goods is pooled. This means the economy model where people interact as a peer-to-peer (P2P) based activities for sharing access where all have same opportunities.
- The achievement of shared value. The objective of shared value is to generate economic value in a manner that additionally forms value for society by focusing on its specific needs and problems, which represents a new focus for producers to determine business opportunities related to social aspects by concentrating on optimizing the competitive benefit of resolving social problems. This can be accomplished via the preconception of markets and products, the redefinition of profitability within the value chain, and the creation of clusters at the firm's locations to support the sector.

2.9 Conclusion

Examples of autonomic and non- autonomic self-healing materials, where the material with a healing mechanism automatically reacts to damage, have been successfully demonstrated. Self-healing polymers can be considered as a new class of smart materials which has the feature and characteristic of an extended lifetime by repairing itself when damaged, without any external intervention, and can take different forms that can be categorized as either intrinsic or extrinsic. These polymers possess the ability to heal different kinds of damage or fractures, and. while considerable progress has been achieved recently in the area of 3D printing of polymers this has to be extended to include self-healing polymers.

At the core of this suggested development is the understanding that gradual enhancements will be unable to satisfy the challenging demands of the future global environment and what is required is a comprehensive step-change that involves the different academic, social, and commercial challenges be identified. However, man-made self-healing materials pose substantial challenges by requiring complex structures. Although a large number of papers on the self-healing mechanism are published every year; the study of self-healing concepts remains an active field. Within the context of self-healing materials, many areas have been explored to achieve a common goal to prolong the functional life of composite structural elements, while reducing costs. Interest in the areas of 3D printing self-healing development, new improvements in technology, has increased in the last few years.

The promising contribution in the field of damage mechanics is the development of smart capsule dynamics at the micro-level which can allow the added material to unfold in the same direction when the strain is removed due to crack initiation or propagation. No external intervention or initiation is required in the proposed self-healing system. In academic terms, this has importance for the currently published methods, and will, therefore, contributes to the advancement of knowledge. Computer simulations are also an open window of opportunities to design innovative self-healing nano-systems and provides effective direction and

guidance to the efforts of research and scientists for the fabrication of self-repairing systems.

3 THEORY OF SELF-HEALING BASED ON STRAIN RELEASE PHENOMENA UNDER EMBEDDED STRUCTURES

3.1 Introduction

Materials and structural components are characterized by their ability to break or fracture due to the application of external force. This force can be mechanical, thermal, chemical, caused by radiation or a combination of these factors. The working life, efficiency and overall strength reduce when a structure is damaged. However, the type of damage also plays a significant role in the repair mode required for a particular structure, which often makes the overall process complex and time-consuming. The available self-healing mechanisms reported in previous research work are still very far from real-life implementation and are only on a limited, laboratory scale. The underlying reason for such action is the rheological nature of elastomers that resists the origami structure performing its desired function. A bond level chemical reaction is required for complete healing. In contrast, external disturbances such as the increased temperature of the surroundings can also interfere with the process and retard the self-healing rate. These complex requirements, the inclusion of external disturbances, and reactions make the existing self-healing mechanisms almost impossible to implement in 3D printed products. In this research study, a comprehensive design of an origami-based self-healing beam is presented that could be included in the 3D printing process.

3.2 Relationship of Origami Design with Stress and Strain for Activation

Origami-based structures can be used with laminated composites to make lightweight structures capable of reducing the effect of crack propagation. Usually, origami-based self-healing (OSH) is applied to the areas where crack propagation has greatly changed the surface area. An alternative method is to create smart 3D printed products by embedding novel origami-inspired capsules in the layers of a printed component. The application of such capsules could

create an artificial network that will make 3D printed products resilient to external forces and disturbances. Another cost-effective method for producing a self-healing origami design is standard fused deposition modelling (FDM). As stated above, like a human hormone system that actuates when a virus or bacteria enters the body, a strain removal-based actuation for origami-inspired capsules can radically transform the self-healing capacity in components or structures. Strain removal of an entire component can be initiated by surface or subsurface damage. When strain removal occurs below the surface, the capsules begin to unfold and expand (see Figure 3-1). A previous research study introduced zipper-coupled tubes derived from the Miura-ori pattern to undergo kinematic stretching and shear of a thin sheet. The arrangement is light and can be actuated by the action of a force. The research demonstrates that the design of this origami arrangement is ideal for self-healing cantilever beams that carry perpendicular loads.

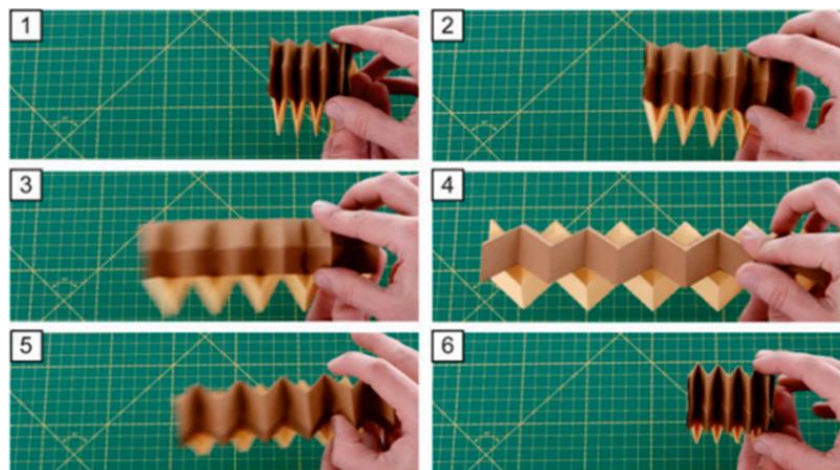


Figure 3-1 Deployment of the sequence of a zipper-shaped origami for a cantilever beam [141].

In rigid and static structures, the encapsulation of folded materials, such as origami, can induce strain-release, promoting self-healing properties. This helps a structure overcome extreme fatigue, micro-crack failure, and material degradation. Moreover, as noted above, by activating the self-healing process, the material becomes safe and durable in operation, reduces inefficiencies due to damage and saves the time and cost of replacing it.

The promising combination of readily available healing conditions (e.g., room temperature) and the useful mechanical properties of thermoplastic polyurethanes (TPU) has drawn a substantial amount of scholarly interest in TPU in the wider domain of self-healing polymers. While various reversible chemistries can facilitate healing, hydrogen bonding between urethane units at the broken interface is usually the most efficient way to engender interfacial healing. However, high reversible bond density can cause micro-crystals to form and inhibit macromolecular dynamics, which impedes healing.

This research will describe how relationships between design and stress and strain for activation manifest themselves in origami. Two of the most important concepts are an understanding of the relationship between origami design and stress/strain for activation, as well as finding ways to measure these relationships experimentally. It will also discuss some new experimental findings concerning origami in regard to stress/strain for activation. There are many techniques used in folding origami shapes. Some of the most common folding techniques and their internal structure are listed in the methodology chapter. The folds create different patterns and shapes depending on how the creases are placed on the capsule, their length, and direction. An origami capsule is designed to fold a series of polymers into a variety of shapes. The design has a particular effect on the stress and strain in the material, which changes the mechanical properties, toughness, strength, and elasticity. The relationship between origami design and stress can be analysed by first understanding how an origami-folded capsule works mechanically.

To better explain the relationship of origami design with stress and strain activation, it is essential to include concepts from Griffith's energy balance, which states that "the energy balance is purely dependent on the strain energy principle and bond energy retained in the surface of the crack".

Mathematically,

$$\begin{aligned} \text{Total energy} = & \text{Bond energy (both surfaces)} + \text{Strain energy of the plate} \\ & + \text{Strain energy removed from the generation of crack} \end{aligned}$$

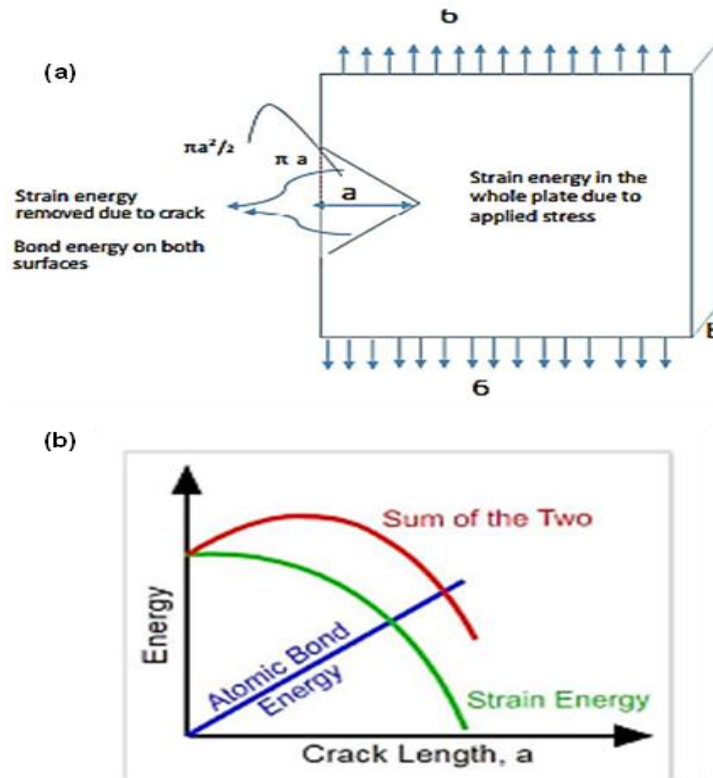


Figure 3-2 a) Schematic of the strain energy in the whole plate due to stress. b). Graphical representation of relation between crack length and energy applied to the beam.

Figure 3-2 shows that the energy associated with the atomic bond is directly proportional to crack length, whereas the strain energy (i.e., the sum of two + whole plate) decreases with crack length. The atomic bonds of elastomers are significantly affected by a change in temperature; therefore, the promising combination of readily available healing conditions (e.g., room temperature) and the useful mechanical properties of TPU has meant TPU has attracted substantial interest in the wider domain of self-healing polymers. While various reversible chemistries can facilitate healing, hydrogen bonding between urethane units at the broken interface is usually the most efficient way to engender interfacial healing. However, the high reversible bond density can cause micro-crystals to form and inhibit macromolecular dynamics, which impedes healing.

Origami design, involving the calculation of folding sequence, is well understood in structures with different thicknesses. Putting these folding principles to use in

morphing panels with limited thickness on the other hand, brings problems with folding, structural integrity, and the ability to fold itself. The orientation of the filaments with respect to the loading direction may give the greatest bending angle for an origami capsule hinge, regardless of whether the hinge is vertical or inclined with respect to the loading direction. Based on this theory, complex origami folding patterns were formed and are shown in the next chapter.

Origami-derived structures exhibit high flexibility, as their properties are dynamically coupled with changes in folding patterns. The folding deformation mode of an origami structure mainly determines its mechanical properties. This kind of structure is capable of transforming from one configuration to another by folding along designed creases, and the self-folding behaviour of capsules with different shapes and different printing orientations were explored experimentally. For the origami capsule shapes positioned at an angle relative to the loading direction, the orientation should be aligned with the loading direction to obtain maximum bending strength and prevent shear deformation.

When a cross or roller origami capsule unit is folded, the capsule surface is fixed, and a uniform load is applied to the adjacent capsule surface. Each capsule surface may be considered a force-balancing surface if the origami unit is folded smoothly at a suitably slow pace. On the surface of the capsule, the two edges that are connected to the cross are just supported edges that can bend when the cross or roller bends.

The folding pattern that allows the stent to fold and unfold longitudinally and radially is one of the most interesting features of origami-derived structures. During folding, the length and diameter of the stent reduce, whereas they expand during expansion. The folding process introduces subunits enclosed by folds, improving the structure's flexibility. These creases allow the folded stents to be flexible due to their tight packing. The structure can shrink and grow without getting tangled or cracking because it is folded instead of connected in a more complicated way.

The four arms of the crosses of an origami capsule are identical parallelepipeds, and the length and width of each capsule surface are far greater than its thickness. During motion, there is no longitudinal load (parallel to the direction of the midplane), so the deformation may be neglected. Consider just the transverse deformation (vertical to the direction of the mid-plane). As a result, each capsule surface can be viewed as a thin-origami element, and the deformation issue of the faces can be reduced approximatively to the bending problem of a capsule exposed to transverse stresses. The capsule's deflection is the amount each point on the mid-origami capsule moves up or down. When the ratio of the deflection to the thickness is less than $1/5$, the problem can be further defined as a small deflection bending problem of a thin capsule. The desired deformation of the origami surface will be very small in practical applications and so the bending theory of a thin origami capsule with small deflection is used. When the thickness of the capsule is not involved, all parameters and variables are referred to as those of the mid-origami capsule.

However, the actuation or unfolding of such capsules under strain release due to crack initiation or growth within a structure requires an understanding of its mechanical behaviour, especially in embedded conditions. To introduce and control such a process requires a workable relationship between the initial stress on the embedded capsules, the displacement of the origami folded parts in a direction to release the strain, and the magnitude of the strain released. An overall understanding of the mechanical behaviour of any selected polymer under elastic and plastic loads is necessary to assess its usefulness in the form of an origami capsule to provide the necessary strain release control.

The encapsulation of folded material, such as TPU in rigid and static structures, can induce self-healing properties in a structure, assisting it in overcoming extreme fatigue conditions, material degradation, and failure due to micro-cracks. Moreover, by activating the self-healing process, the material becomes safer and more durable, saves the time and cost of replacing particular items, and reduces inefficiencies incurred due to damage.

3.3 Theory of Self-Healing Due to Strain Release by Origami Capsules

The basic concept of origami-inspired capsules is as shown in Figure 3-3. The capsules will be designed to be restrained within the layers of the parent components or parts but unfold once damage or a void occurs and overall strain energy within the material is reduced. The extensions fill the damage void while keeping the surface area covered at their original deposited location. The capsules remain inactive in the case that strain removal does not occur.

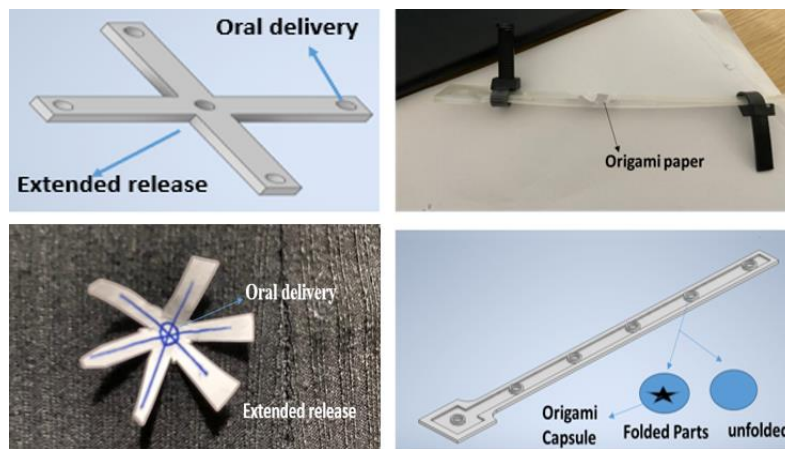


Figure 3-3 Demonstration of the concept of the proposed “origami” healing mechanism

Extending the research on origami-based self-healing, meant investigating the elastic energy behaviour of origami shapes with curved-creases to assess material bending behaviour. For this purpose, a large elastic bending machine was employed for the purpose of finding a better design solution. However, the origami design model is determined by the different patterns that dictate the folds that form the 3D shape. Therefore, deciding on an origami base is considered to be only the first step towards determining the folding process. The model can then be used to determine the origami shape capsule and predict the likely results. Once the results are experimentally validated, the healing process can be correctly determined.

The experimentation in this research included strain gauges of different thicknesses. These were tested for conductivity and then loaded onto a load frame and tested for deflection, which generated strain curves. The results of both parts of the test, including the effects of the material and binder on the 3D, printed ABS, were observed. Previously investigations of simple polymeric origami embedded in structures did not include their bending behaviour. This research, however, addresses this gap by examining the ABS simple beam, origami capsule, and origami capsule embedded inside the structure, in a capsule structure.

Origami-based encapsulation has shown some promising results. even when the mechanical strength and healing properties were tested on soft and weak materials helping these structure to overcome extreme fatigue conditions, micro-crack failure, and material degradation. Addition of origami capsules make such material safer and more durable in operation, saving time and cost of replacement, and reducing the inefficiency due to damage.

3.4 Conclusion

The chapter discusses the theory of self-healing based on strain release phenomena with embedded structures. Preliminary concepts, such as bonding-level reaction, external disturbances, and the rheological nature of elastomers, will be discussed in the light of self-healing. Additionally, the effect of strain release during the crack propagation process will be presented in the light of mathematical calculations to attain the optimal design for the origami. Peer reviewed research will be presented and discussed to support the arguments on origami capsule design and application. Applying the concepts learned, research will fabricate an origami structure made of self-healing material, such as ABS and TPU, that can help the damaged section regain strength and rigidity. The results will be analysed using graphical analysis to assess the influence of changing such parameters as thickness, material, applied force, strain rate and modulus on the beam's strength and self-healing properties.

4 METHODOLOGY

4.1 Introduction

In this research, we will analyse the effect of applied force, position and deflection on the behaviour of a simple beam, with and without origami capsules. First the deflection elastic curve of a simple beam was determined for the general case, as were the equations that determine the strain energy of each position on the elastic curve. These equations will be solved numerically with aid of MATLAB. Furthermore, research obtained an approximation for the deflection of a simple beam with origami capsules from the equations presented for simple beam.

In this research, the response of polymeric beams of ABS and TPU materials under elastic and plastic loads was investigated. The experimentation process included the use of strain gauges of different thicknesses to determine the deflection of the cantilever beam under test. The tests included observation of the effects of the material and binder on two types of 3D-printed beams and were designed to test their elastic and plastic responses under different bending loads. As explained above, these responses were used to develop an origami capsule-based novel self-healing mechanism triggered by crack propagation due to strain release in a structure.

However, the bending load and delamination of a double cantilever beam were also tested so as to learn more about the elastic and plastic behaviour of the beam. A layer-by-layer assembly technique was applied to prepare the self-healing mechanism with ABS, TPU and thermoplastic elastomers (TPE). In this process, the model was sub-divided into a number of layers, which were later printed one by one. In the FDM process, thermoplastic filaments were used as the starting material. The filaments were heated in the nozzle and then distributed on the printing plate layer by layer to produce the desired 3D structure. These techniques have been well developed, and commercial apparatus could be used. However, the mechanism behind the tests should be understood to analyse the results accurately. Therefore, the study analyses the origami-embedded beam structures and concepts involved during the self-healing process. Firstly,

research considered elastic and plastic regimes for simple beams using different materials (ABS, TPU and TPE) and then observed the responses of the materials in helping the damaged section regain strength and rigidity as shown in Figure 4-1. And from those observations, research created capsules which were then tested in various shapes.

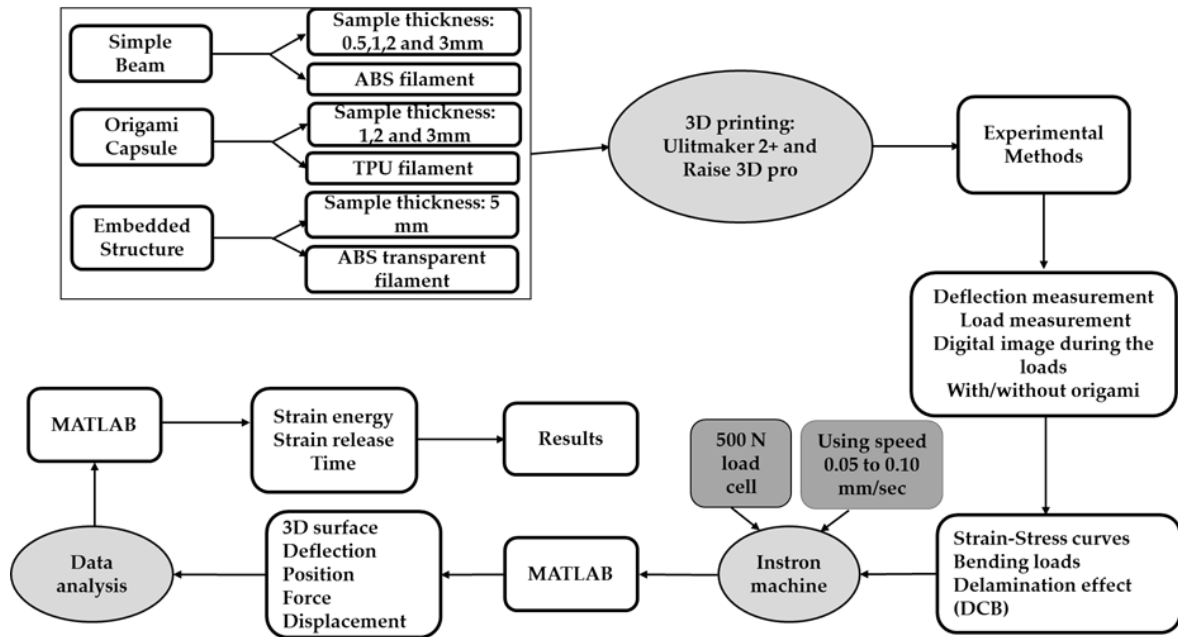


Figure 4-1 Methodology diagram

Due to its folded and unfolded states, origami is an excellent starting point for conceal-and-reveal motion design. It is evident from the findings that origami is an emerging technology that can transform from, effectively, a 2D shape into a 3D shape that can be used for reforming a material and aiding the self-healing process within that material. The research on the encapsulated origami placed inside the double cantilever beam indicated positive results for self-healing (see Figure 4-1), providing experimental validation of the effectiveness of using embedded capsules. Once the model is validated, it can be used to design origami folding patterns for capsules utilising the modelling equations which have been derived from empirical results. Next, research will utilise these patterns to study different origami shapes in, say, ABS using the empirical formula and approaches utilised so far. Thus, the model will be used to determine the likely

behaviour and effect of the origami capsule. Afterwards, research will test the capsules and verify the results. Once the capsules have been validated, research will apply them to the specimens, and then induce cracks in the specimen and observe its behaviour to determine whether the presence of the origami capsules is assisting healing. In this way, research will be validating our model.

4.2 Elastic and Plastic Behaviour of ABS Simple Beam Under Different Loads.

The bending load is a powerful tool in characterizing the mechanical properties of Acrylonitrile butadiene styrene (ABS) plastic. The relationship between the cantilever beam and the bending behaviour of ABS cannot be understood without some grasp of the thermodynamics that result in the corresponding behaviour of plastic ABS. The applied load and deflection were applied on the free end, close to the fixed support. Specifically, bending loads were placed on the ends of rectangular beams of the polymeric materials to better understand their elastic and plastic behaviour.

4.2.1 Material Selection

The first polymeric material selected was ABS, one of the most common raw materials used for printing beams via fused deposition modelling [142]. ABS has good impact resistance, high rigidity, and strain resistance, etc., even at low temperatures [143], properties that make it a suitable material for the intended application. The ABS used was in the form of a filament which would be extruded using the hot ends of the 3D printer nozzle by inputting the required geometry into the 3D printer [144]. The ABS filament used in this research has a diameter of 2.85 *mm*. Sample parts were fabricated at variable parameters and tested for bending strength. More details of the FDM ABS are presented in Table 4-1. A Ultimaker Cura 4.0 printer was used to print the ABS simple beam, as shown in Figure 4-2.

Table 4-1 Ultimaker Cura 4.0 acrylonitrile butadiene styrene (ABS) filament specifications.

Filament Specification	Value
Diameter	$2.85 \pm 0.10 \text{ mm}$
Tensile modulus	1681 Mpa
Elongation at yield	$3.5 \% \text{ ISO 527 (50 mm/min)}$
Flexural modulus	2070 Mpa
Melting temperature	$225\text{-}245 \text{ }^{\circ}\text{C}$
Vicat softening temperature	$97 \text{ }^{\circ}\text{C}$



Figure 4-2 Ultimaker 2⁺ printer 3D printing

4.2.2 Printing Parameters

The 3D printed sample produced with two printing parameters (i.e., layer thickness and raster orientation) were investigated at different temperatures. The platform was heated to $80 \text{ }^{\circ}\text{C}$ with a screw speed of 50 mm/s . At least 1 kg of filaments with a diameter of $2.85 \pm 0.10 \text{ mm}$ served as the extender. During the printing process, the slicer programmed used this diameter to calculate the required feed rate. These parameters also had an impact on other aspects of the FDM process, such as manufacturing time and cost.

Orientation: this was configured using 3D printing software as the path on which the nozzle passed over each layer of the FDM section.

Layer thickness: this was also configured using 3D printing software. It determined the number of layers in each part and the height of each layer.

To cover the typical range of printing parameters, three values were assessed for each parameter; these are typically used as the default setting in Ultimaker Cura® software. The raster orientation options cover two extreme cases, where the external load and fibre direction are parallel or perpendicular. The default profile was also used to calculate layer thickness. These values provided excellent printing quality while also covering the typical setting range of the chosen 3D printer. The mechanical printer parameters are presented in Table 4-2 and depicted in Figure 4-3 and Figure 4-4 [145]–[147].

Table 4-2 Printing parameters

Parameters	Values
Nozzle size (<i>mm</i>)	0.4
Layer thickness (<i>mm</i>)	0.1,0.2
Build orientation	0, $\pm 45^\circ$, 90°
Infill density (%)	100

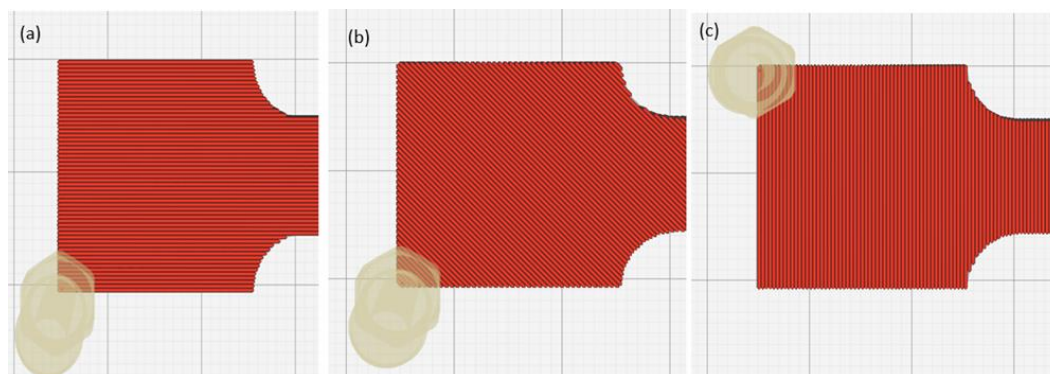


Figure 4-3 Printing Directions of ABS: (a) 0 orientation; (b) ± 45 orientation; (c) and 90 orientation. (Top views of the beam)

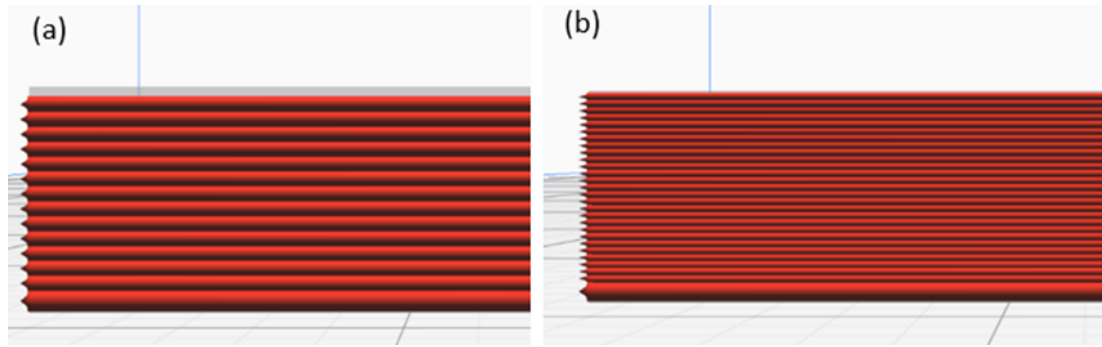


Figure 4-4 Layer thickness: (a) 1 mm and (b) 2 mm

When the temperature changes, the mechanical properties of ABS change dramatically. Because of this, three environmental temperatures were chosen for this purpose: 50 °C, 60 °C and 70 °C. Because ABS is temperature sensitive, 70 °C was chosen as the upper limit of temperature. When the temperature rises, the mechanical strength declines [148]. When the environmental temperature exceeds 70 °C, the structure becomes too soft to support the experiment [149].

4.2.3 Specimen Preparation and Manufacturing

The specimen geometry was designed for a simple beam using the Invector software. The cantilever beam was designed using the Invector software. The specimen and selected dimension for ABS are shown in Figure 4-5. The specimen type was printed at thicknesses of 0.5 mm, 1 mm, 2 mm, and 3 mm. The bending specimen was first created in Invector software, exported in stereo lithography (STL) format, and then imported into G-code files for printing using Ultimaker Cura 4.4 software (Ultimaker 2+ printer), as shown in Figure 4-6.

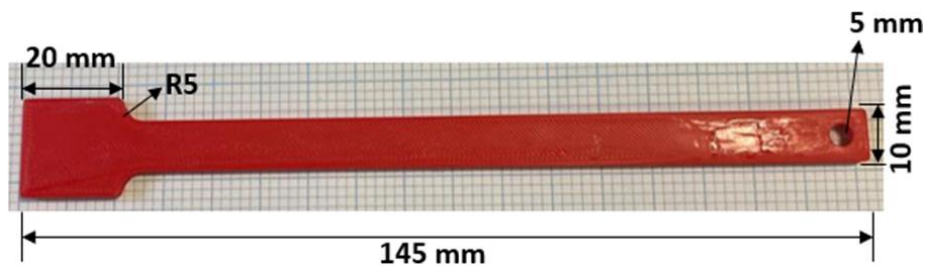


Figure 4-5 Sample printed with 0.4 mm nozzle

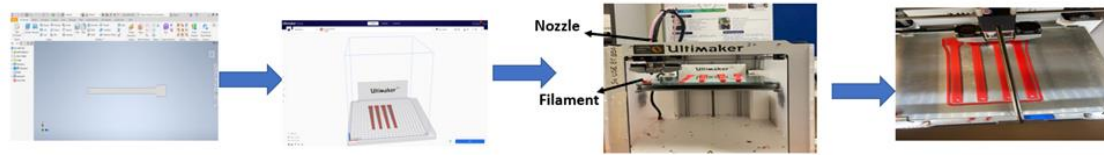


Figure 4-6 The process flow of fused deposition modelling

The ABS samples were printed under two different conditions. The printing speed was kept constant at 60 mm/s , the layer height was set at 0.4 mm , and the bed temperature was 80°C . One sample was printed at a print-head temperature of 235°C and 0.4 mm infill distance. The second sample was printed at a temperature of 240°C and 0.4 mm infill distance. The blend was composed of 40 wt%, 60 wt%, and 80 wt% ABS. The properties of the selected materials were considered suitable for application. The simple beams were fabricated in several thicknesses and tested for bending strength. These specimens were further subjected to test strain gauge and bending load with the help of a universal testing machine (UTM). The specimens fractured in different ways due to vibrations in the process thickness. The stresses were calculated according to the applied load and deflection point obtained by the UTM system.

Maximum beam Deflection in Equation (4-1):

$$\delta_{max} = \frac{PL^3}{3EI} \quad (4-1)$$

Bending stress:

$$\sigma = \frac{1}{12}bh^3 \quad (4-2)$$

$$\text{Strain} = \frac{\text{bending stress } (\sigma)}{\text{young modulus } (E)}$$

where the P is Applied load (N), L is length (mm), b is width of specimen (mm), h is thickness of specimen (mm).

4.2.4 Experiment Setup

The simple beam structure in this study was investigated under bending load. This experiment was simply to record flexural stiffness using a bending experiment on a beam specimen. The beam had been 3D printed using ABS polymer. The bending load was considered to fill the gap. As a result, the research created a specially designed experimental setup, which is described in this section.

The entire experimental setup, the reason is that the bending stress increases near the free end is depicted in Figure 4-7. A universal testing machine was used for this purpose. The changes that had to be made were as follows. This machine was chosen because of its high level of calibration and low error percentage, which obviated the need to calibrate manually using individual components. The tensile loading setup depicted in Figure 4-8 was replaced with a one-point bending mechanism, as shown in Figure 4-8. The experimental methods used four specimens of different thicknesses and were repeated three times.

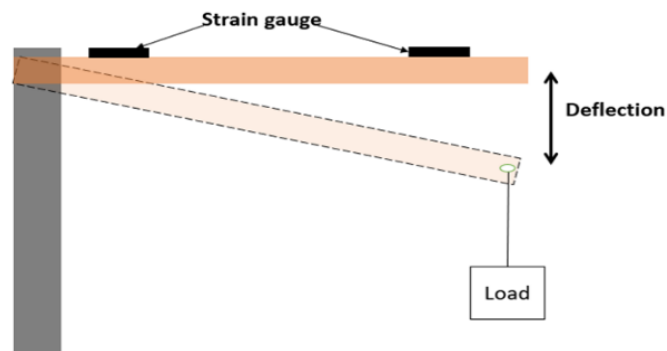


Figure 4-7 Bending moment diagram of the beam with single load at the end.

The assembly applies accurate force to the end of the beam. The signal express generator was used to get the strain gauge. The simple beam was closed in fixed support by the UTM. The point bending experiment was conducted at room temperature. Two of the strain gauges were used on top of the beam, one at the free end and the other in closed fixed support. The applied load was used at the free end to get the load; deflection, and time data were recorded for 10 s by a

camera. Four ABS samples (0.5 to 3 *mm* in thickness) were tested to obtain useful data, and the readings were averaged, recorded, and combined into a single graph on excel. To define the stress and strain rate dependent on material behaviour, self-healing requires bending tests to be performed at different rates of deformation; thus, bending tests on ABS were performed at several deformation rates ranging from 10 to 60 *mm/s*. This meant that the load on the beam varied with deflection during the test. The digital image correlation optical method was used to measure the deflection in the bending tests.

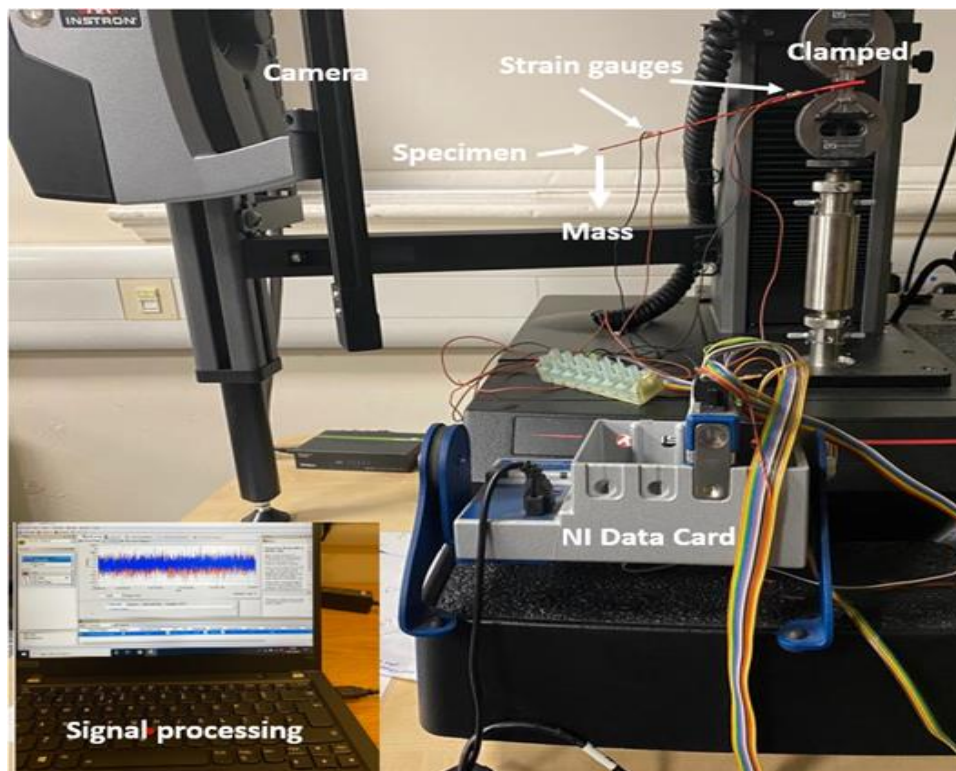


Figure 4-8 Experimental apparatus

4.3 Elastic and Plastic Behaviour of Polymeric Origami Capsules

4.3.1 Material Selection

The origami materials tested in this study were Thermoplastic polyurethane (TPU) and thermoplastic polyester elastomer (TPE) which were used to produce origamis in Idea-Maker software. The second material chosen was TPU. This is

of interest because of its versatility over a wide range of mechanical properties, good abrasion resistance and low density. TPU is more elastic than ABS and very suitable for folding into capsules. TPU has more advantages than other polymers, such as being extremely flexible, durable and smooth to the touch. The third material used in this study was TPE. Copolymers with soft amorphous and hard crystalline regions are thermoplastic elastomers. These materials, in particular, exhibit a combination of two distinct characteristics: high elasticity, high flexibility and a thermoplastic nature (for instance, withstanding processing temperatures above their melting temperature and recyclability). All these produced filaments of $1.75 \pm 0.05 \text{ mm}$ in diameter for the present experiments; more details of these materials are given in Table 4-3.

Table 4-3 Properties of the printing materials used for experiments.

Filament specification	Melting temperature	Tensile modulus	Tensile elongation	Printing temperature
1. TPU (98A)	225 °C	150 <i>Mpa</i>	450 %	235 ± 10 °C
2. TPE	175-195 °C	14 <i>Mpa</i>	990 %	60 °C

4.3.2 Printing Parameters

A Raise-3D Pro printer was used to print the origami capsule (star and roller) shown in Figure 4-9. The 3D printed capsules were produced with printing parameters, layer thickness and orientation as discussed in section 4.2.2. Experimental tests were run using the Raise 3D Pro printer with two nozzles and Idea-Maker software for generating the specified printing parameters. The nozzles used in both extrusion heads had a die diameter of 0.4 *mm*. TPU was placed in the first position in the printer, and TPE on the second. The platform was heated to 60 °C with printing speed from 20 to 75 *mm/s*. At least 500 *kg* of filaments with a diameter of $1.75 \pm 0.05 \text{ mm}$ serving as the extender were supplied by RS Components. During the printing process, the slicer programme used this diameter to calculate the required feed rate. The printing parameters were constant for all samples in Table 4-4, excluding the surface layer, where the top and bottom patterns were changed.

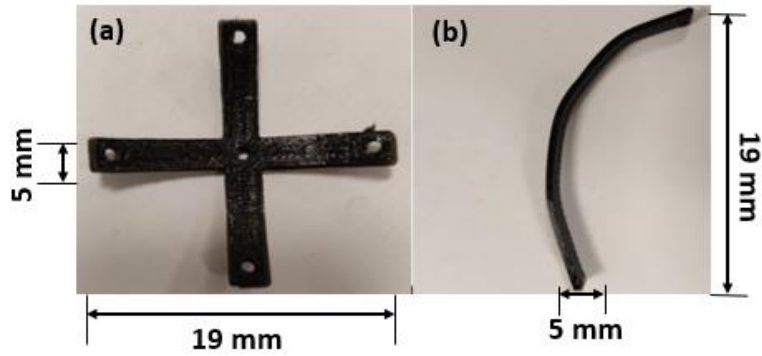


Figure 4-9: Origami capsules: (a) star, and (b) roller

Table 4-4 Printing parameters for TPU and TPE

Printing setting	Extruder 1: TPU	Extruder 2: TPE
Layer Height	0.2 mm	0.2 mm
Infill density	1.16 g/cm ³	1.09 g/cm ³
Printing speed	75 mm/s	20 mm/s
Infill pattern	Grid/Line	Grid/Line

The top and bottom layers are involved in interface adhesion. The Idea-Maker software supported two top and bottom patterns: Lines and Grid. In this study, two patterns were compared: Lines and Grid in various configurations. Figure 4-10 depicts an example of the configuration and method of applying the second material layer through the printer nozzle.

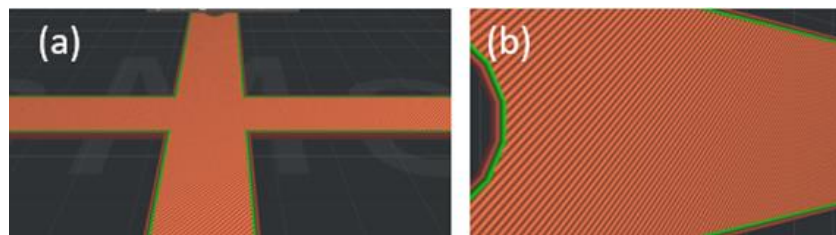


Figure 4-10 Layer height of the path of filament application through the printing nozzle. Layer thickness: (a) 1 mm (b) 2 mm.

4.3.3 Capsule Preparation and Manufacturing

The 3D printed capsules were produced from the extruded filaments using a Raise 3D printer. In this research two types of capsules were printed: star and roller shapes for bending load with the diameter shown in Table 6-1 above. These capsules were designed using Inventor software; the 3D models were exported

in an STL format, processed by slicer, and exported in G-code format as shown in Figure 4-11. A star infill density of 100 % was selected with the angle set at configuration 0/0, to maximise the density and the mechanical properties of the resulting samples. A roller infill with a density of 80% was selected. After a process optimization, the following parameters, were selected for the 3D printing: layer height 0.2 *mm*, nozzle temperature 250 °C, bed temperature 60 °C, and nozzle 0.4 *mm*.

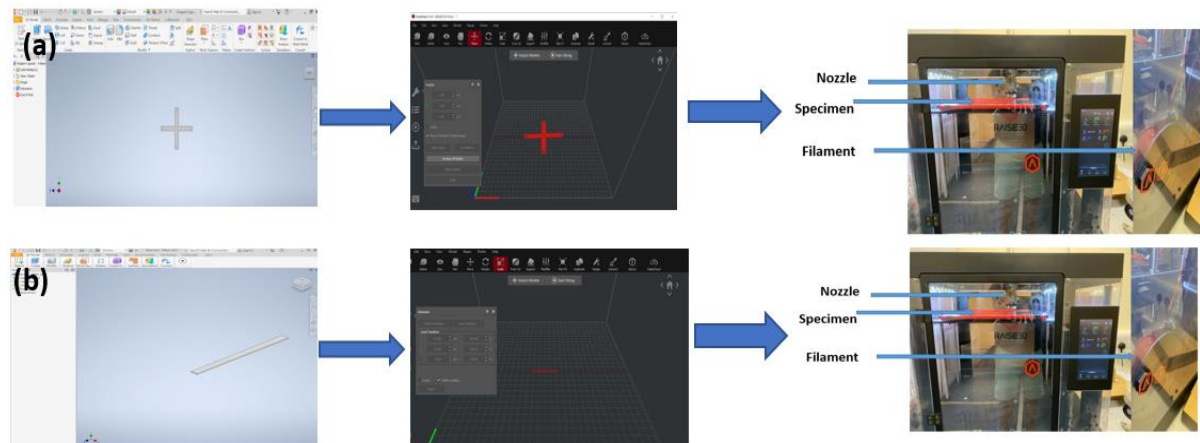


Figure 4-11 Three steps in fused deposition modelling (a) Cross and (b) Roller

4.3.4 Experiment Setup

The simple ABS beam was replaced by one with an origami insert, first a cross and then a roller (see Table 6-1). The loads were applied to the origami capsule and measurements taken via the computer using the signal conditioning unit and data logger. The experiment was carried out with three tubes, one 1.0 *mm* thick, one 2.0 *mm* thick, and one 3.0 *mm* thick. Each time the camera was set to a required value, and the corresponding strain values were recorded. After repeating the experiment three times, the average value of the results was obtained and noted. The origami capsules were designed using Inventor software with different shapes to test the workability of different capsules, (see Figure 4-9). The designs of the capsules were such that their geometrical features were determined by the initial pre-stressed conditions. The bending load was considered to fill the gap.

4.4 Analytical Approach to Determine the Strain Release and Capsule Wing Displacement

Bending strength is defined as the ability of a material to resist deformation under a load; it represents the highest stress experienced within the material at its moment of bending. The bending test exerts uniform stress on the free end. In this section the deflection amplitude under the bending strength is also calculated.

The geometry of the pin-supported beam is illustrated in the above Figure 4-12.

Consider a pin-supported beam of length (L_b) at equilibrium. The force (F) is applied at an extreme point of the free end of the beam, which is supported by a spring underneath having a reaction of force L , as shown in Figure 4-12. Reducing the amount of force from the beam decompresses the spring, and the beam is lifted at an angle (θ) from the horizontal axis.

In order to estimate the potential energy displacement of the spring, let us consider the beam subjected to deflection due to the decompression of the spring. This occurs when the force (F) from the beam no longer keeps the beam compressed. The free body diagram shows that there are three dominant forces that are responsible for deflecting the beam, namely:

Work done by the force = Work done by the spring's potential energy

By applying Moment at pin support, we get the following equation:

$$M_{pin} = F(L * \cos n \theta) - R_{spring} (L * \cos n \theta) = 0 \quad (4-3)$$

Since R is the reaction force of the spring, which is given as:

$$M_{spring} = K_s * (L \sin n \theta) \quad (4-4)$$

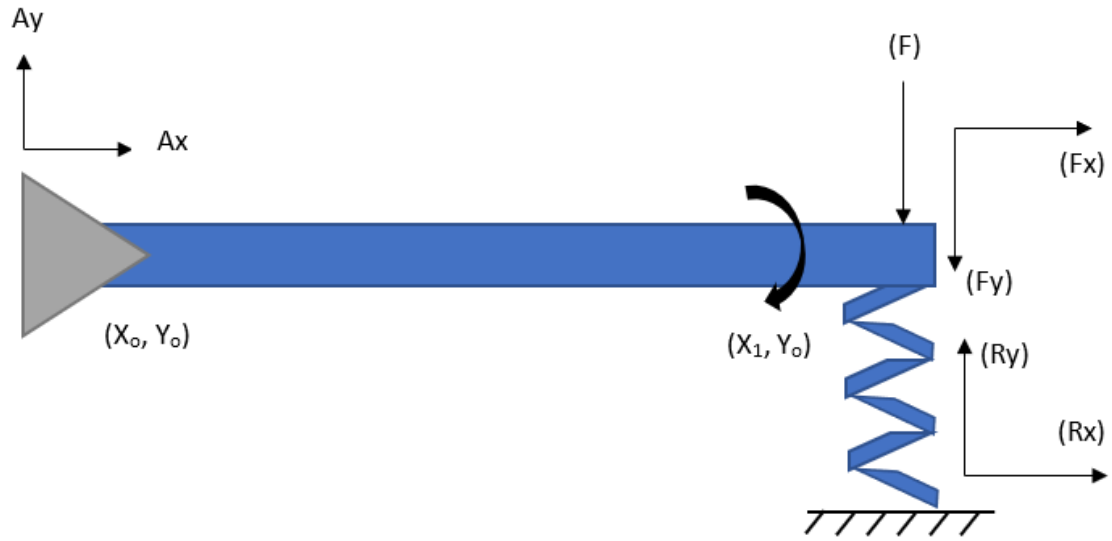


Figure 4-12 Analytical modelling description

Here, K_s is the stiffness of the spring (N/m).

Putting the value of Equation (4-4) and (4-3), we get:

$$F(L * \cos n \theta) - R_{spring}(L * \cos n \theta) = 0$$

$$F(L * \cos n \theta) - k_s * (L \sin n \theta) * (L * \cos n \theta) = 0$$

$$F(\cos n \theta) = k_s(L^2 \sin n \theta \cos n \theta)$$

$$F(\cos n \theta) = k_s * L \sin(n \theta) \cos(n \theta)$$

$$F = k_s * L \sin(n \theta)$$

$$\left(\frac{F}{k_s * L} \right) = \sin(n \theta)$$

$$\sin^{-1} \left(\frac{F}{k_s * L} \right) = n \theta \quad (4-5)$$

Now, finding the angle by using Equation(4-5) and assuming the values of the parameters, we get:

$$n=1$$

$$\sin^{-1} \left(\frac{F}{k_s * L} \right) = \theta \quad (4-6)$$

Here, k indicates the stiffness of beam and given as:

$$k = \frac{3EI}{l^3}$$

The above expression is valid for the spring supported beam [150].

where I indicates the moment of inertia (mm^4), b is the breadth (mm), h is the height (mm), E is the elastic modulus (N/m^2), and L is the length of the beam (mm).

$$I = \frac{1}{12}bh^3$$

The area of the beam is determined by the formula:

$$A = bh$$

4.5 Experimental Approach to Investigate the Possibility of Strain Released Based Origami Self-Healing Capsules

This experimental approach concentrated on the self-healing mechanism and ability of origami capsule inside an embedded structure. Two tests were used in these experiments: one is the bending load test, and the other is the delamination test of a double cantilever beam. When a specimen is bent, its beam experiences a range of stresses across its entire depth. The mechanical behaviour test of damaged materials following the self-healing process can manifest via changes in the bending strength, young modulus, strain energy and strain release. The following tests can be used to evaluate the self-healing behaviour.

4.5.1 Bending Test

The behaviours were studied of the ABS simple beam and origami capsule (TPU & TPE) subjected to gradual increases of the applied load at the free end to determine the strain energy and time. A bending test is the classical method for measuring the deflection of material using a simple beam and origami capsule

shape [151]. The test sample has a uniform cantilever beam of rectangular cross-section, loaded at its free end by concentrated applied force of magnitude such that the beam weight may be ignored (Figure 4-13). This situation may be regarded as a case of beam stress provided that the beam thickness t is 0.5 mm to 3 mm relative to the beam length. In the bending test, the ABS simple beam and origami capsule (TPU and TPE) are supported by two strain gauges in the top, and a load is applied at the end of the beam. The elastic modulus of ABS, TPU and TPE, which involves the measured load L ; corresponding measurements of the deflection δ , are given in Equations (4-1).

Samples were prepared for the bending test from all three materials: ABS, TPU and TPE. Figure 4-13 shows a 3D printed cantilever beam shaped test of a simple beam and origami capsule under bending test conditions, using the Instron 5944 Universal Testing Machine as shown in Figure 4-14.

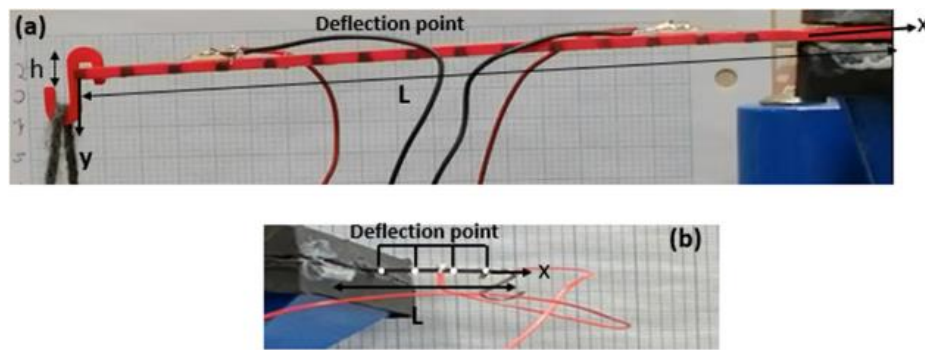


Figure 4-13 Deflection points of end load of (a) ABS simple beam and (b) origami capsules

Generally, none of the specimens returned to their original position. The ABS printed samples showed that they did not break even when bent at 90° . The TPU and TPE origami capsules were more flexible than the ABS sample as proved by the bending test at a 90° angle. Bending damaged the test specimens [152], but they recovered almost completely, with a self-healing efficiency of approximately 97%. Wu et al [153] also demonstrate the self-healing of a fractured and delaminated multi-ply polymer matrix composite.

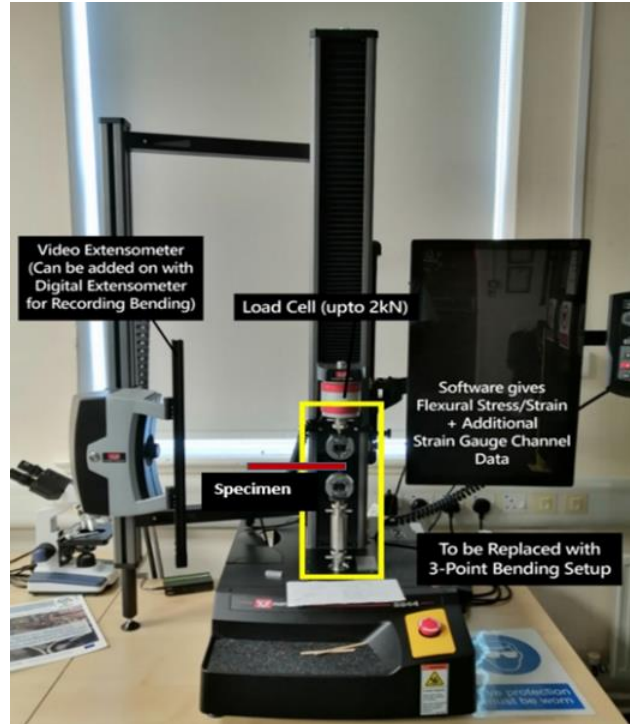


Figure 4-14 Instron 5944 Universal Testing Machine

4.5.1.1 Testing Machine and Experimental Setup

Testing of the sample began by setting the thickness of the beam. Moreover, to test the bending properties of a material system, a single test set-up was created. The samples were tested at a rate of 1.5 mm/min for the test methods at room temperature (20°C). Custom fixtures were manufactured to load the specimens in a test Instron Universal Testing Machine equipped with a 500 N load cell. The fixtures, shown in Figure 4-5 and Figure 4-9, used a simple beam and origami capsule to ensure that the load path through the sample was free of bending. Next, all thicknesses were tested, by applying the loads at the free end and getting a reading from the strain gauge, to calculate the deflection for each point. With regard to bending testing, the average stress in the samples at any applied load was determined by dividing the load by the cross-sectional area. The necessary deflection data were collected through the use of digital image correlation (DIC). It was extremely important not to change the position of the camera once it was fixed. It was expected that the modulus readings from the

gauges should be closely related to each other (i.e., there should be little difference between the readings).

This method compensates for a variety of potential flaws in loading and specimen geometry that occur during testing and cause inaccuracies. Because of the potential for grip slippage, loading mechanism compliance, and load cell compliance in such tests, DIC was chosen for strain measurement rather than crosshead displacement. In addition, when testing polymers, electrical resistance strain gauges mechanically reinforced the specimen, but they also raised strain gauge self-heating issues. The measurement of DIC strain on both sides of the sample compensated for any bending during loading. Using this single camera setup in front of the sample compensated for the rigid body motion by averaging the deflection from the side. The ABS simple beam preparation required only a light speckle pattern of black paint on the specimen and the white plastic background, thus obtaining a negligible reinforcement effect. Images of the samples were captured on camera to determine the deflection. During the processing in camera, the standard subset size of 30 and step size of 3 were used, which provided adequate strain and deformation data. After a sample was loaded into the testing machine and the preload was applied, a pair of reference images (one or two possible images) were taken at each point of the sample. To determine the deflections over the course of the testing cycle, these reference images were compared to images taken from the corresponding sides of the sample.

From the results research calculated the beam up to its deflection point, where it would go to a plastic regime. A further assumption was that the elastic regime would return it to its original position (0, 0) once the load was lifted. In the plastic region, it was unknown how much it would elongate. After confirming the results from the previous part, the behaviour of elastic regime had to be tested for loads from 1 to 410 *g*. In theory, the beam should come back to its original position. Whenever it reached the plastic regime, a new beam specimen was taken, and load was applied greater than the previous load to see how far it came back to its original shape. It should be noted that no beam that had already attained some

plasticity should be used for higher loads. In this way, research plotted a response between deformation and a plastic regime. The same procedure was followed for the elastic regime. After collecting the responses and empirical data, an experimental equation was devised to validate the formulation. After its validation, the dimensions were changed and lower values for the capsule were sought, to establish how much of the original shape was regained with different load values. Knowing this enabled us to design for our capsule. With the already established equation, research determined the behaviour of the capsule once we knew how much deformation affected the fold.

This methodology proved to be efficient, because research could test a single specimen, including mounting the specimen in the loading fixtures, taking initial undeformed DIC images, and loading the specimen through failure, in a matter of minutes. The complete DIC and universal testing machine set-up used for bending load testing is shown in Figure 4-14.

4.5.2 Delamination Test of a Double Cantilever Beam Test

The double cantilever beam test, introduced in [154], has been widely used to assess the self-healing properties of materials. The healing agent employed in double cantilever beam specimens filled an open delamination crack and repaired it. The load-displacement data were recorded using the delamination crack induced during a mode-I fracture test. The crack healing efficiency was evaluated through fracture toughness tests performed on virgin and healed specimens by origami capsules. After the first fracture, the specimen was left long enough for the crack to heal.

Quasi-static DCB tests were performed three time for three holes and pillars with a tensile test machine as shown in Figure 4-15. The loading value was measured with a load-cell attached to the tensile test machine. The opening displacement, time and crack length were measured with a camera. Different standards for mode-I fracture toughness have been developed. Several experimental works used the double cantilever beam (DCB) test, which involved measuring the critical strain energy release rate.

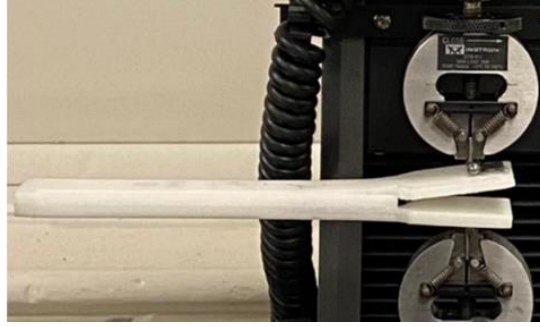


Figure 4-15 Photograph taken to measure the crack length and displacement during the quasi-static DCB test

4.5.2.1 Experimental Set Up

4.5.2.1.1 Beam Behaviour with the Origami Capsule Contained Within it

The set-up and experimental design for the DCB test is shown in Figure 4-17. The beams were 30 *mm* wide and 193.0 *mm* long, as shown in Figure 4-16, with a 40 *mm* longitudinal pre-crack extending from the front of the specimen (see Figure 4-17). End tabs of 30 *mm* width was glued to the external faces of the specimens on either side of the pre-crack and pinned to an electromechanical uniaxial testing machine with a 500 *N* load cell. The DCB tests were performed on an Instron testing machine with displacement rates that could be varied between 0.05 and 0.10 *mm/sec*.

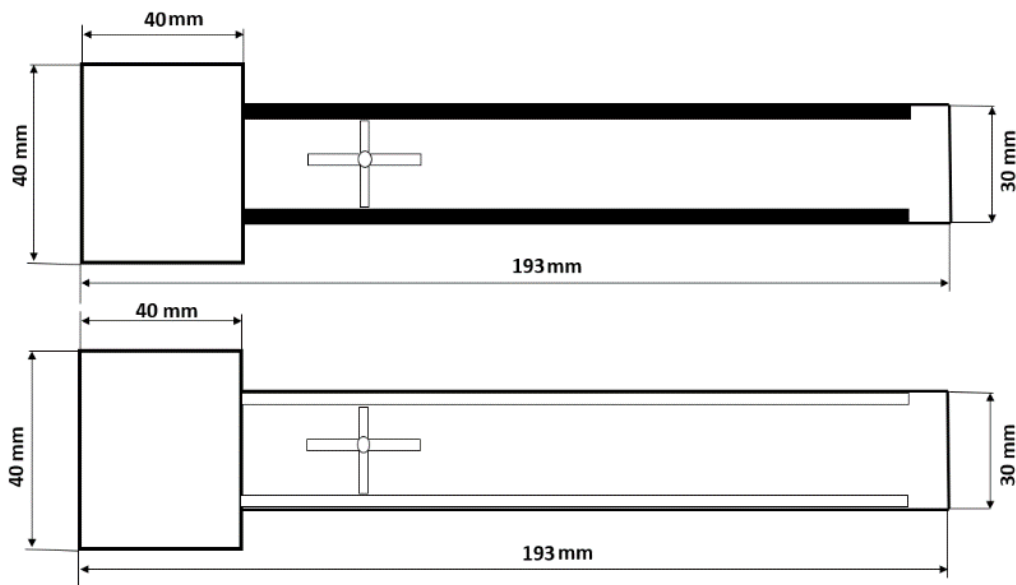


Figure 4-16 Geometry of double cantilever beam (DCB) (with hole and pillars)

Because the ABS samples were transparent, crack length was directly recorded from the top using a camera. Each sample was tested 3 to 5 times. The corresponding energy release rates and critical energy release rates were calculated using a simple beam. The programmed loading history was not monotonic: indeed, eight loading and unloading cycles at the same displacement rate were programmed into the machine to verify the absence of permanent deformations, which would indicate parasite sources of energy dissipation. For each cycle, the maximum displacement at loading was defined, as well as a minimum force at unloading, set at 500 *N* to avoid compression of the test specimen.

Three different types of specimens were printed, specified by Table 4-5, one for each set of parameters, of 1 *mm*, 2 *mm* & 3 *mm* thickness. Three specimens were manufactured and tested under the same conditions for each thickness to confirm the experimental repeatability of the results obtained.

Table 4-5 Specimen set-up (DCB)

Specimen	Beam thickness (<i>mm</i>)	Dimension, (<i>mm</i>) (Length/width)	Type of structure
1- With origami capsule	5 <i>mm</i>	193L/30W	With holes and pillars
2- Without origami Capsule	5 <i>mm</i>	193L/30W	With holes and pillars

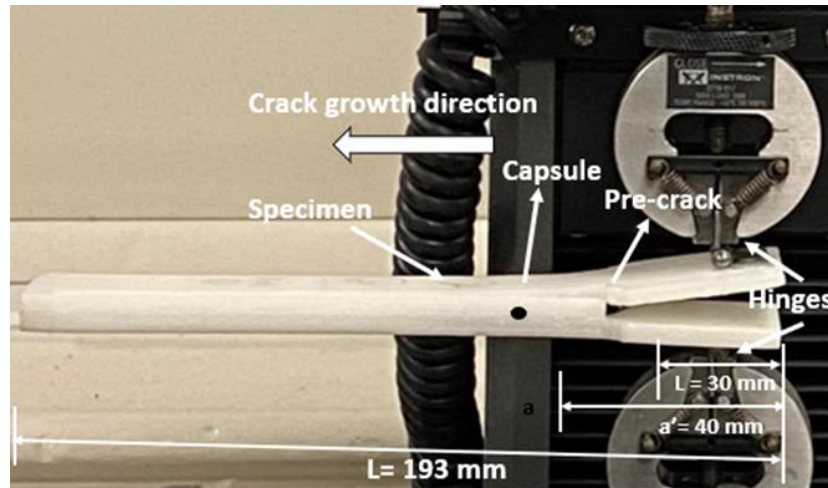


Figure 4-17 Double cantilever beam test setup and showing pre-crack

Mode-I interlaminar toughness tests were performed on DCB beams (see Figure 4-17) containing an origami capsule orientated in the direction of crack growth [155]–[159]. The DCB specimens had a 40 *mm* long pre-crack at the front of the specimen (see Figure 4-17). Two hinges were glued onto the top and bottom surfaces of the sample so they could hold the ends of the arms of the DCB specimen. The delamination crack growth in the direction of the origami capsule was as shown in Figure 4-17. The applied loading and crosshead displacement (δ) were recorded during the test.

4.6 Conclusion

The discussion in this chapter concerned the self-healing mechanism in the 3D printing of an ABS simple beam, origami capsule and embedded structure. Among the results, many analyses and experiments were carried out. However, the active part also joined in; the experimental deformation to assess the behaviour of simple and origami shaped polymeric beams under elastic and plastic loads led to assessing the self-healing ability of the materials under review.

Two experiments were conducted to investigate the workability of the designed capsules under different values of strain release by bending load and delamination tests of a double cantilever beam. For the purpose of conducting the experiment, 51 samples of 3DP were produced of three types of simple beam,

origami capsule and embedded structure (three times each), using FDM Idea-Maker 3D pro and FDM Ultimaker 2⁺, Inventor software and ABS, TPU and TPE filaments. Different parameters of 3DP were set, varying in layer thickness and orientation but with a constant nozzle 0.4 *mm* at different temperatures. The purpose of the test was to validate the experiments using embedded capsules. Once the model was validated, this model could be used in designing the origami for fold capsules. Next, research made folds in an origami design, trying to use equations in the process, which were inferred from our empirical results. Research used these folds to study different shapes. The kind of shape posited by ABS was studied using an empirical formula and the approaches already taken. Thus, the model could be used to determine the behaviour of the origami capsules. Then research tested the capsules and verified the results. Once the capsules were validated, research could apply them to the specimens and then try to induce cracks in the specimens and check the behaviour of the origami capsules to see if they were healing correctly. The snapped results were then processed with MATLAB software. The experimental results of the beam were collected and analysed using graphical, simulation, and statistical techniques. The MATLAB results were subjected to show the parametric relationship between force, deflection, and the position of the beam.

To further assess the self-healing with the origami capsule of the 3D printer, the beam deflection on application of a load was tested by a bending test. Three filaments were used in this research, ABS, TPU and TPE, with different dimensions and thickness as presented in above. In addition, Instron 5944 Universal Testing Machine was used with a load cell of 500 *N* and displacement of roughly 0.05 to 0.1 *mm/sec*. As a result, the load deflection curve was no longer linear and the large displacements during the crack growth led to a change in the geometry, in particular a shortening of the bending arms [160]. Consequently, the correction factor (F) was incorporated in the fracture toughness calculations.

The results and discussions are presented in the following chapters, the experiment results and analysis may be found in the chapters after that.

5 ELASTIC AND PLASTIC BEHAVIOUR OF SINGLE POLYMERIC CANTILEVER BEAM

5.1 Introduction

This chapter discusses part of the first objective of the research, which was to design different origami-inspired capsules in such a way that their geometrical features will remain constrained under initial pre-stress conditions. The pre-stressed condition is available in the form of strain release in real 3D printed products when a crack or other damage is initiated or propagated. Bending tests were used to determine the mechanical strength of the materials and to see how the samples worked. The samples exhibited the behaviour of an ABS simple beam during the bending tests. Their self-healing ability was found to be affected by both strain energy and time. This self-healing ability is itself discussed in the chapter, as well as the elastic and plastic regimes (the results and discussions in this chapter have been published in a polymer journal). Moreover, measuring strain is extremely useful in designing and in creating a stress-strain diagram, which is one of the most important curves in the science of mechanics. The purpose of this chapter is to present the results of developing and investigating ABS simple beam designs printed by 3DP. The discussion is divided into two sections. The first section concerns the strain gauge test. The second section focuses on the results of testing ABS simple beam behaviour and of bending tests based on the following factors: load, deflection, and position.

5.2 Design of Experiment

A bending load test was carried out as follows. The set of experiments began by printing a sample, the ABS simple beam. The sample was then subjected to a bending load test using an Instron 5944 Universal Testing Machine (UTM). Specifically, the bending load was applied to model the elastic and plastic behaviour of ABS for study. The stresses were calculated according to the force provided by the UTM. In addition, video images taken during the loading to determine the deflection of the beam at 15 different points along its length. This showed the overall response of the beam under bending load. In this research

the parameters and the dimensions of the ABS simple beam given in were set as shown in Table 5-1.

Table 5-1 Experimental set-up for simple beam

Sample number	Beam thickness <i>mm</i>	Dimensions, <i>mm</i> (Length/Width)	Loads (<i>g</i>) attached to the beam
1	0.5	145/10	1,2,3,4,5,6,7,8,9,10
2	1.0	145/10	1,3,5,10,15,25,35,45,55,75,100
3	2.0	145/10	5,10,20,30,50,70,90,110,160,210,310,410
4	3.0	145/10	5,10,20,30,50,70,90,110,160,210,310,410

5.3 Experimental Procedure

For each specimen, the following procedures was carried out.

- I. First the surface of the test piece was prepared by applying conditioner and neutralizers. A step-by-step procedure was developed (see Figure 5-1). The process of bonding the strain gauge had to be carried out precisely and without errors. Notably, the surface area of the strain gauge had to be prepared for sticking by first being cleaned with sandpaper and then being conditioned to neutralize the free-end and the fixed support. Finally, to complete the surface preparation of the beam, a generous volume of the neutralizer was applied and wiped off with a cottonwool ball.
- II. To further elaborate the process for educational purposes, the bonding area must be cleaned with an alcohol/acetone. Next, the necessary marks must be made on the bonding site, preferably with a fine graphite pencil, such that no residual deposition will affect the measurement.



Applying the M-prep Conditioner, Neutralizer and scrubbing the surface using abrasive paper

Figure 5-1 The surface preparation procedure

- III. Clamping the beam: the flat portion of the ABS beam was clamped in the test machine as shown in Figure 4-8.
- IV. Placing the strain gauges on the sample. One at free end and the other close to the fixed support, as show in Figure 5-2.

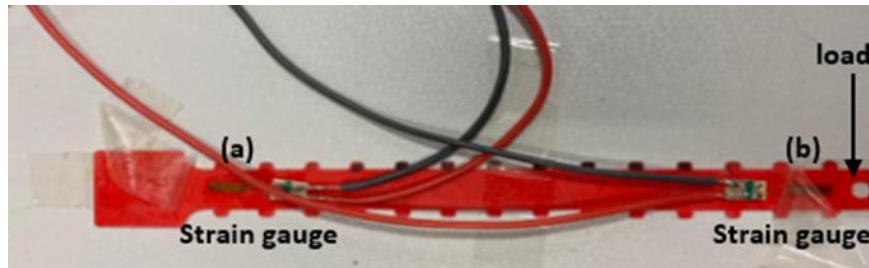


Figure 5-2 Plane view of strain gauge mounting points on test beam (a) fixed support and (b) free end.

- V. Connecting the strain gauges to the DAQ-card and the Signal-Express software.
- VI. Calibrating the strain gauges with no load on the sample and set readings to zero.
- VII. Measuring the distance between free end of each sample and the nearest strain gauge.
- VIII. Applying loads progressively from 0 N to 4.02 N and measuring the corresponding strain on each of the two strain gauges. To produce a hysteresis plot, the masses have to be moved in the reverse order to the one in which they were added.
- IX. Placing the protractor parallel to the edge of the clamping machine (i.e., starting point of the beam): the fixing should be firm to prevent unwanted movement by the protractor.
- X. Orienting the camera: the camera was placed parallel to the longitudinal side of the beam such that the protractor could be easily seen. The distance between the camera and the beam was 30 cm , as depicted in Figure 5-3.

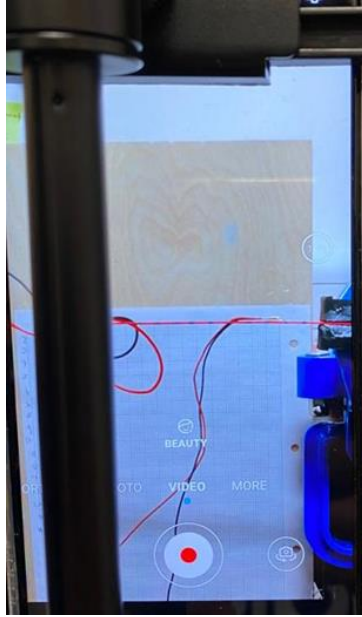


Figure 5-3 Camera view

A simple ABS beam of 145 *mm* length (see Figure 4-5) was fixed at one end as a cantilever beam. An HD camera was chosen for strain measurement rather than crosshead displacement because of the compliance of the loading mechanism and load cells, which is typical in such tests. HD Camera deflection measurement on both sides of the sample compensates for any lateral bending during loading. The procedure for testing the sample begins by setting the selected beam thickness. Next, the loads were applied at the free end and readings of the deflections were taken. Each point of every deformation was photographed. Specimen preparation required only a light-ordered pattern of black paint on the beam (see Figure 5-4) on the white plastic background. Images of the samples were captured via camera and the deflection data obtained. After a sample was placed in the testing machine and a preload applied, a pair of reference images (one image per camera) were taken of each side of the sample. The applied loads ranged from 1 *g* to 410 *g*, depending on beam thickness (see Table 5-1 above). These were placed at the end of the beam (see the Figure 4-7). The wires used to connect the strain gauge to the DAQ (NI 9235) can be seen in Figure 4-8 [161]. The D-card meter was connected to the computer via chassis (NI cDAQ-9174) for post-processing and data analysis.

This methodology proved to be efficient, and a single specimen could be tested in a matter of minutes, including mounting the specimen, taking initial undeflected images, and loading the specimen, through to failure. The complete set-up, including the camera and universal testing machine used for bending load, is shown in Figure 4-8, above.

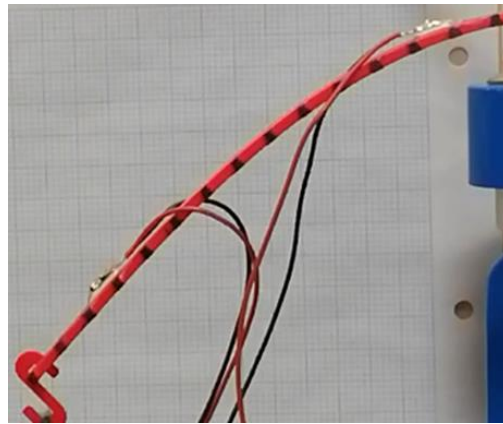


Figure 5-4 Deflection points

5.4 Strain Gauge Tests

As shown in Figure 4-8 above, each strain gauge consists of an insulated metal foil on a flexible substrate. The two leads send a current through the gauge, and the change in resistance is detected when the surface of the item being measured stretches or contracts. This change in resistance is proportional to the change in surface length of the tested item, as shown in Equation (5-1) below. Strain gauges measure the variation of electrical resistance across a thin conductive foil. The gauge factor (or "gauge factor") is the strain gauge's sensitivity (usually 2). It transforms the resistance change to a length change.

$$\frac{\Delta R}{R} = k \cdot \varepsilon \quad (5-1)$$

where R is resistance, ΔR is changed resistance, ε is strain, k is gauge factor.

5.4.1 Gauge Factor

The mechanical deformation of the detecting area caused by the applied force is converted by most force sensors into a change in resistance, capacitance, or

reflectance that may be monitored by means of electrical signals. Strain gauges bonded to a bending beam, for example, are used in some force sensors [162]. The strain on the strain gauge (ε) can be represented as follows, assuming an elastic cantilever beam.

$$\varepsilon = \frac{y}{R} \quad (5-2)$$

The distance between the neutral axis and the strain gauge is denoted by y , while the radius of curvature is denoted by R , or is expressed as follows:

$$\frac{I}{R} = \frac{Px}{EI} \quad (5-3)$$

where P is the applied load, x , denotes the distance between the strain gauge and the position where the force is applied, and E and I denote the beam's elastic modulus and area moment of inertia, respectively. When the cross-section of the beam is a rectangle and the stiffness is uniform, P can be calculated from Equations (5-2) and (5-3), using the following Equation (5-4):

$$P = \frac{bEh^2\varepsilon}{6x} \quad (5-4)$$

where b and h are the width and thickness of the beam, respectively. Research may determine the applied force (p) from the strain (ε) recorded by a strain gauge attached to a beam, such as a 3D printed ABS simple beam and origami capsule. However, once the strain gauge is glued to the beam, changing the measurement range and sensitivity is impossible. The deformation range, for example, is determined by the sensor material, and changing these requirements after the sensor has been manufactured is challenging.

Beam thicknesses of 0.5 mm, 1mm, 2mm and 3 mm were used on the tests, are shown in Figure 5-5.

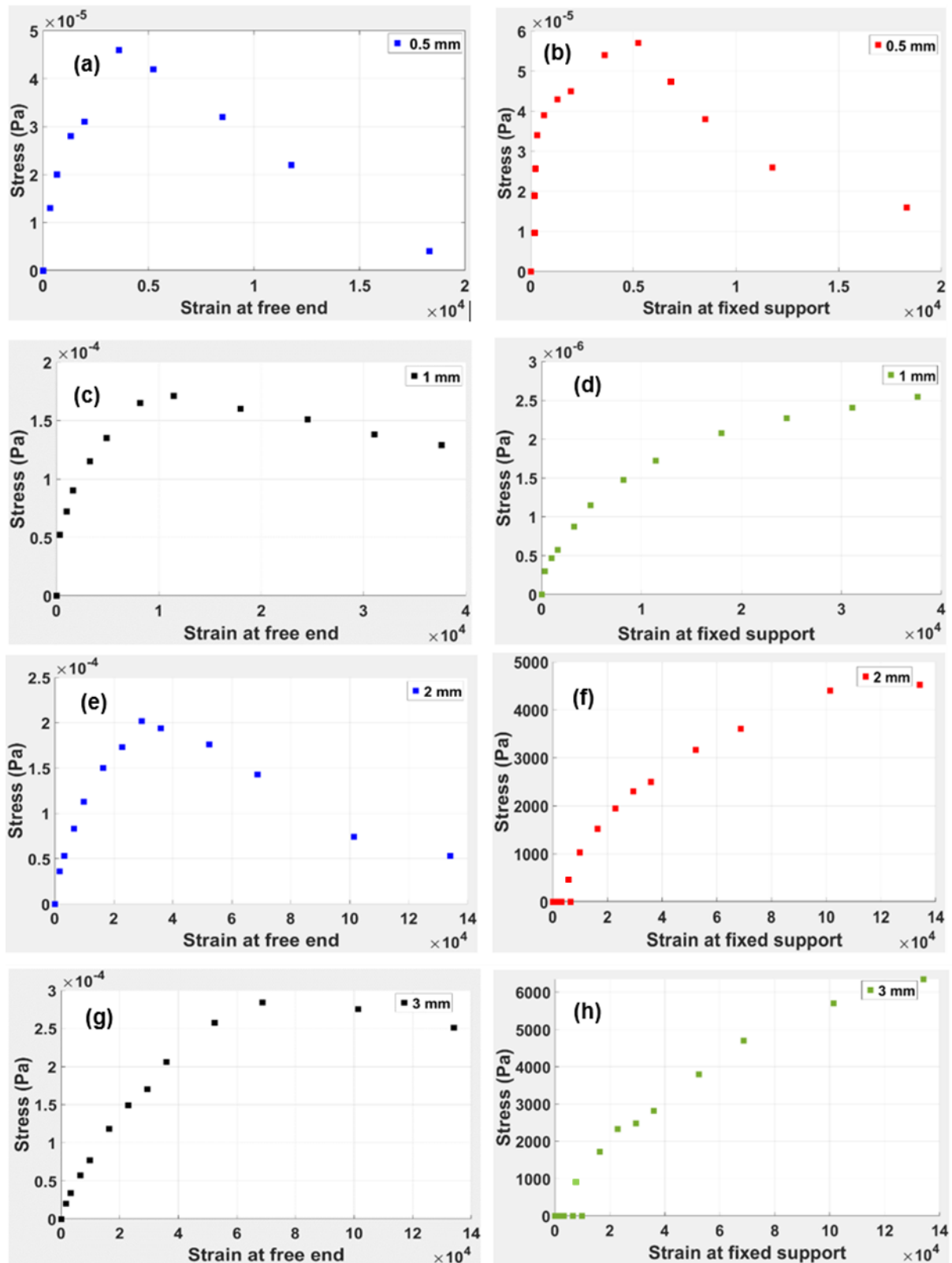


Figure 5-5 Stress-strain gauge at the free end and close to fixed support for all thicknesses

S.G. 0.5 *mm* is the closest strain gauge to discontinuity and gives the maximum stress.

S.G. 3 *mm* is the furthest strain gauge from discontinuity and gives the nominal stress.

In Figure 5-5, a load P is applied on the cantilever beam and two strain gauges measure the developed strain in the specimen's free end and fixed support. The strain gauge was initially mounted onto a frame through two sides, one at the free end and the other one in fixed support. During calibration, the applied force and the deflection were read from the camera orientation. At the same time, the output voltage signal of the strain gauge was recorded. The strain gauge sensitivity could then be calculated as the ratio of output voltage and applied force. Moreover, the table shows that all strain gauge values increased with every increase in the applied force. Because the deformation signals were obtained in the time domain and the load depends on time, the measured signal had to be manipulated to obtain the magnitude of the observed strain. The manifold value of the deformation measured is considered to be the resulting deformation on the proof body.

There is a relationship between the stress and the measured strain gauge at the free end, close to the fixed support. Compared with the deviation results that revealed a correlation deflection of 66.1 *mm*, 78.6 *mm*, 86.9 *mm*, and 85.9 *mm* (see Figure 5-5), the actual deflection is slightly smaller, which suggests that the actual load is stiffer than the correlation load. Several factors may account for this: i) The strain gauges were glued to the surface of the beams. Once the glue has hardened, the gluing procedure keeps the strain gauges and printed beams together. However, as the beam thickness increases significantly after gluing, so does the stiffness; thus, ii) unexpected minor printing errors may occur on a regular basis due to nozzle under/over extrusion, layer separation and splitting, overheating, and vibrations. The induced printing errors made the printed beams exactly the same dimension as those designed in the specimen.

5.5 Discussion on Strain Gauge Measurements

It is clear from all the graphs obtained from the experimental test results that as the temporary fastener was tightened the fatigue of the ABS simple beam increased. The amount of fatigue is related to the longitudinal stress reduction at the hole edge because of the clamping force that was applied. The longitudinal stress (σ_x) increases near the hole when a higher force is applied.

A reduction in stress was seen as the thickness of the simple beam increased; this was due to the larger surface of the stress having to be dissipated.

The data are recorded in Figure 5-5. In the first test, with 3 *mm*, the reading became more logical until the 310 *g* returned to the plastic regime. In the second test, with 2 *mm*, the reading showed the elastic regime until 110 *g* and then a return to the plastic regime. This can be referred to as the zero offsets of the gauge indicator device that alters the measurement considerably at low stress. In the third test, with 1 *mm*, the elastic regime went on until 35 *g*. In the fourth test, with 0.5 *mm*, the reading went up to 11 *g* after the return to the plastic regime. Afterwards, the readings became more logical. The zero-offset error resulting from the improper balancing of a channel shifted the balance point of another, and an error was generated when readings were taken from all channels simultaneously.

The curve of the stress-strain gauges (see Figure 5-5) implies that the strain gauge is properly fixed on the surface of the beam. The strain is measured when a beam undergoes axial strain. When the surface stretches through the applied load, the strain gauge stretches with it. In Figure 5-5, the resistance of the strain gauge is shown to have increased when the beam stretches. The measurement of the strain depends on the change of resistance that occurred in the strain gauge. The two strain gauges are fixed to the beam. One is fixed on the free end and the other is attached to the fixed support side of the ABS beam. In this experimental investigation, the beam was symmetrical in cross-section. The test specimens of the ABS simple beam size measured 145 *mm* x 10 *mm* x 3 *mm*, 145 *mm* x 10 *mm* x 2 *mm*, 145 *mm* x 10 *mm* x 1 *mm*, and 145 *mm* x 10 *mm* x 0.5

mm. The experimental results for the ABS simple beam are shown in Figure 5-5, with the different process factors and their level. The strain gauges were fixed to beams of different thicknesses.

5.6 Results for ABS Simple Beam Behaviour

The displacement responses of the ABS materials with bending loads applied at the tip are shown Figure 5-6. It is evident that for the 3.0 mm thick beam within the elastic limit, the maximum stress yielded a deflection of 56 mm. However, for the 0.5 mm thick beam, observed a deflection of 79 mm. Within the elastic limit, for small deflections, the value of the stress is directly proportional to the force and inversely proportional to the thickness:

$$Deflection \propto \frac{f (force)}{f (thickness)} \dots\dots\dots (5-5)$$

The values of force and maximum deflection were used to calculate the strain energy of the beam in Equation (5-6). It was assumed that the amount of stress applied is wholly converted into strain energy, which is represented as:

$$Maximum Strain Energy of the beam (U) = \frac{\sigma^2}{2E} Ba \qquad (5-6)$$

where σ represents the stress applied (N/m^2), E is the elastic modulus of the material (N/m^2), B is the beam thickness (mm), and a indicates the length of the beam (mm).

From the force-deflection curves shown in Figure 5-6, it is seen that maximum deflection for the beam of 3.0 mm thickness was 64 mm at the maximum applied force of 4.022 N. The maximum deflection for the beam of 2.0 mm thickness was 78 mm and the maximum applied force was again 4.022 N. The maximum deflection for the beams of 1.0 mm and 0.5 mm thicknesses was 93 mm at maximum applied forces of 1.73 N and 0.55 N, respectively. Hence it follows that in Table 5-2:

Table 5-2 The calculation of the maximum strain energy beam at different thickness

Thickness (mm)	Length (mm)	Stress (N/m ²)	Elastic modulus (N/m ²)	Maximum strain energy (Nmm)
0.5	145	191.48	1681	7907
1	145	98.19	1681	4158
2	145	87.48	1681	6601
3	145	38.88	1681	1956

From the calculated values in Table 5-2, it is noted that maximum strain energy is observed for the 0.5 *mm* thick beam, 7907 *Nmm* and the least value of strain energy is observed for the thickest beam, of 3.0 *mm*, which is 1956 *Nmm*. This validates the finding that maximum force and beam thickness yield minimum strain energy and the lower the magnitude of the force and beam thickness, the higher the strain energy.

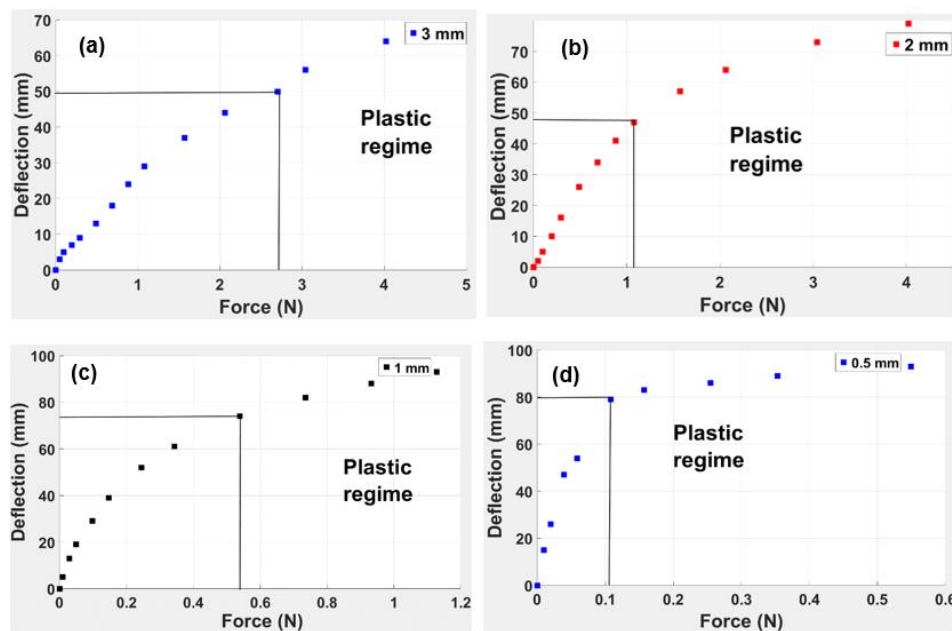


Figure 5-6 Deflection of end loaded simple ABS beam 145 *mm* long, 10 *mm* wide and thicknesses: (a) 3 *mm*, (b) 2 *mm*, (c) 1 *mm* and (d) 0.5 *mm*

In Figure 5-6 the vertical black lines indicate the initiation of the plastic regime of each beam; it is clear that the greater the thickness of the beam, the greater the force required. This is the reason why the plastic region for the 0.5 *mm* beam

commenced at 0.15 N , whereas for the 3.0 mm beam the force required was 3.04 N .

With the observed changes for the maximum deflection with respect to different loads, there is a need to analyse whether or not the values change with position. This was done by plotting a 3D surface graph in the next section (see Figure 5-7). The examples of each position of point shown in Figure 5-8 demonstrate the parametric relationship between force, deflection, and the position of the beam.

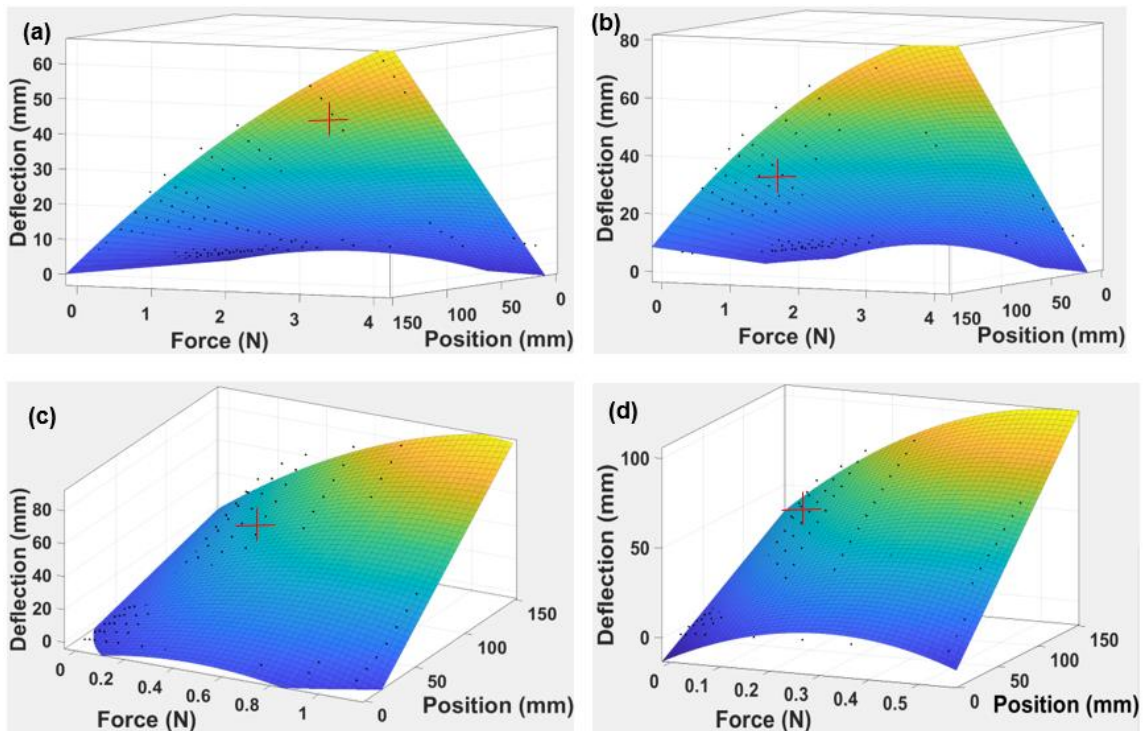


Figure 5-7 3D-gradient graph of ABS beams the showing relationship between applied Force (N), Position (mm), and Deflection (mm) for four beam thicknesses: (a) 3 mm , (b) 2 mm , (c) 1 mm , and (d) 0.5 mm

There are multiple benefits of 3D graphs, which can outweigh the analysis and experimental work. This includes viewing control of the graph from any position in real-time 3D. Besides, data integration with a 3D graph is easy as the real-time behaviour pattern of very large amounts of categorical data set is less cumbersome. The presentation of mathematical formulas with a visual effect is possible. 3D mouse interaction provides a better view of the relationship between

various parameters. Lastly, 3D graphs are clean, polished, and easy to understand

It is evident that the gradient increases in value as the thickness of the beam increases in four stages from 0.5 mm to 2.0 mm.

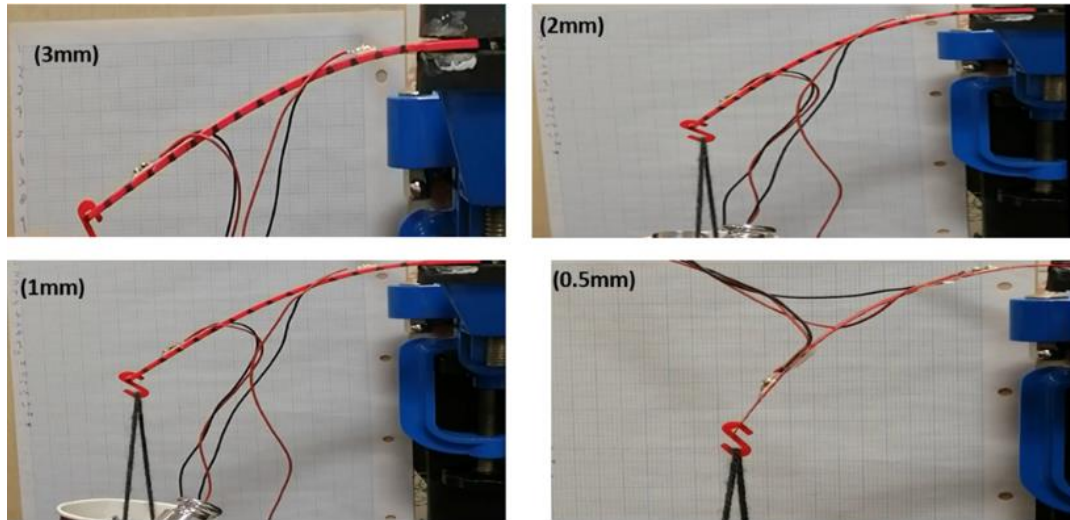


Figure 5-8 Positions of ABS simple beam at each point of: (a) 3 mm, (b) 2 mm, (c) 1 mm and (d) 0.5 mm

With respect to different position of the beam, it is assumed that deflection at different forces varies accordingly.

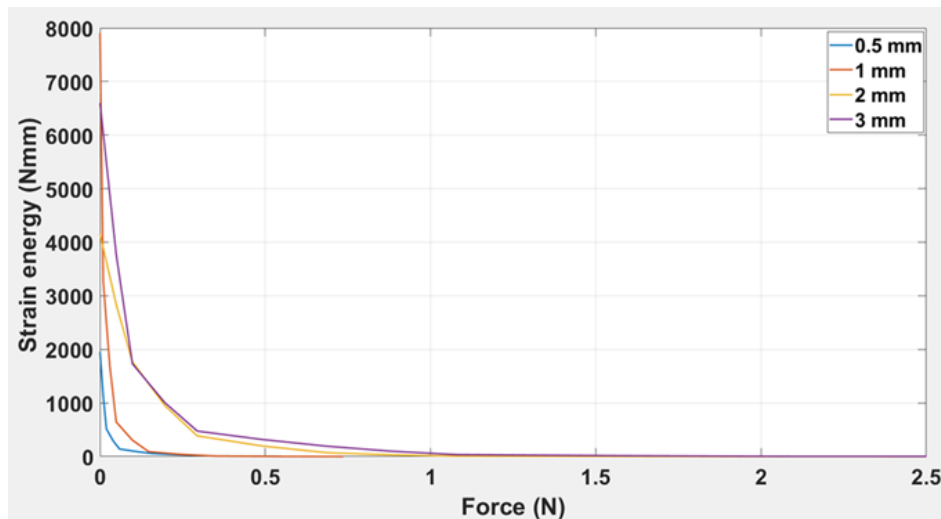


Figure 5-9 Strain energy vs applied force for simple ABS beams of thickness: 0.5 mm, 1 mm, 2 mm, and 3 mm

The curves shown in Figure 5-9 demonstrate strain energy as a function of applied force for simple ABS beams of a) 0.5 mm, b) 1.0 mm, c) 2.0 mm, and d) 3.0 mm thickness. The trend indicates that the strain energy attained its maximum value for 0.5 mm thickness (7907 Nmm), followed by 6600 Nmm for 2.0 mm, 4158 Nmm for 1mm, and 1955 Nmm for 3mm. It was also noted that the strain energy for all thicknesses except 2.0 mm had reached zero before 0.5 N, while the strain energy for the 2.0 mm thick beam reached zero value only as the force approached 1.0 N. This shows that the greater the value of the beam thickness, the greater the strain energy, and the more gradual will be the process of strain energy decay over time.

$$deflection = f (force, position)$$

Mathematically,

Each of the 3D surfaces shown in Figure 5-7 is approximated using a polynomial equation as given in Equation (5-7):

$$\begin{aligned} & \text{Deflection of the beam } (f = (\text{force } (N)), y = \text{position at any point } (mm)) \\ & = p_{00} + p_{10}f + p_{01}y + p_{20}f^2 + p_{11}fy \end{aligned} \quad (5-7)$$

where $p_{00}, p_{10}, p_{01}, p_{20}$, and p_{11} are the coefficients of the polynomial.

The results of the coefficients at various beam thickness are presented in Table 5-3.

Table 5-3 Different values of coefficients for simple ABS beams of different thicknesses.

Thickness	P ₀₀	P ₁₀	P ₀₁	P ₂₀	P ₁₁	R-squared
0.5 mm	-10.25	134.8	0.3297	-209.2	0.6598	0.9681
1 mm	-7.013	37.79	0.1968	-38.41	0.4525	0.9632
2 mm	-6.002	10.3	0.1247	-2.804	0.1259	0.9662
3 mm	-2.196	4.519	0.0363	-1.402	0.1112	0.9819

By substituting the coefficients in Equation (5-7), the polynomial equation for each beam thickness can easily be found.

$$0.5 \text{ mm } f(f, y) = -10.25 + 134.8f + 0.3297y - 209.2f^2 + 0.6598fy \quad (5-8)$$

$$1 \text{ mm } f(f, y) = -7.013 + 37.79f + 0.1968y - 38.41f^2 + 0.4525fy \quad (5-9)$$

$$2 \text{ mm } f(f, y) = -6.002 + 10.3f + 0.1247y - 2.804f^2 + 0.1259fy \quad (5-10)$$

$$3 \text{ mm } f(f, y) = -2.196 + 4.519f + 0.0363y + p20f^2 + 0.1112fy \quad (5-11)$$

From the above Table 5-3, it is clear that as the thickness increases the absolute value of the coefficients decreases, which ultimately reduces the R-squared values. This is the reason why the 3.0 mm thick beam has the lowest values of coefficients and the highest R-squared value. The results can be further simplified in terms of reducing the variables and coefficients. This is done by plotting the curves of coefficients against beam thickness, which allows the corresponding slopes of the curves (the coefficients w1, w2, and w3) to be determined (see Figure 5-10).

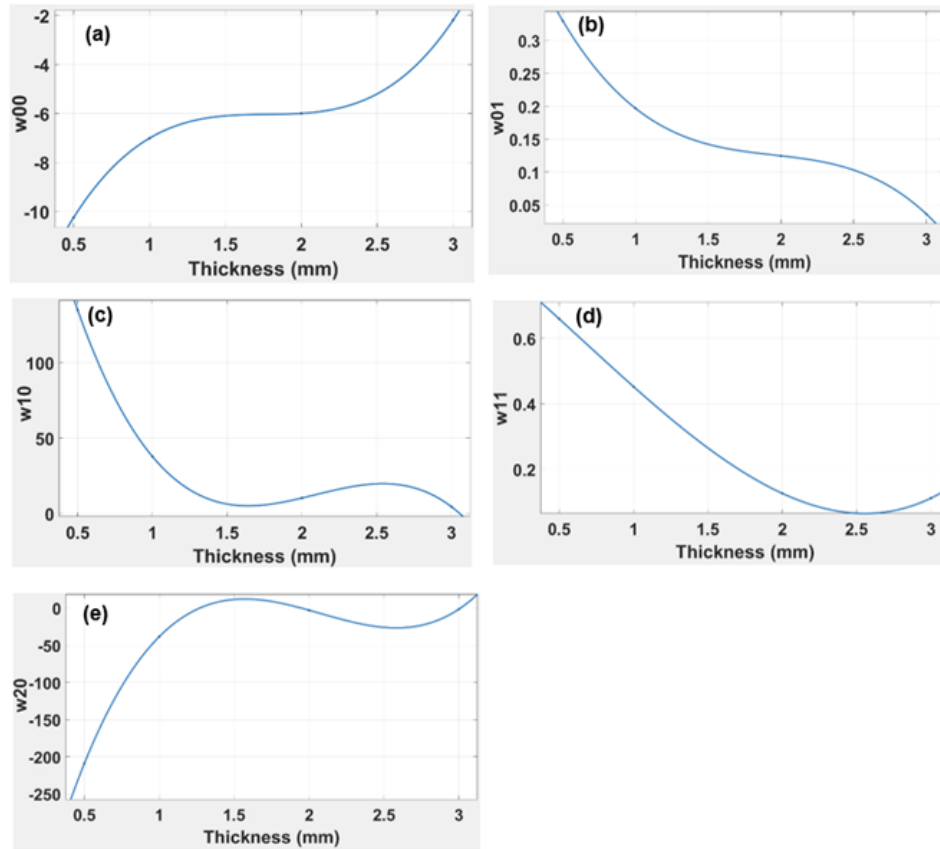


Figure 5-10 Graphs indicating the relationship of simple ABS beam thickness vs correlation coefficient for (a) w_{00} (b) w_{01} (c) w_{10} (d) w_{11} and (e) w_{20}

Each plot in Figure 5-10 is fitted for third-degree polynomial, so the generalized equation becomes:

$$f(x \text{ thickness}) = w_1 x^3 + w_2 x^2 + w_3 x + w_4 \quad (5-12)$$

where w_1, w_2, w_3 , and w_4 indicate the coefficients of the polynomial equation and x indicates the thickness of the beam (mm).

Table 5-4 Values of linear equation coefficients for ABS beam of all thickness.

Coefficient	w_1	w_2	w_3	w_4	R-squared
w00	2.016	-10.70	18.99	-17.32	1.00
w01	-0.054	0.321	-0.6517	0.582	1.00
w10	-40.07	251.3	-500.8	327.4	1.00
w11	0.038	-0.077	-0.366	0.857	1.00
w20	74.75	-465.6	909.2	-556.7	1.00

The generalized equation, Equation (5-12), is simpler to analyse than Equation (5-7, and is effective in determining the coefficient whatever the thickness of the beam.

By substituting the values of coefficient in Equation (5-12), the generalised equation.

$$w_{00} f(x) = 2.016x^3 - 10.70x^2 + 18.99x - 17.32 \quad (5-13)$$

$$w_{01} f(x) = -0.054x^3 + 0.321x^2 - 0.6517x + 0.582 \quad (5-14)$$

$$w_{10} f(x) = -40.07x^3 + 251.3x^2 - 500.8x + 327.4 \quad (5-15)$$

$$w_{11} f(x) = 0.038x^3 - 0.077x^2 - 0.366x + 0.857 \quad (5-16)$$

$$w_{20} f(x) = 74.75x^3 - 465.6x^2 + 909.2x - 556.7 \quad (5-17)$$

They above equations are formulated by substituting the values in the generalised equation. The R-squared values for each coefficient is 1.00, which shows a perfect fit of curve, as indicated in Table 5-4. The equations are set for a third-degree polynomial in each case, so there is virtually no discrepancy in the value of any coefficient. This equation can be used to analyse the response of a simple ABS beam of any thickness in the range 0.5 to 3.0 *mm* under different loads up to the elastic limit.

5.6.1 Discussion of Behaviour of ABS Simple Beam

The experimental results of the beam were collected and analysed using graphical, simulation, and statistical techniques. The deflection, position, and force vary with thickness and a 3D gradient graph was plotted in MATLAB to show this (see Figure 5-7). It is evident from this figure that, because the thickness of the beam increased from 0.5 *mm* to 2.0 *mm*, the gradient shifted towards a smaller deflection. The 0.5 *mm* thick beam reached a maximum of deflection of 93 *mm* (see Figure 5-7 (a)). The 1.0 *mm* beam achieved a maximum deflection of 90 *mm* (Figure 5-7 (b)); the 2.0 *mm* beam reached a maximum

deflection of 78 *mm* (Figure 5-7 (c)), and the 3.0 *mm* thick beam showed a deflection of 64 *mm* (Figure 5-7 (d)). Moreover, the value of R-squared for the four thicknesses (i.e., 0.5 *mm*, 1 *mm*, 2 *mm* and 3*mm*) were 0.9681, 0.9632, 0.9662, and 0.9819, respectively. This confirms that the thickness of the beam is a critical parameter that moderates the deflection at different values of position and applied force. These values are also significant because they demonstrate that the values of the deflection of the beam can be correlated through a regression model (Table 5-3).

Of all the results, the beam with the 0.5 *mm* thickness reported the maximum deflection value, and 3 *mm* reported the minimum value. This indicates that the thickness of the beam is a critical parameter that modulated the deflection at different values of position and force.

The analysis of the beam's elastic modulus helped compute the ABS' resistance to elastic deformation. From the results shown in Figure 5-6, it can be seen that as the thickness of the beam increased from 0.5 *mm* to 3.0 *mm*, the elastic modulus decreased from $3.6 \times 10^9 \text{ Pa}$ to $1.8 \times 10^8 \text{ Pa}$. This shows that increasing the thickness of the beam reduces the elastic modulus of the beam. The initiation of the plastic region is indicated by red crosses as shown in Figure 5-7. For a 0.5 *mm* thick beam, the elastic region lasted until the load was 0.108 *N*, and the plastic region was maintained until 0.549 *N*. For a beam of 1.0 *mm* thickness, the elastic region was maintained till 0.343 *N* and the plastic region existed up to the maximum load of 1.128 *N*. For 2.0 *mm* thickness, the elastic region extended to a load of 1.08 *N*, significantly more than for the 0.5 *mm* and 1.0 *mm* beam thicknesses. Lastly, for a 3.0 *mm* thick beam, the plastic region was sustained till 4.02 *N*, showing that for the 3.0 *mm* thickness, the plastic region commenced at an end load of mass 310 *gm*.

The minimum strain calculated to activate the plastic region for the four beams was 0.5 *mm* - 1.79×10^{-6} ; for 1.0 *mm*, - 5.70×10^{-6} ; for 2.0 *mm*, - 1.74×10^{-5} ; and for 3.0 *mm* - 4.56×10^{-5} . This shows that as the thickness increased, the plastic region was activated at a greater magnitude of force, and a greater overall strain rate.

In Figure 5-9, it is clear that the strain energy is obtained at maximum 1 N for all four beams. However, the beam thickness significantly affected the decay of the overall strain energy. This shows that ABS beam may be ideal for low stress release applications, but for higher stress, the material may not be sufficiently resilient.

To simplify the calculation and apply variable thicknesses, the values of all five coefficients from the model equation $w_{00}, w_{01}, w_{10}, w_{20}$, and w_{11} were plotted against thickness in Figure 5-10, and the R-squared values for all four coefficients were 1.0. The R-squared was evaluated for a third-degree polynomial equation but increasing the degree placed the value out-of-range.

From the experimental results, it is evident that the modulus of ABS increases with strain rate. From the material point of view, the ABS beam depends on both compression and shear rates, which are different for different thicknesses. The elastic limit is reached more rapidly for thin beams and gradually increases as the thickness increases. The reasons for this are the moment of inertia and elastic modulus of the beam, which depend on the properties and cross-sectional dimensions of the material. ABS as a polymer sustained the load to 4.02 N for a 3.0 mm thick beam, indicating that the load sustainability of the designed polymeric beam is suitable for further research work.

5.7 Conclusion

This chapter gives a full and integrated look at the behaviour of beams of different thickness in the elastic and plastic regimes.

- The maximum stress in an ABS simple beam could be at the point of discontinuity (hole, notch, etc.), or at the root of the beam furthest from the point of the application of force.
- A strain measurement was performed using a strain gauge on a simple ABS beam.
- For strain measurement, different parameters such as applied load, deflection of the strain gauge, and deformation were used.

- Strain gauges can be very helpful for obtaining the measurements of strain, which can be used to figure out stress and estimate when a structure will give way permanently.
- The results of experiments to assess the behaviour of simple beams under elastic and plastic loads were given.
- ABS/ ABS was used as a specimen to remain as a beam.
- From the experimental results, it is evident that the modulus of ABS increases with strain rate.
- The deflection, position, and force vary with thickness, and a 3D gradient graph was plotted in MATLAB.
- Values of all five coefficients from the model equation w_{00} , w_{01} , w_{10} , w_{20} , and w_{11} were plotted against thickness in Figure 5-10, and the R-squared value for all four coefficients was 1.0.
- Moreover, it was clear that images are useful in understanding the processing behaviour of elastic and plastic materials. Furthermore, in each position, an image can capture the deflection point being moved.
- However, these images should be analysed with some advanced image analysis techniques like MATLAB to extract more fine information from different experimental conditions.
- The behaviour of the ABS simple beam material was studied under one-point bending and found to significantly affect the span length and deflection rate. For the material model to accurately anticipate the ABS response, bending stress-strain curves indicated the strain energies.

For this reason, TPU was used as a capsule because it is more flexible. The next chapter describes the behaviour of the origami capsule.

6 DEVELOPING ORIGAMI CAPSULES WITH THE IDEA OF A FOUR-BEAM FLOWER

6.1 Introduction

This chapter describes the response of the polymeric beam of TPU material under elastic and plastic loads. The experimentation process included the use of strain gauges of different thicknesses to determine the deflection of four beam flowers and rollers under testing. The tests included observation of the effects of the material and binder on two types of 3D printed beam and were designed to test their elastic and plastic responses under different bending loads. These responses were used to develop an origami capsule-based novel self-healing mechanism triggered by crack propagation due to strain energy release in the structure. Two types of TPU origami capsule, the cross and the roller, were developed and are reported in this chapter. Some origami capsules were cross-shaped, made up of four small beams that could be folded, and other capsules were roller-shaped, made of small beams that could be folded or elastically deformed. Under the strain energy due to crack propagation in the main beam, the small beams of the origami capsule unfolded in the direction of the path of the crack. It was demonstrated that the cross and roller modes can be accurately controlled and that the fold and unfold constraints can act as mode directors. The results and discussions of this chapter have also been published in a polymer journal.

6.2 Design of Experiment

In this research, where evidence of the bending load of capsules was sought, experiments were designed to deal with the interpretation of the tests. The geometry of capsules one specimen has been shown in Figure 4-9 above. Because this research evaluated both the bending load and crack propagation, an origami capsule beam was used in the experiments to heal the crack as soon as it occurred. The bending load of origami capsule can vary greatly with changes in the dimensions and thickness. Consequently, two factors were considered in this study to determine the size of the specimen. To begin with, the study

considered the size of many capsules with which FDM polymers were applied. Two origami capsule shapes used in this study are shown in Table 6-1. The deflection data and deformation load were recorded, and the data (about strain, applied load and deflection) were plotted using excel.

Table 6-1 TPU Origami capsule designs

Origami Capsule shape	Thickness (<i>mm</i>)	Dimensions (<i>mm</i>)	Loads (<i>g</i>)
Cross	1.0, 2.0, 3.0	19 <i>L</i> /10 <i>W</i> /3 <i>T</i>	1,2,4,6,11,16,26,36,56,86,106
Roller	1.0, 2.0, 3.0	19 <i>Diameter</i>	1,2,4,6,11,16,26

6.3 The Valuation Procedure

The purpose of the experiment was to evaluate the influence of geometry and internal density on the elastic properties of materials. In addition, this study sought to characterize the specific properties for the design and development of customised products by AM. Two shapes of capsules, star, and roller were designed to study the elasticity of each type of specimen with respect to the interior lightening percentage, to see how the self-healing mechanism works. These experiments were used to apply a deflection on the end of the capsule (see the composition in Figure 6-1). As mentioned before, the origami capsules were tested 37 times in total. The bending load tests were carried out on the UTM machine, with maximum applicable applied load of 106 *g* and maximum deflection of 25 *mm*. All tests were recorded on camera to compare the performance of all the capsules.

It should be noted that the aim of this research is to see the behaviour of the capsules, and how they work to heal cracks before they propagate. Therefore, bending tests were performed under applied loads until the deflection point of the origami capsule was reached.

The results obtained in terms of bending strength through the stress-strain curves were analysed, and the elastic modulus of the different origami capsule tested was evaluated to quantify the elasticity according to [163]. Stress was obtained according to Equation (4-2).

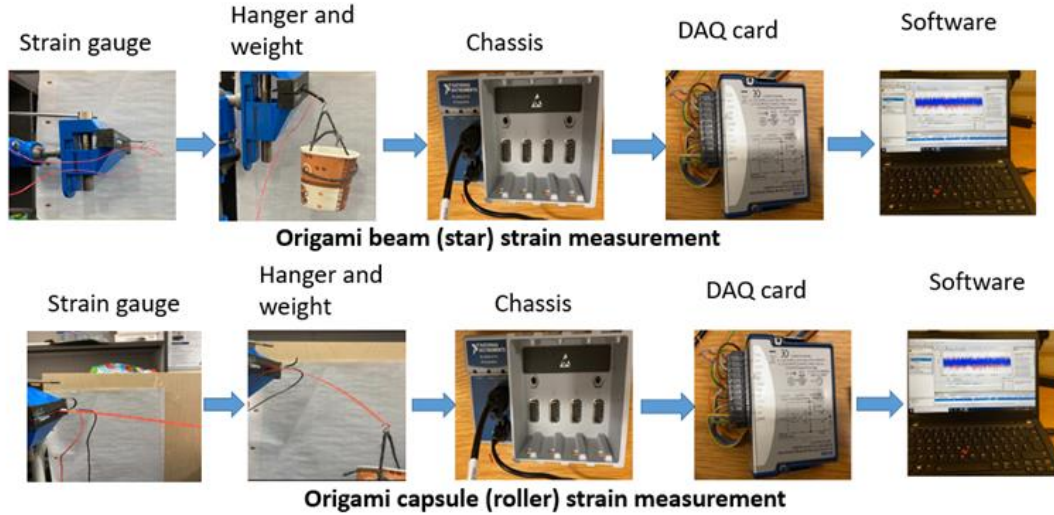


Figure 6-1 Experimental setup for the TPU origami capsules, cross and roller

6.4 Results With the Cross-TPU Origami Capsule

In the laboratory it is possible to design simple experiments in order to examine the deflection of a “cross” TPU capsule held at one tip and with a load applied at the free end; this is effectively a cantilever beam of length 19 mm , width 5 mm and a thickness of 1.0 mm , 2 mm and 3.0 mm . The deflection vs force curves obtained with the origami capsule for these three thicknesses are shown in Figure 6-2. The maximum deflection observed for the 3.0 mm thick capsule was 19 mm with an applied force of 1.5 N ; the maximum deflection for the 2.0 mm thick capsule was 17 mm for an applied force of 1.3 N ; and the maximum deflection for the 1.0 mm thick capsule was 15 mm for an applied force of 1.0 N .

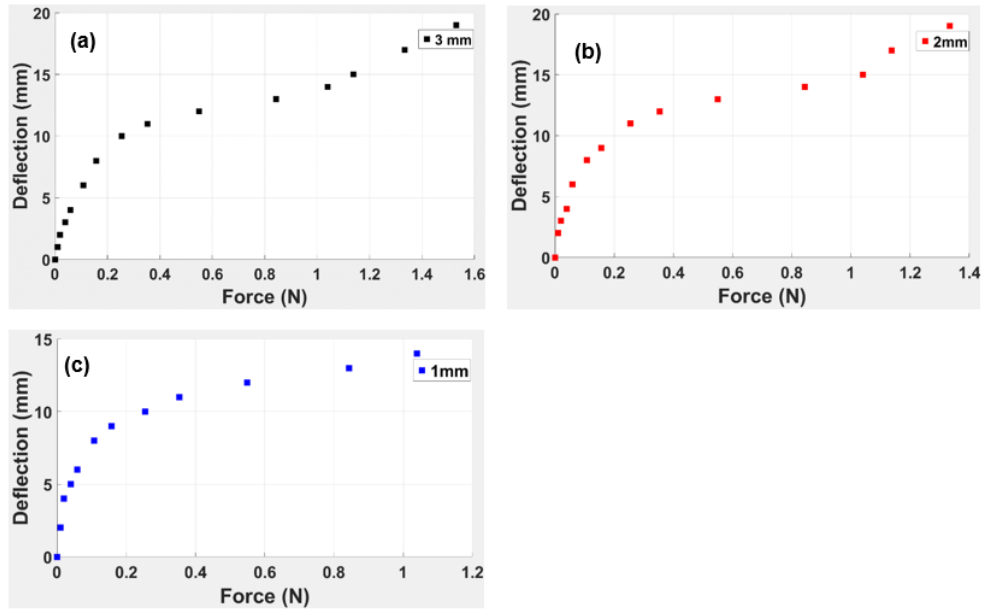


Figure 6-2 Deflection of an origami TPU “cross” capsule acting as a cantilever beam as a function of force for “capsule” thicknesses: (a) 3 mm, (b) 2 mm and (c) 1 mm.

Using a similar technique to that used with the simple ABS beam, 3D surfaces graphs for the TPU “cross” were plotted using MATLAB (Figure 6-3).

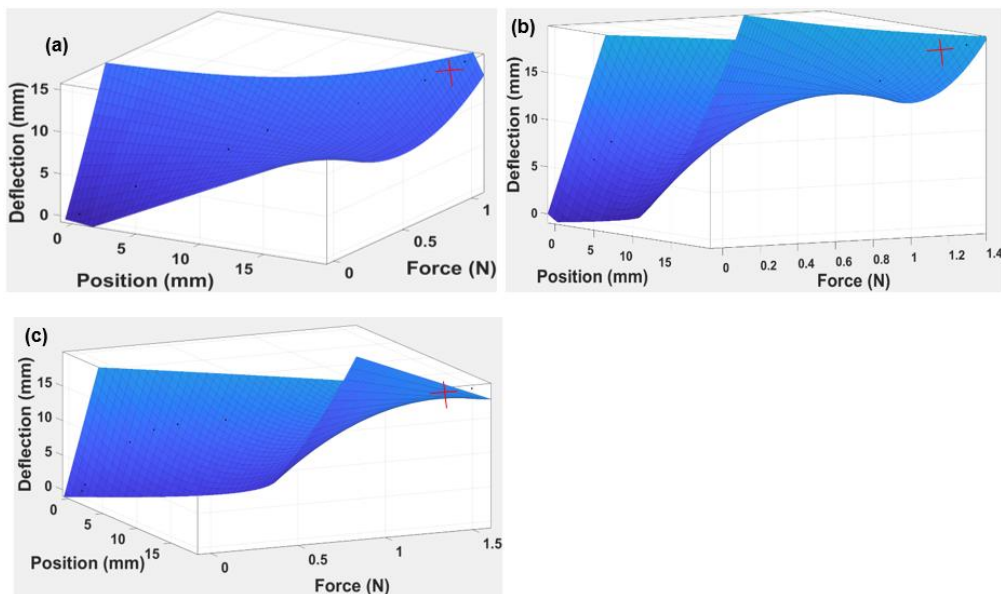


Figure 6-3 Three-dimensional gradient graph of TPU capsule “cross” showing relationship between Force (N), Position (mm), and Deflection (mm) for three beam thicknesses (a) 1.0 mm, (b) 2.0 mm, (c) 3.0 mm

Figure 6-4 illustrates the response of strain energy with force applied to the TPU “star” beam. It is clear from the trends that, for all beam thicknesses, the beam’s responsiveness to strain energy is exponential and decreases with the increase in applied force. It is evident that a force of 0.25 N is the maximum force at which all three beam thicknesses showed the response of strain energy.

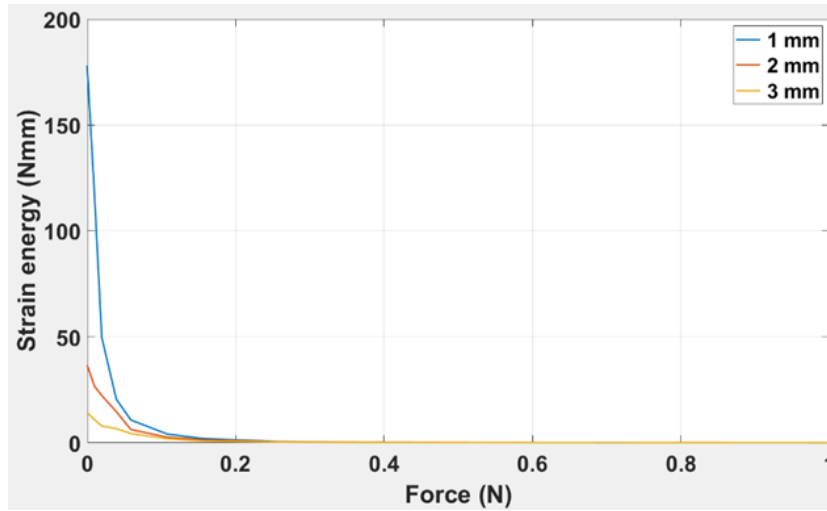


Figure 6-4 Strain energy versus applied force for TPU “cross” capsule for thicknesses 1.0 mm, 2.0 mm, and 3.0 mm.

Deflection as a function of force and position is observed for TPU. From the 3D surface graphs, it is evident that a plastic region was achieved at the maximum values of applied load for each thickness of the TPU “cross” beam.

Mathematically expressed,

$$deflection = d(f = force, y = position)$$

For the TPU “cross”, the generalized equation for any arbitrary point can be presented by Equation (5-7) above.

$$\begin{aligned} Deflection\ of\ the\ beam\ (f = (force, y = position\ at\ any\ point)) \\ = p_{00} + p_{10}f + p_{01}y + p_{20}f^2 + p_{11}fy \end{aligned}$$

where, $p_{00}, p_{01}, p_{10}, p_{20}$, and p_{11} indicate the coefficients of a polynomial equation in which x is the thickness of the origami capsule.

Table 6-2 Different values of coefficients at different TPU “cross” capsule thicknesses

Thickness	P ₀₀	P ₁₀	P ₀₁	P ₂₀	P ₁₁	R-squared
1 mm	0.5864	49.29	0.5673	14.57	-3.208	0.9966
2 mm	1.176	-18.06	2.483	37.92	-2.87	0.9818
3 mm	-0.0533	-24.81	3.927	21.46	-2.373	0.9674

By substituting the coefficient values in Equation (5-7) above, the polynomial equation for each thickness can easily be found.

$$1 \text{ mm } f(f, y) = 0.5864 + 49.29f + 0.5673y + 14.57f^2 - 3.208fy \quad (6-1)$$

$$2 \text{ mm } f(f, y) = 1.176 - 18.06f + 2.486y + 37.92f^2 - 2.87fy \quad (6-2)$$

$$3 \text{ mm } f(f, y) = -0.0533 - 24.81f + 3.927y + 21.46f^2 - 2.373fy \quad (6-3)$$

The R-squared value for each thickness (see Table 6-2) was found to be 0.9966, 0.9818, and 0.9647 respectively for the 1-, 2-, and 3.0-*mm* thicknesses of the “cross” capsule. This indicates that as the thickness of the TPU capsule increases, the accuracy of the model equation declines. As with the ABS, the polynomial equation for the TPU “cross” can be simplified using only its thickness. By plotting the corresponding slopes on the curves, the coefficients (*w*₁, *w*₂, and *w*₃) are determined as indicated in Figure 6-5.

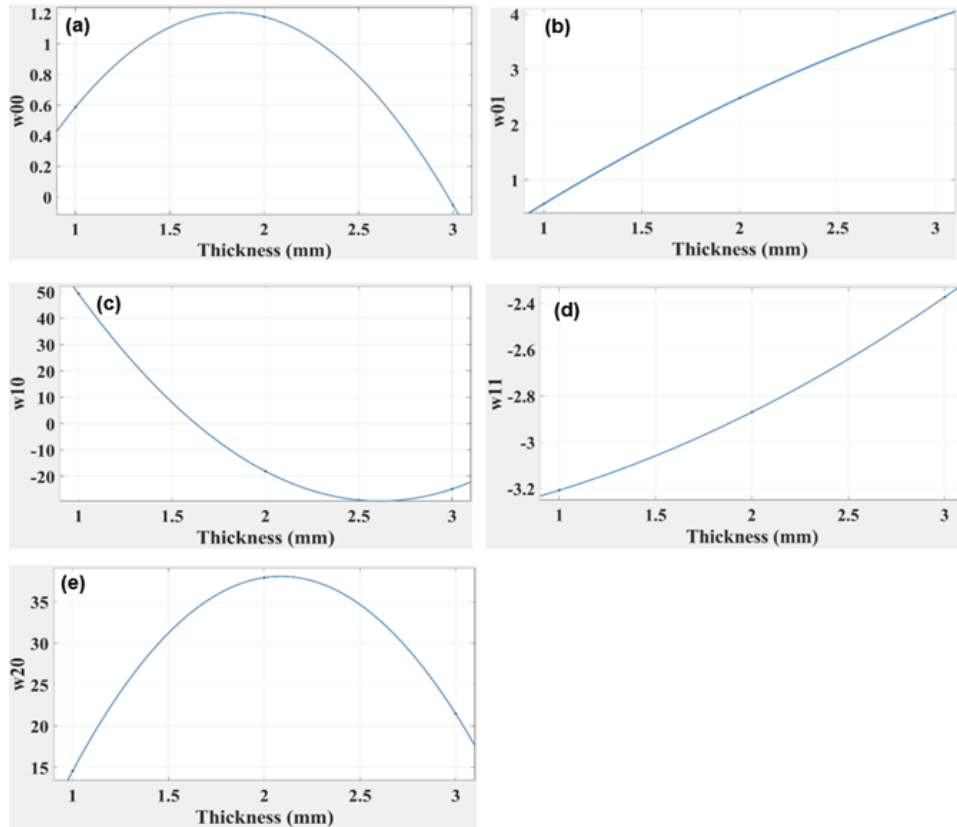


Figure 6-5 Graphs indicating the relationship of the TPU “cross” capsule thickness versus the coefficient for (a) w_{00} , (b) w_{01} , (c) w_{10} , (d) w_{11} , and (e) w_{20}

Each graph in Figure 6-5 was fitted with a second-degree polynomial, so the generalized equation becomes:

$$f(x = thickness) = w_1x^2 + w_2x + w_3 \quad (6-4)$$

Table 6-3 Values of the linear equation coefficients and parametric coefficients for all three thicknesses of the TPU “cross” capsule.

Coefficient	w_1	w_2	w_3	R-squared
w_{00}	-0.9095	3.318	-1.822	1.00
w_{01}	-0.2359	2.623	-1.82	1.00
w_{10}	-30.3	-158.3	177.2	1.00
w_{11}	0.0795	0.0995	-3.387	1.00
w_{20}	-19.91	83.07	-48.59	1.00

By substituting the values of the coefficient in Equation (6-4), the generalized equations become:

$$w_{00} \quad f(x) = -0.9095x^2 + 3.318x + 1.822 \quad (6-5)$$

$$w_{01} \quad f(x) = -0.2359x^2 + 2.623x - 1.82 \quad (6-6)$$

$$w_{10} \quad f(x) = -30.3^2 + 158.3x + 177.2 \quad (6-7)$$

$$w_{11} \quad f(x) = 0.079x^2 - 0.0995x - 3.387 \quad (6-8)$$

$$w_{20} \quad f(x) = -19.91x^2 + 83.07x - 48.59 \quad (6-9)$$

The R-squared values for all four coefficients as indicated in Table 6-3, were 1.0, for a second-degree polynomial, suggesting a perfect fit for TPU “cross” origami capsule, whereas a perfect fit for the ABS required a third-degree polynomial.

6.4.1 Bending Properties of 3D Printed Capsules.

Capsules were prepared for bending tests from both the differently shaped beams and those of different thickness: both “cross” and roller were composed of TPU materials. Figure 6-6 shows a 3D printed cross-shaped test capsule under a bending test using a bending load. The loading moved down at a rate of 0.1 mm/sec. Generally, no capsules returned to their original position. The TPU cross and roller shaped printed capsules returned to a position that was close to the original but did not break even when bent at an angle of at 90°. The TPU capsules were more flexible than the ABS beam, as demonstrated by the bending test to 90° for the self-healing mechanism. During the bending, the loads of the cross shaped capsules of thickness 1, 2, and 3-mm were 1.0 N, 1.3 N, and 1.5 N, respectively. The magnitude of the bending modulus of the different shapes also followed the same trend as the tests had shown.

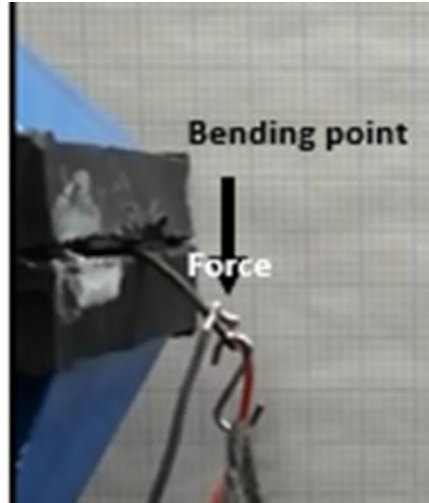


Figure 6-6 A 3D printed origami capsule in bending test

6.4.2 Discussion of the TPU Cross Capsule's Behaviour

The TPU “cross” beam was characterized in order to extend the research work and scope of the study. The analytical process was similar to that for the simple ABS beam, involving beam deflection for different beam thicknesses, in this case from 1.0 *mm* to 3.0 *mm*. From an analysis of the 3D curves as shown in Figure 6-3, it is evident that the plastic regime had been achieved at the maximum values of applied load for each thickness of the TPU “cross” beam. The R-squared value was 0.9966, 0.9818, and 0.9674, respectively, for the 1.0, 2.0, and 3.0-*mm* capsule thicknesses. This indicates that as the TPU “cross” origami capsule thickness increases the accuracy of the model equation decreases, as indicated in Table 6-2. It can be inferred that the equation is less well-adapted to thicker beams. The maximum stress values recorded for the 1.0, 2.0, and 3.0-*mm* capsules, respectively, were $6.24 \times 10 \text{ Pa}$, $7.61 \times 10 \text{ Pa}$, $3.88 \times 10 \text{ Pa}$.

Upon examination of Figure 6-2, it is evident that the capsule's elastic limit for the 1.0 *mm* thick capsule was about 1.04 *N*, for 2 *mm*, 1.33 *N*, and for 3 *mm*, 1.33 *N*. Compared to the ABS, the highest elastic modulus was for the 3.0 *mm* thick beam: $3.88 \times 10 \text{ Pa}$, corresponding to the maximum load of 4.02 *N*. This demonstrates that for the same beam design, the ABS will yield a higher elastic modulus than the TPU “cross”.

In Figure 6-5 w_{00} , w_{10} , w_{01} , w_{20} , and w_{11} are plotted against thickness using the model equation; research correspond to the R-squared values for all coefficients being 1.0. In conclusion, from the experimental results for the TPU “cross” capsule, it is clear that the elastic modulus had a lower value than was achieved with the simple ABS beam. However, one prominent effect that was highlighted for the TPU “cross” capsule was that the beam’s plastic region was activated at relatively low values of applied force. This also suggests a high flexibility in the TPU “star”, which can be used to advantage in those designs where the beam needs to be folded and activated even when there is little change in the applied force. The TPU “cross” is more likely to remain elastic under deformation; this is why chose to use the TPU “cross” as the material for the capsule and chose ABS to be the beam. It was clear from Figure 6-4 that the strain energy is obtained at maximum 0.25 N for all three capsules. However, the capsule thickness significantly affected the overall decay of strain energy. This suggests that the TPU “cross” capsule may be ideal for higher stresses because the material may be more resilient.

Thus, the research inserted a TPU “cross” capsule inside the DCB and calculated the strain energy released by crack propagation in the DCB to assess whether it would activate the TPU “cross”. Since the values of strain had been calculated above it was easy to pinpoint the amount of strain energy released during crack propagation. The question is whether the amount of strain energy released would activate the TPU “cross” module. The behaviour of the “cross” is observed to be duplicated by the roller under a bending load.

6.5 Results With the TPU Roller Origami Capsule

6.5.1 The Bending Load Setup

All the origami capsules were prepared with a dimension of 19 mm x 5 mm but had different thicknesses: 1 mm , 2 mm , and 3 mm . Figure 6-7 shows that the capsule “roller” was first folded to the machine and then, the deflection point of whole capsules was measured until it unfolded. The healed capsules were held by claws to the fixed support and unfolded during the bending test, deforming at

different rates. Three tests were done for each healing time. The origami capsules demonstrated an autonomous self-healing mechanism without any energy input.

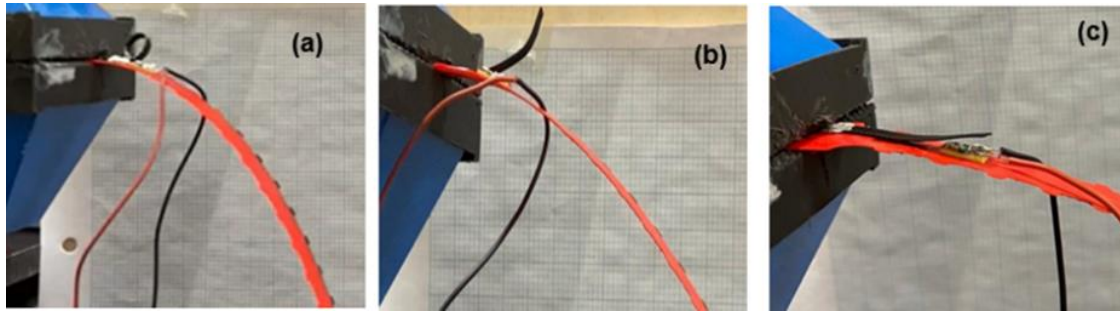


Figure 6-7 The self-healing experiment. (a) the capsule folds. (b) capsule opened, (c) capsule unfolded during a bending test.

6.5.2 Resulting Behaviour of the TPU Roller Capsule

This section describes the displacement response of the TPU “roller” material with different thickness values and bending loads applied at the tip of the capsule. The behaviour under an elastic regime for each origami capsule and a plastic regime for each model is shown in Table 6-4. Initial examination of the findings reveals that the deflection of the results varies, yielding a maximum deflection of 19 *mm* for the 1 *mm* thick capsule, within elastic limits. However, for the 2 *mm* thick capsule, a deflection of 17 *mm* was observed. For a 3 *mm* thick capsule, the maximum stress yielded a deflection of 15 *mm*. Table 6-4 also represents the green values, which is a primary indication of initiation of the plastic regime of each capsule at different beam thicknesses. The results and discussions of this section have also been published in the International Journal of Applied and Physical Sciences.

Table 6-4 Data collected for force and maximum deflection for the TPU origami capsule "roller".

1 mm		2 mm		3 mm	
Force (N)	Max Deflection (mm)	Force (N)	Max Deflection (mm)	Force (N)	Max Deflection (mm)
0	0	0	0	0	0
0.00981	2	0.00981	2	0.00981	2
0.01962	4	0.01962	4	0.01962	4
0.03924	7	0.03924	7	0.03924	5
0.05886	9	0.05886	10	0.05886	7
0.10791	13	0.10791	12	0.10791	9
0.15696	17	0.15696	15	0.15696	11
0.25506	19	0.25506	17	0.25506	13
-		0.35316	19	0.35316	15
-				0.54936	17
-				0.73575	19

Given the observed changes for the maximum deflection with respect to different loads, it is helpful to analyse whether the values change with position or not. This was done by plotting a 3D-surface graph. To clearly understand this concept, a 3D-surface plot that shows the parametric relationship between force, deflection, and position of the capsule, was used to observe the results (see Figure 6-8).

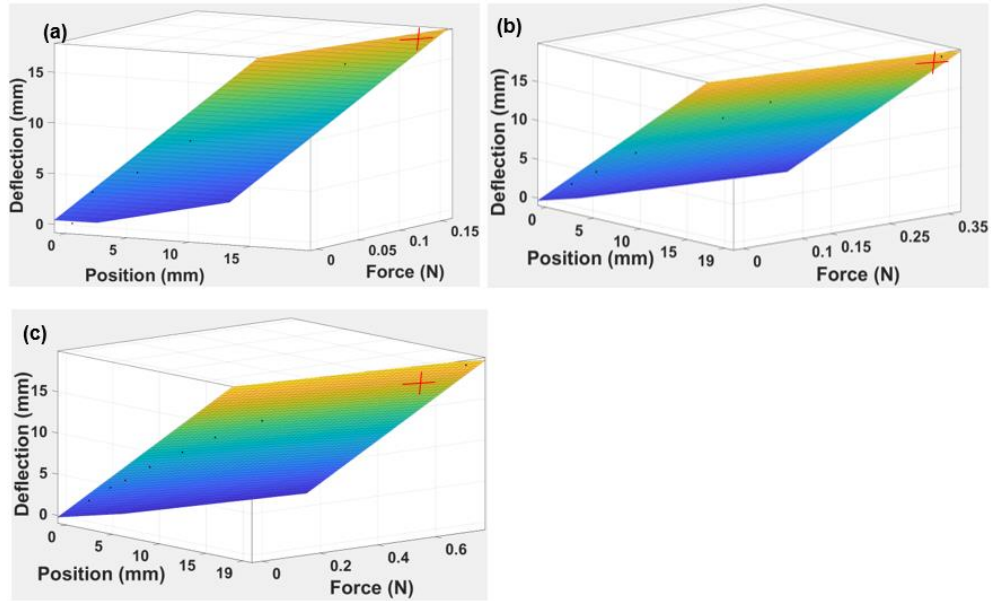


Figure 6-8 3D gradient graph of the TPU capsule "roller" plotted between Force (N), Deflection (mm) and Position (mm) at thicknesses of (a) 1mm, (b) 2mm, and (c) 3mm

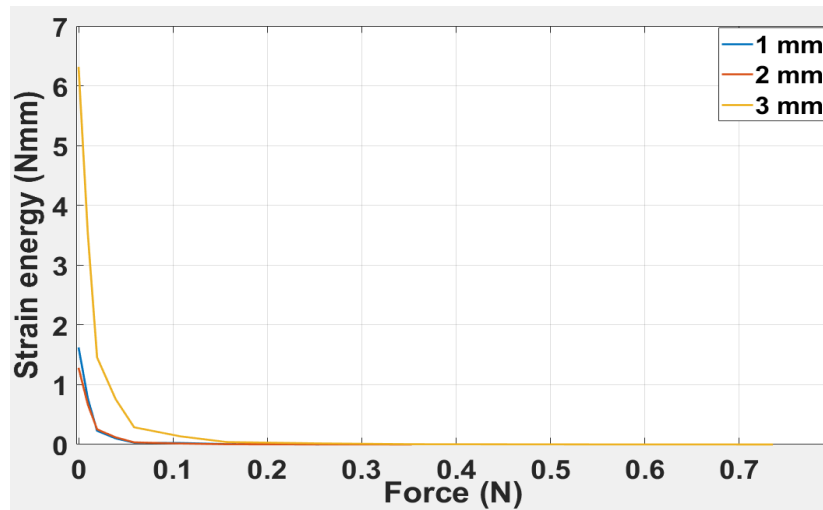


Figure 6-9 Strain energy versus applied force for the TPU "roller" capsule for thicknesses of 1.0 mm, 2.0 mm, and 3.0 mm

Figure 6-9 indicates the response of strain energy with force applied to the TPU "roller" capsule. It is clear from the trends that the responsiveness of the origami capsule to strain energy is exponential and, for all capsule thicknesses, diminishes as the applied force increases. It is evident that a force of 0.2 N is the

maximum for showing the response of strain energy from all three capsule thicknesses.

$$deflection = d (force, position)$$

For the TPU “roller”, the generalized equation for any arbitrary point to Equation (6-10) is:

$$\begin{aligned} d \text{ deflection } (f = \text{force}, y = \text{position at any point}) \\ = m_{00} + m_{10}x + m_{01}y \end{aligned} \quad (6-10)$$

where, m_{00} , m_{10} , and m_{01} indicate the coefficients of a polynomial equation in which x is the thickness of the capsule.

The results of the coefficients at different small beams thickness are summarised in Table 6-5.

Table 6-5 Different values of coefficients of TPU "roller" capsules of different thicknesses.

Thickness	m_{00}	m_{10}	m_{01}	R-squared
1 mm	1.20	-23.57	1.05	0.9865
2 mm	0.58	-8.39	1.12	0.9977
3 mm	0.67	-3.10	1.07	0.9970

By substituting the coefficients in Equation (6-10), the polynomial equation for each thickness of the roller capsule can easily be found.

$$1.0 \text{ mm} \quad f(f, y) = 1.20f^2 - 23.57f + 1.05y \quad (6-11)$$

$$2.0 \text{ mm} \quad f(f, y) = 0.58f^2 - 8.39f + 1.12y \quad (6-12)$$

$$3.0 \text{ mm} \quad f(f, y) = 0.67f^2 - 3.10f + 1.07y \quad (6-13)$$

As Table 6-5 above shows, the R-squared values for each thickness were found to be 0.9865, 0.9977 and 0.9970, respectively for the 1 mm, 2 mm, and 3 mm “roller” capsule thickness. This is why the 3.0 mm thick capsule has the lowest values of coefficients and highest R-squared values. The results can be simplified even further if the variables and coefficients are reduced by plotting the coefficient curves against beam thickness, allowing the corresponding slopes of the curves to be determined (the coefficients r_1 , r_2 , and r_3) as shown in Figure 6-10.

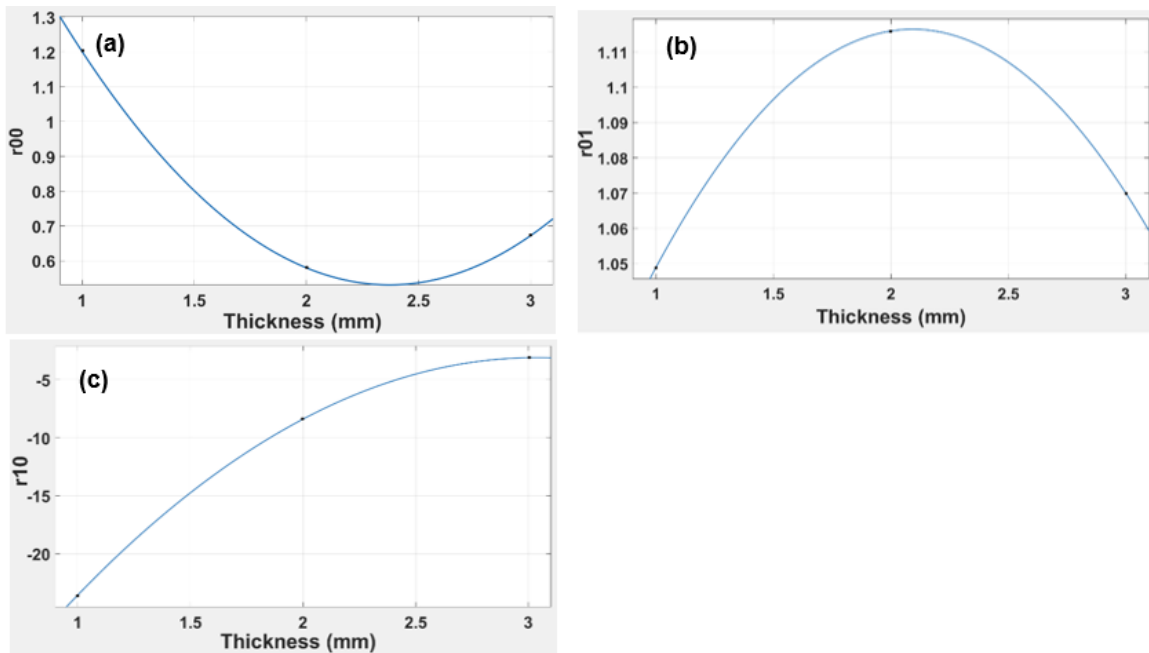


Figure 6-10 Graphs indicating the relationship of TPU "roller" capsule thickness versus coefficient for (a) r_{00} , (b) r_{01} and (c) r_{10} .

Each graph in Figure 6-10 was fitted with a second-degree polynomial, so the simplified equation becomes:

$$f(x = thickenss) = r_1 x^2 + r_2 x + r_3 \quad (6-14)$$

Table 6-6 Values of linear equation coefficients for all three thickness of TPU "roller" capsule.

Coefficient	r_1	r_2	r_3	R-squared
r_{00}	0.357	-10.692	2.536	1.00
r_{01}	-0.0565	0.2365	0.869	1.00
r_{10}	-4.943	30.01	-48.63	1.00

The generalised equation is obtained by substituting the values of the coefficients in Equation (6-14):

$$r_{00} \quad f(x) = 0.357x^2 - 10.692x + 2.536 \quad (6-15)$$

$$r_{01} \quad f(x) = -0.0565x^2 + 0.2365x + 0.869 \quad (6-16)$$

$$r_{10} \quad f(x = thickenss) = -4.943x^2 + 30.01x - 48.63 \quad (6-17)$$

The above equations are formulated by substituting the values in the generalised equation. The R-squared value for each coefficient is 1.00, which shows a perfect fit of curve, as indicated in Table 6-6.

6.5.3 Discussion of the TPU Roller Capsule's Behaviour

The current analysis is predicated on the observation that elastic and plastic strains are not independent and that the influence of transformation plasticity may be included in a general phenomenological analysis that conforms to the formalism of macroscale elasticity theory. Figure 6-8 depicts the experimentally obtained mean load, deflection, and position of the bending tests for each thickness of roller, in this case 1.0 mm, 2.0 mm, and 3.0 mm. The plastic region was attained at the maximum values of applied load for each thickness of the TPU "roller" capsule, according to the analysis of 3D curves as shown in Figure 6-8. The R-squared value for the thickness values was 0.9865, 0.9977, and 0.9970 respectively for the 1.0 mm, 2.0 mm and 3.0 mm capsules. As shown in Table 6-5, as the TPU "roller" capsule thickness increases, the accuracy of the

model equation decreases. This demonstrates that the equation is less suitable for thicker beams. The maximum stress values for 1.0 mm, 2.0 mm, and 3.0 mm capsules were $0.22 \times 10^6 \text{ Pa}$, $0.73 \times 10^6 \text{ Pa}$, and $0.90 \times 10^6 \text{ Pa}$, respectively.

Table 6-4 shows the recorded values for the TPU “roller” capsule. The elastic limit of the beam was observed to be about 0.26 N for the 1.0 mm thick beam, 0.26 N for 2 mm, and 0.35 N for 3 mm after the green values, which is a primary indication of the initiation of the plastic region of the capsule at different thicknesses.

Figure 6-9 shows that the strain energy for all three capsules is obtained at a maximum of 0.2 N. However, the overall strain energy decay was significantly affected by the capsule thickness. Because the material is more resilient, the TPU “roller” capsules may be ideal for higher stresses. In Figure 6-10 r_{00} , r_{01} , and r_{10} are plotted against thickness using the model equation and corresponding to the R-squared values of 1.0 for all coefficients (see Table 6-6). In conclusion, the elastic modulus of the TPU “roller” capsule was lower than that of the TPU “cross” capsule, according to the experimental results. However, one notable effect for the TPU “roller” capsule was that the plastic region of the capsule was activated at relatively low values of applied load. This also suggests that the TPU “roller” has a high degree of flexibility, which can be used to advantage in designs where the beam must be folded and activated in response to even minor changes in applied load. The TPU “roller” is more likely to remain elastic under deformation. To check this, inserted a TPU “roller” capsule in the DCB and calculated the strain energy released by crack growth in the DCB to see what would activate the TPU “roller”. Because the strain values were calculated above, it was simple to represent the amount of strain energy released during crack propagation. The question is whether the quantity of strain energy released is sufficient to activate the TPU “roller” module.

6.6 Conclusion

This chapter studied the strain energy behaviour of self-healing mechanisms under elastic and plastic conditions for TPU capsules. First, the equations

corresponding to the general case of TPU "cross" capsule research were obtained and from these the equations corresponding to the case of the TPU roller capsule were deduced. Origami capsules were made in the shape of a cross with four small beams comprising the arms and in the shape of a roller, folded, or elastically deformed and embedded in the main beam structure. The elastic-plastic load, deflection and position behaviour of a capsule containing different thicknesses were noted. The elastic analysis of the stress and the strain energy concentration resulting from the cross and roller shapes of the origami capsule indicated that the maximum stress concentration occurs at the tip of the capsules and in the load application region. It was also demonstrated that the deflections of the origami capsule could easily be studied by means of a simple, easy-to-assemble, low-cost experiment, which allowed us to experimentally study the deflection of the origami capsule using a series of simple measurements, for example, of load and position. The results of the bending test were processed by capturing images of the capsule in different deflections and positions, and then processed in MATLAB software to get the equation for each thickness.

Therefore, from the findings presented in this chapter, it cannot be disputed that, overall, 3DP TPU origami capsule shapes permit good long-term healing as long as the parameters are set up to meet the self-healing mechanism. With the strain energy of the TPU origami capsule justified, the next chapter describes how a TPU capsule was inserted in the DCB and how the strain energy released by crack propagation in the DCB was calculated to assess whether it would activate the TPU.

7 EMBEDDING THE CAPSULE INSIDE THE POLYMERIC STRUCTURE COMPOSITE

7.1 Introduction

This chapter focuses on the self-healing mechanism of embedding the capsule inside the polymeric structure composite. The strain release behaviour of the double cantilever beam (DCB) was observed using the delamination test, and the chapter investigates the self-healing behaviour was further. The self-healing mechanism of the samples was found to be dependent on the healing time and the strain release.

Some origami capsules were cross shaped, made of four small beams that could be folded; others were roller shaped, elastically deformed, and embedded in the main beam structure. Under the strain released due to crack propagation in the main beam, the small beams of the origami capsule unfolded in the direction that the crack was taking and hence increased the resistance of the structure to crack propagation. This increase in the crack resistance was confirmed in a delamination test of a double cantilever specimen under quasi static load conditions.

In summary, this chapter examined the time and strain released due to crack propagation and explained its self-healing mechanism, including the origami capsules inside the embedded structure. The results of this chapter also have been published in polymer journal.

7.2 Design of Experiment

7.2.1 Origami Capsule Embedded Inside Structure of the Beam

A simple experiment was conducted to record load and displacement using a delamination test on the specimen beams printed using an ABS transparent polymer, as shown in Table 7-2. The stress/strain relationship with and without the origami capsule was then evaluated.

The initial hypothesis was that specimens containing the origami structures would be more resilient and exhibit higher tensile strength when loaded axially. Conversely, specimens that did not have origami structures embedded within them were predicted to exhibit lower resilience or lower tensile strength. To test this hypothesis, two hollow 3D beam samples were printed that could be joined later by mechanical means. One of the samples contained a 3D printed origami structure embedded inside using an adhesive. The other, the control, was the same 3-D printed beam, but without the origami structure embedded within it. The specimens were loaded and pulled (tensile loading) axially. Force vs. displacement (F/D) curves were obtained, which corresponded to the stress/strain relationship. To convert F/D curves to a stress/strain relationship, the force values were divided by the cross-sectional area of the beam, while the D values were divided by the initial gauge length. A schematic of the experimental procedure is presented in Table 7-1.

Table 7-1 Experiment scheme in embedded structure

Specimen Type	Crack Length	Thickness of Capsule	Mechanical Testing
DCB origami	40 mm	1 mm, 2 mm, 3 mm	Delamination test
DCB without origami	-	-	Delamination test

Table 7-2 Specimen set-up (DCB)

Specimen	Beam thickness (mm)	Dimension, (mm) (Length/width)	Type of structure
With origami capsule	5 mm	193L/30W	With holes and pillars
Without origami Capsule	5 mm	193L/30W	With holes and pillars

7.2.2 A Double Cantilever Beam Testing Procedure

Before each test, the DCB specimen was prepared and measured. The measurements consisted of specimen width, thickness and length b , h and L , respectively, as well as the initial value of the delamination length from load line a , denoted a_0 , and the initial delamination length from the edge of the specimen a' (see Figure 4-17). See also [164] for more information on specimen measurements. To mount the specimen in the loading machine, hinges were glued onto the specimen. A camera was attached to the front of the specimen so as to calibrate the pictures taken during the test. All experiments were carried out under displacement control at a rate of 0.05 to 0.1 mm/sec (see Figure 7-1). During crack initiation and propagation, two parameters were reported simultaneously by the testing machine: displacement (δ) and load (P). When the actuator displacement d reached a certain value in most quasi-static tests, the specimen detached from the support. The initial crack length in all the specimen with or without capsule was 40 mm . The applied load and crosshead displacement were recorded during the test. The test was concluded after the delamination had spread about 45 mm . In some cases, images were captured by a camera placed in front of the specimen after about 5 mm of propagation and at the end of the test. In addition, after the test was completed and the specimen was removed from the loading machine, the final delamination length was measured.



Figure 7-1 Testing machine

Samples of the first type (without origami) were tested monotonically. The specimen was loaded until the crack opening length reached 40mm . Then samples of the second type (with origami) were tested in the same way. The load and the crack opening displacement were recorded throughout the test of each specimen, and the results with origami and without origami were compared. Figure 7-2 illustrates the difference between the two types. After the first test, the crack had extended along the mid-plane where the origami opened and gradually the crack was repaired before it spread further.

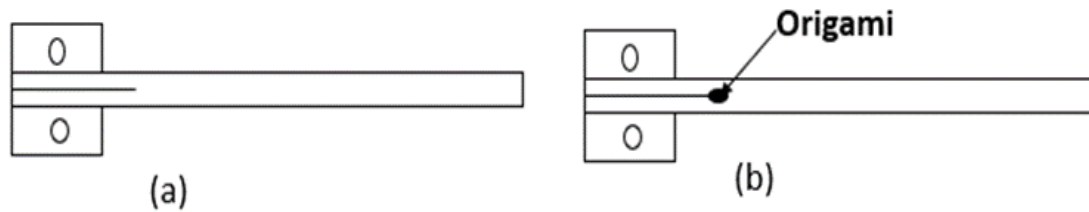


Figure 7-2 Specimen preparation (a) without origami, (b) with origami

7.3 Results for Origami “Cross” Module Embedded Structure

For the DCB test, instead of having interlaminar crack growth in the DCB, one of the arms was broken (see Figure 7-3). The responses of the DCB model can help us to analyse the behaviour of the origami capsule and whether it activates a self-healing mechanism. The analytical process seeks to estimate how much stress is released when the beam is deflected due to the application of a force. With the DCB, it is assumed that the force is dependent on the strain energy release phenomenon. The response of force vs displacement for the DCB is presented in Figure 7-3. Here, the proposed standard was modified by adding a video recorder and camera to the test set-up: a picture, which coincided with the force and displacement measurements, was taken every 10 s and was used to visually evaluate and measure the position of the crack tip during the tests with the TPU origami capsule in place.

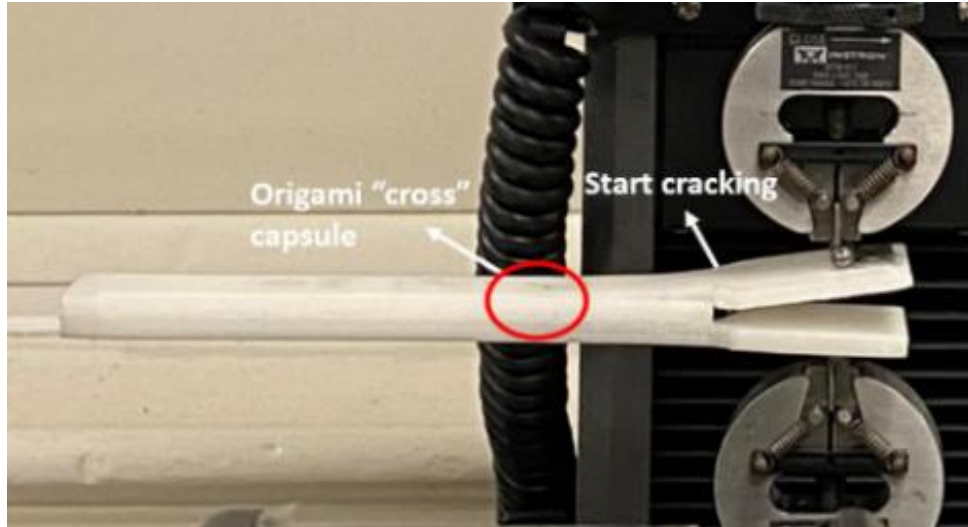


Figure 7-3 Measuring DCB crack length and displacement during the test

The load-displacement graphs obtained for the beams with origami capsule and without origami capsule are as shown in Figure 7-4 (a), (b), (c), and (d). Nonlinearities in the load-displacement relation were observed. For the specimen with the origami capsule. Figure 7-4 (a), the maximum resistant force is 25 *N*. For the specimen without origami, Figure 7-4 (b), it is clear that the maximum force that can be resisted is 19 *N* at a total displacement of 6.4 *mm*.

Noticeable is the sudden and substantial drop in force that occurs in both cases, with and without the origami capsule. When the capsule is present the drop is from about 15 *N* to 5.4 *N*, starting at a displacement of about 11 *mm*. When the capsule is absent, the drop is from about 15 *N* to 8 *N*, starting at a displacement of about 8 *mm*. This sudden failure precedes the full collapse of the DCB. However, the maximum displacement of the beam without the capsule reaches 20 *mm*, which is significantly higher than that for the beam with the capsule.

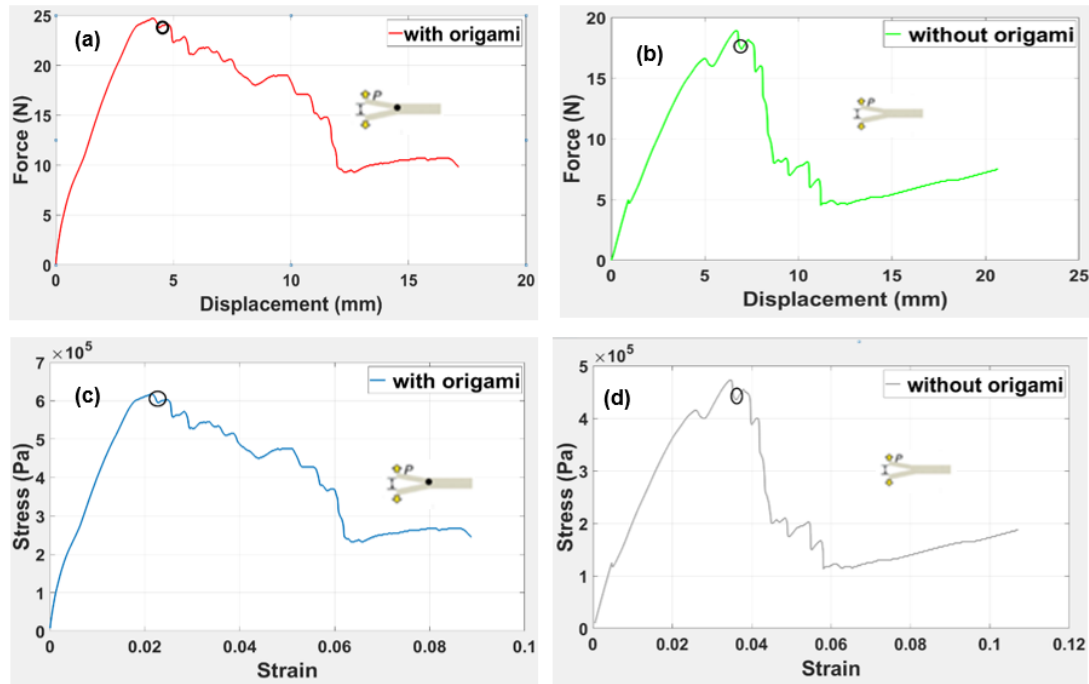


Figure 7-4 Crack length in DCB under the quasi-static conditions

The research can estimate the percentage error in the experimental deviation using the time and strain released.

$$\text{Strain release due to crack } (U) = \frac{\sigma^2}{2E} B\pi a^2 \quad (7-1)$$

where σ represents the stress applied (N/m^2), E is the elastic modulus of the materials (N/m^2), B is the area length (mm), π is the area from middle DCB to the open area and a indicates the length of the beam (mm).

Table 7-3 Experimental and theoretical model of the beam a) with origami, b) without origami

	With Origami (5 mm)	Without Origami (5 mm)
Experimental value of strain release	$\epsilon = 8.87 \times 10^{-2}$	$\epsilon = 2.62 \times 10^{-2}$
Theoretical value of strain release	$\epsilon = 1.53 \times 10^{-3}$	$\epsilon = 4.61 \times 10^{-6}$

Percent Deviation in strain release	$\Delta\epsilon = 0.0871$ (8.71%)	$\Delta\epsilon = 0.0267$ (2.67%)
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Table 7-3 indicates the experimental and theoretical values for the strain released (see Table 7-3) during the beam test with and without origami. The results indicate that the difference of strain in the beam with origami is 0.0871, and without origami is 0.0267, which comes to 8.71% and 2.67%, respectively. This shows that the strain released without origami is greater than that with origami. The response of the TPU which have observed separately is the same as that of the DCB. In order to use the model equation in calculations relating to self-healing behaviour, the research have to include the calculated deviations.

7.3.1 Discussion for Origami “Cross” Module Embedded Structure

This research assessed the behaviour of origami capsules embedded in the DCB structure. The DCB tests were carried out on an Instron test machine with displacement rates varying from 0.05 to 0.10 *mm/sec*. The energy release rate and values of critical energy were calculated on the basis of the configurations. The material of the specimen was ABS, which was used to evaluate the stress-strain relationship for the DCBs with and without the presence of origami capsules. The results show that the presence of an origami capsule results in a more robust and resilient beam, that can withstand greater fluctuations than a beam without an origami capsule. A mathematical analysis of the force vs. displacement and stress vs. strain curves was performed to help assess whether the hypothesis and research arrangement were valid.

From the experimental results, two pairs of graphs were obtained for the beams with origami and without origami, as shown in Figure 7-4 (a), (b), (c), and (d). Figure 7-4 (a), shows that with the origami capsule present, the graph proceeds as an almost straight line from 0 *N* to the maximum force of 24 *N*, at which the total displacement was 4.8 *mm*. This denotes the elastic limit of the beam and the resistance at the maximum load. After this point, the beam continued to

extend and the displacement increased, reaching a maximum displacement of 17.5 *mm*. This was the plastic region of the beam.

For the specimen without origami, as indicated in Figure 7-4 (b), it is clear that the maximum force that can be resisted is 19 *N* at a total displacement of 6.4 *mm*. The sudden and substantial drop in force from 15 *N* to 5.4 *N* after this failure was obvious; it was enough to damage the overall beam before it fully collapsed. The maximum displacement of the beam reached 20 *mm*, which was significantly higher than for the beam with origami.

This is evident from a comparison with the results of previous research work by Simon et al. [156], who carried out load vs. displacement tests on specimens with and without a laminate lay-up. There was a clear difference in delamination lengths for the two specimens with a rapid drop in load for the non-laminated lay-up compared to a gradual decline in force for the laminated lay-up. This result is similar to our beam results, as shown in Figure 7-4.

These results indicate that a beam with the origami capsule resists failure better than a beam without the capsule. In research observations, the beam dimension may also play a significant role in defining the strength of the material. A study by Brunner et al. [158] on the applicability of delamination resistance of different materials indicates that multi-directional lay-ups pose issues due to crack branching and deviation from the plane. The delamination resistance seen in DCB tests depended on the fibre orientation. Alternating the orientations of the cross-ply composites in the beam from 0° to 90° yielded a 50% deviation from the mid-plane.

Figure 7-4 (c) and (d) presents graphs of stress and strain, with and without the origami capsule. With the capsule present the maximum stress was 6×10^6 *Pa* and the strain was 0.09, whereas for the specimen without the capsule, the maximum stress was 4.5×10^6 *Pa* and the strain was 0.11. The stress-strain relation has also been studied by Chen et al. [165] using high-density stitched beams. When the load vs. displacement curve were compared, it was evident that the load increased linearly with the displacement, but when the stitches

broke, crack initiation caused a sudden drop in load. Results closer to those in our study are reported by Kato, et al., [166], they found reported an example of crack propagation in DCB made from a satin weave E-glass fabric. The results are comparable in the sense that the delamination was 1.0 *mm* in width. Additionally, the load fluctuation was also steady, like that of origami, which indicates the high tensile strength of the material sufficient to bear the increasing load, even during crack formation.

In conclusion, the proposed TPU “star” origami capsule tends to absorb a sudden fluctuation in load and retards the displacement that may lead to failure. This contrasts with the results of the beam without an origami capsule: these showed a rapid decrease in load with an excessive displacement that led to the failure of the beam. Therefore, the hypothesis that specimens which integrate origami structures are more resilient and exhibit higher tensile strength when loaded axially is supported. Similarly, DCB beams that do not have origami structures embedded within them exhibit lower resilience or lower tensile strength.

7.4 Results for a Comparative Study for Strain Energy Activation in An Embedded Structure Versus a Simple TPU Capsule.

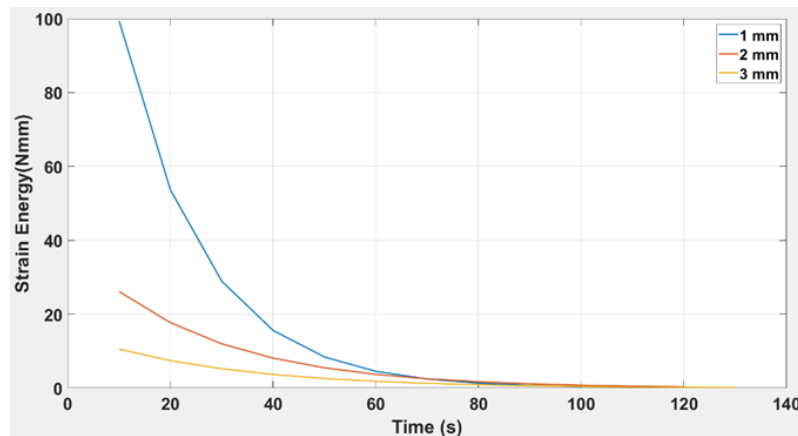


Figure 7-5 Strain Energy versus time for TPU capsule structure of thickness 1.0 *mm*, 2.0 *mm*, and 3.0 *mm*

The results presented in Figure 7-5, indicate a correlation between time and strain energy for simple TPU capsules 1, 2, and 3.0 *mm* in thickness. It is seen that the

magnitude of the strain energy increases with the thickness of the beam, since 3.0 mm showed the highest and 1.0 mm showed the least responsiveness over time.

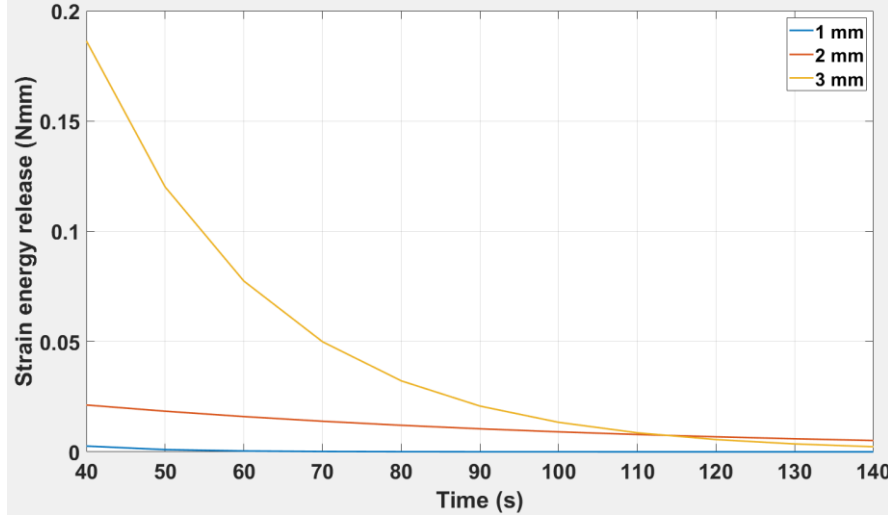


Figure 7-6 Strain energy release versus time for TPU-embedded DCB beam for thicknesses 1.0 mm, 2.0 mm, and 3.0 mm

Figure 7-6 indicates the strain energy release over time for the beam with embedded capsule. It is clear from the trends that the embedded beam of greatest thickness has the highest strain energy release and vice versa. The shape of the curves was exponential for all thicknesses. Compared to the normal TPU beam structure in which the strain energy lasted for 75 s, in the TPU-embedded structure, the strain energy release covered a period of 140 s. The average of strain energy release for 1, 2, and 3-mm beam thickness were 0.00038, 0.01153, 0.0473. Similarly, the standard deviations were 0.00075, 0.00507, and 0.05626 for beams of 1, 2, and 3-mm thickness, respectively.

Generalized equation for any thickness of the beam is represented as:

$$y = \text{Strain energy} = f(t = \text{time}) = ae^{bt} \quad (7-2)$$

where y indicates the strain energy (Nmm), a and b are coefficients, and t represents time (s).

Table 7-4 Coefficients for DCB with embedded TPU capsule and simple TPU capsule, for three beam thicknesses.

Thickness	Coefficients	Embedded structure DCB (Average)	TPU capsule thickness (Average)
1 mm	a	0.11991	184.3
	b	-0.09576	-0.06174
2 mm	a	0.03747	38.61
	b	-0.01419	-0.03903
3 mm	a	1.0784	14.96
	b	-0.04389	-0.03509

By substituting the values of a and b into Equation (7-2), the corresponding equation for each thickness can be represented as:

Embedded structure (DCB):

$$1.0 \text{ mm} \quad f(t) = 0.11991e^{(-0.09576t)} \quad (7-3)$$

$$2.0 \text{ mm} \quad f(t) = 0.03747e^{(-0.01419t)} \quad (7-4)$$

$$3.0 \text{ mm} \quad f(t) = 1.07838e^{(-0.04389t)} \quad (7-5)$$

Simple TPU (origami capsule) thickness:

$$1.0 \text{ mm} \quad f(t) = 184.3e^{(-0.06174t)} \quad (7-6)$$

$$2.0 \text{ mm} \quad f(t) = 38.61e^{(-0.03903t)} \quad (7-7)$$

$$3.0 \text{ mm} \quad f(t) = 14.96e^{(-0.03509t)} \quad (7-8)$$

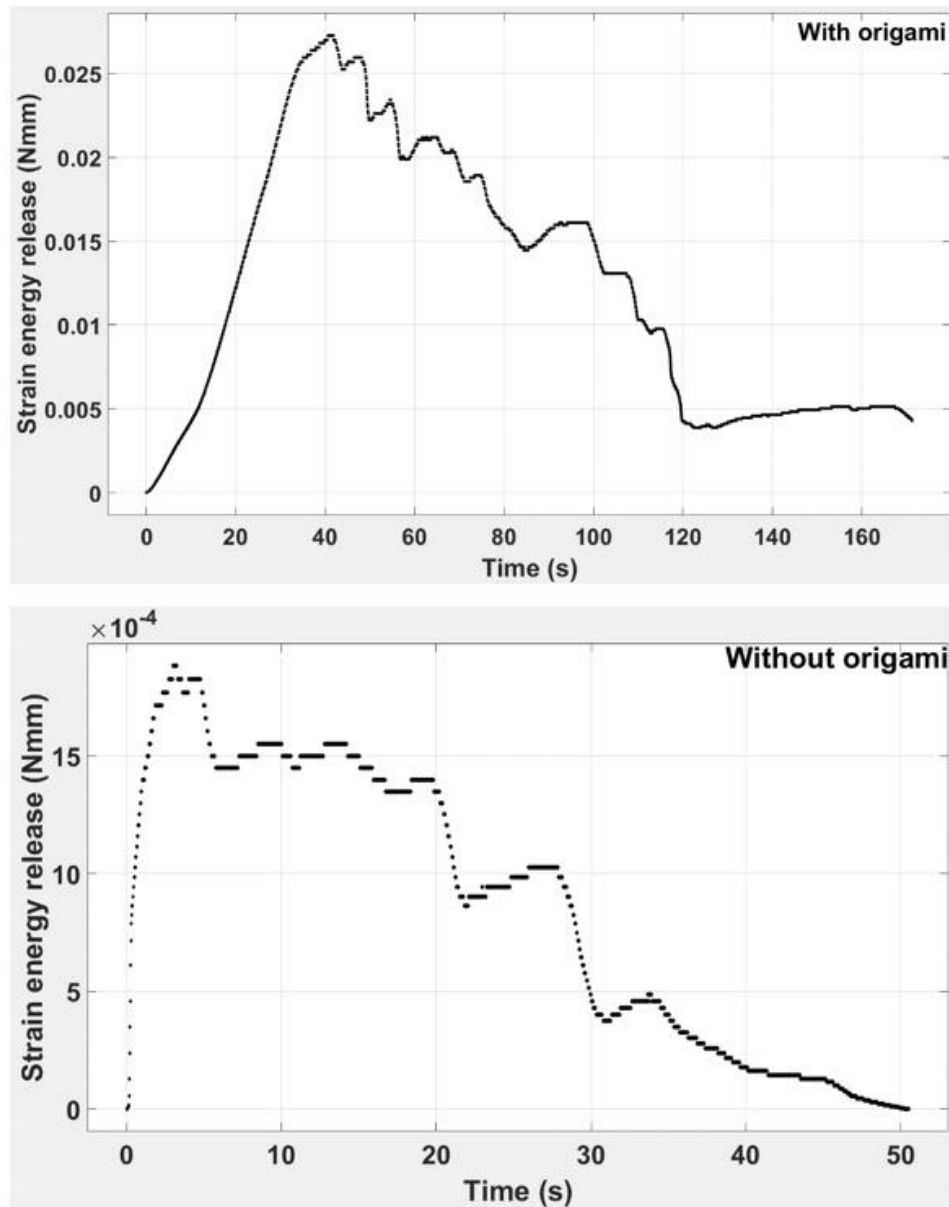


Figure 7-7 Strain energy release vs time for DCB (a) with origami capsule and (b) without origami capsule.

Figure 7-7 indicates the responsiveness of the strain release. It is evident that strain energy release for the DCB with and without the origami capsule has different response times. Research see that maximum strain release was attained at 40 s for the beam containing the capsule and 3.5 s for the beam with no capsule. This shows that strain energy release in the beam with a capsule is higher than for the beam without a capsule.

From the graphs presented in Figure 7-5 and Figure 7-6, a third-degree polynomial was used to fit the data points, so the generalized Equation (7-9) becomes:

$$f(t = \text{time}) = s_1 t^3 + s_2 t^2 + s_3 t + s_4 \quad (7-9)$$

where s_1, s_2, s_3 , and s_4 indicate the coefficients of the polynomial equation and t indicates the time of the beam (see Table 7-5).

Table 7-5 Values of the linear equation coefficients and parametric coefficients for origami and non-origami capsules.

Coefficient	S_1	S_2	S_3	S_4	R-squared
With origami capsule	4.971×10^{-8}	-1.479×10^{-5}	0.001144	-0.003213	0.9200
Non origami capsule	5.415×10^{-8}	-4.429×10^{-6}	6.075×10^{-5}	0.001356	0.9333

The R-squared values for with-origami and non-origami capsules are found to be 0.9200 and 0.9333, respectively. This indicates high accuracy for the model equation.

7.4.1 Discussion of Strain Energy Activation in An Embedded Structure Versus Simple TPU Origami Capsule

In a structural analysis of the beam's response to strain energy, it is notable that the beam resists external actions by developing internal stresses induced in the material of the beam by the external forces and their subsequent displacements. The response of these internal stresses also changes with secondary parameters, such as those of geometry and dimensions. In the present research, it was evident that the strain energy for both the embedded structure DCB and the simple TPU beam produces an exponential decay curve. The generalized equation of the curve is indicated in Equation (7-2) and is as shown in Table 7-4. For both the embedded structure and the simple TPU origami capsule, the value of the constant, a , increases and the value of the exponent, b , decreases with increasing thickness.

Given the similarity in trends for the simple TPU origami capsule and embedded structure, it is evident from Figure 7-5 and Figure 7-6 that the magnitude of strain energy increases with the thickness of the beam. In Figure 7-6 it is observed that the embedded beam with greatest thickness has the highest strain release, and the converse also holds. Compared to the simple TPU beam structure in which the strain energy lasted for 75 s, the strain release in TPU-embedded structure, extended over a period of 140 s. This shows that strain release was more slowly dissipated in the beam embedded with a TPU capsule than in the simple TPU beam. The response of the 3.0 mm beam is also significant; it shows that the embedded structure can sustain higher strain energy values than the same structure without an embedded capsule. Therefore, when including a healing mechanism in a beam where high strain energy is required, it is necessary to select thickness of the highest value.

To ascertain the healing rate, the research calculated from Figure 7-5 and Figure 7-6 the difference between a TPU in embedded structure and a simple TPU origami capsule from the extended rate of strain energy. It was found that the embedded structure had an extended dissipation time of 55 s for all three beams before the trend reached zero. In Figure 7-7, the time response to the strain energy release was plotted for beams with and without origami capsule inserts. It is evident that the strain energy release had a different response time depending on whether an insert was present. For instance, the beams attained maximum strain energy release at 40 s and 3.5 s, with the larger value corresponding to the beam with the insert, meaning that a crack will not propagate so fast when it is being healed. Because the strain energy release is dependent on how far the crack has propagated, the strain released due to the presence of the origami capsule acts to resist the crack's tendency to propagate.

7.5 The Roller TPU Origami Capsule and DCB in An Embedded Structure

7.5.1 Results For Origami “Roller” Module in An Embedded Structure

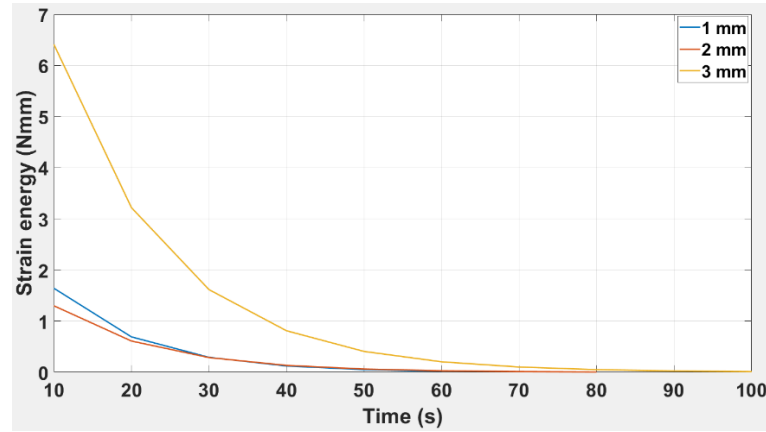


Figure 7-8 Graphical representation of the rolled TPU origami capsule on strain energy vs time with various thickness. 1 mm, 2 mm, and 3 mm

Figure 7-8 indicates the response of strain energy over time for the rolled TPU origami capsule. It is clear from the trends that the rolled TPU with a thicker beam has the highest strain energy; the converse also holds. The exponential curve remained the same for all thicknesses.

The generalized Equation (7-2) for any thickness of the beam is represented as:

$$y = f(t) = ae^{(bt)}$$

y indicates the strain energy (Nmm), a and b are the coefficients, and t represents time (s).

Table 7-6 Correlation coefficients for the roller TPU capsule and an embedded structure at the different beam thickness.

Thickness	Coefficients	Normal TPU roll	Embedded DCB with TPU
1 mm	a	3.893	47.36
	b	-0.08637	-0.00909
	a	2.765	0.00267

2 mm	b	-0.07551	-0.01852
3 mm	a	12.76	1663
	b	-0.06887	-0.03787

Normal TPU roller

$$1 \text{ mm} \quad f(t) = 3.893e^{(-0.08637t)} \quad (7-10)$$

$$2 \text{ mm} \quad f(t) = 2.765e^{(-0.08637t)} \quad (7-11)$$

$$3 \text{ mm} \quad f(t) = 12.76e^{(-0.06887t)} \quad (7-12)$$

Embedded DCB with TPU thickness

$$1 \text{ mm} \quad f(t) = 47.36e^{(-0.00909t)} \quad (7-13)$$

$$2 \text{ mm} \quad f(t) = 0.00267e^{(-0.01852t)} \quad (7-14)$$

$$3 \text{ mm} \quad f(t) = 1663e^{(-0.03787t)} \quad (7-15)$$

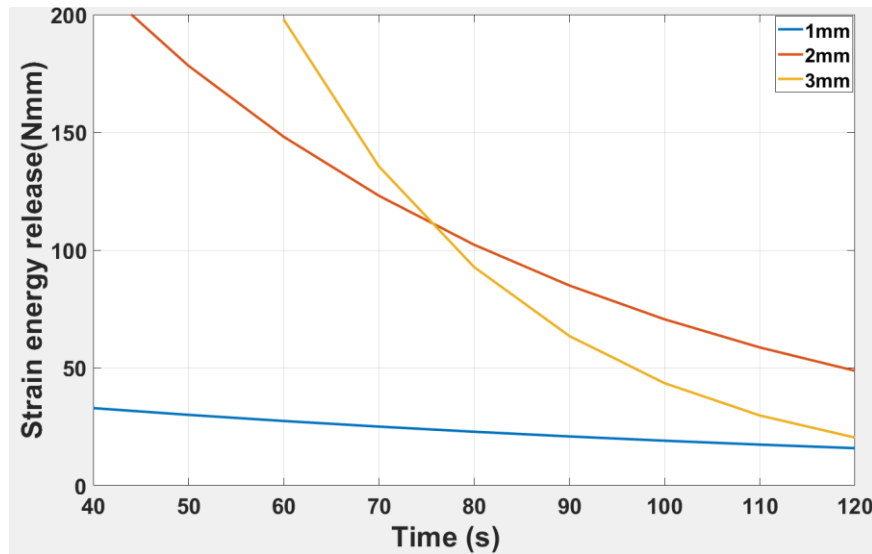


Figure 7-9 Graphs indicating the relationship between time strain energy release for the DCB roller for different beam thicknesses: 1 mm, 2 mm, and 3 mm

In Figure 7-9, the time responsiveness of the strain energy release for the DCB rolled is plotted in MATLAB. It was evident that strain energy release for each

DCB rolled structure had a different response time. For instance, a beam 1 *mm* thick attained a maximum strain release time of 116 *s* with the maximum strain release value of 27×10^{-4} *Nmm*. The beam that was 2 *mm* thick yielded a maximum strain release time of 92 *s* with a maximum strain release value of 13×10^{-4} *Nmm*, and lastly the beam of 3 *mm* thickness showed the maximum strain release, up to 30×10^{-4} *Nmm* with a total time of 53 *s*. This shows that the strain release for the DCB rolled structure is higher for the thicker beams, and the total time is considerably extended for beams that are less thick. The graph of the above figure is formulated in the following equation:

$$f(x = \text{thickness}) = u_1x^3 + u_2x^2 + u_3x + u_4 \quad (7-16)$$

where, u_1, u_2, u_3 and u_4 indicate the coefficients of the polynomial equation and x indicates the thickness of the beam (*mm*).

By substituting the coefficient values in Equation (7-16), the polynomial equation for each thickness can easily be found.

$$1.0 \text{ mm} \quad f(x) = -0.00040x^3 + 0.09733x^2 - 7.966x + 240.5 \quad (7-17)$$

$$2.0 \text{ mm} \quad f(x) = 1.144 * 10^{-8}x^3 - 1.826 * 10^{-6}x^2 + 8.39^{-5}x - 0.0002 \quad (7-18)$$

$$3.0 \text{ mm} \quad f(x) = -0.00056x^3 - 0.0023x^2 + 1.431x - 1.658 \quad (7-19)$$

Table 7-7 Values of the linear equation coefficients and parametric coefficients for the DCB roll capsule.

Thickness	U ₁	U ₂	U ₃	U ₄	R-squared
1 <i>mm</i>	-0.00040	0.09733	-7.966	240.5	0.9211
2 <i>mm</i>	1.144e-08	-1.826e06	8.385e-05	-0.0001996	0.9032
3 <i>mm</i>	-0.0005554	-0.00233	1.431	-1.658	0.9041

The R-squared value for rolled DCB beam is above 90%, which shows high accuracy of the tested model.

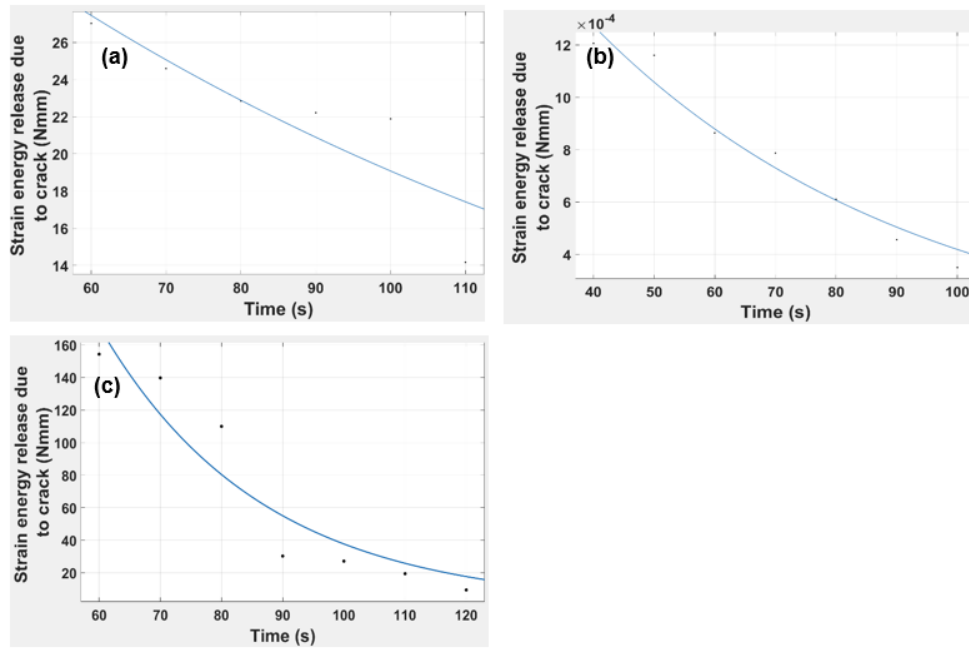


Figure 7-10 Graphical representation for DCB roll capsule for strain energy release due to crack vs time for thicknesses a) 1 mm, b) 2 mm, c) 3 mm

Figure 7-10 indicates the response over time to strain energy release due to cracking for the rolled DCB beam structure. It is clear from the trends that the rolled DCB with the thicker beam has the highest strain release due to cracking, the converse also applies. However, a thicker beam releases strain in much less time than a thinner DCB rolled beam. The exponential curve remained the same for all thicknesses. The generalized Equation (7-2) for a beam of any thickness is represented as:

Table 7-8 Different values of coefficients at different DCB roll capsule thicknesses.

Thickness	Coefficients	DCB roll due to crack
1 mm	a	47.36
	b	-0.009092
2 mm	a	0.00267
	b	-0.01852
3 mm	a	47.43
	b	-0.03212

$$1 \text{ mm} \quad f(t) = 47.36e^{(-0.00909t)} \quad (7-20)$$

$$2 \text{ mm} \quad f(t) = 0.00267e^{(-0.01852t)} \quad (7-21)$$

$$3 \text{ mm} \quad f(t) = 47.436e^{(-0.03212t)} \quad (7-22)$$

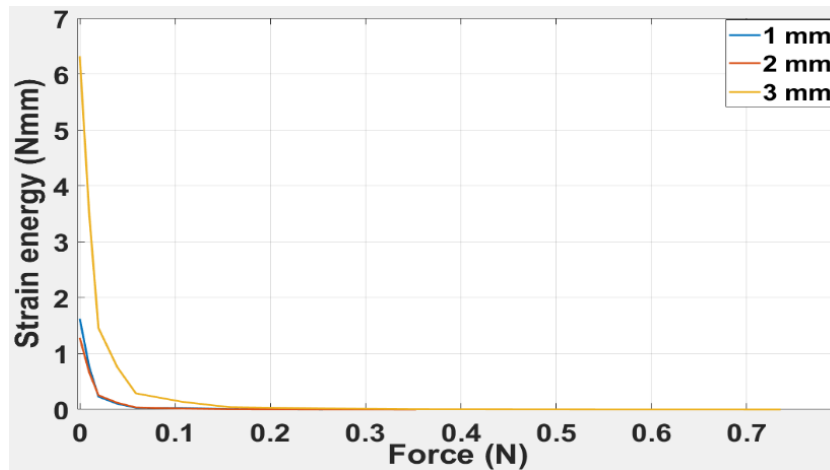


Figure 7-11 Graph between Force vs Strain Energy for TPU roller for various thickness: 1 mm, 2 mm, 3 mm

Figure 7-11 shows the curves plotted between strain energy and force for the rolled origami capsule for a) 1 mm, b) 2 mm, c) 3 mm thickness. The trends indicate that the strain energy has attained its maximum value for 3 mm beam thickness, which is above 6 Nmm, 1.5 Nmm for 2 mm, and 1.6 Nmm for 1 mm thickness. It is also to be noted that all strain energy for 1mm thickness reaches decay at 0.08 N, whereas for 2 mm and 3 mm rolls it reaches decay at 0.1 N. Therefore, it shows that the greater the thickness value, the greater will be the strain energy, and the more gradual will be the process of strain energy decay over time.

Table 7-9 Various values of coefficients at different thicknesses of normal TPU origami capsule roller.

Thickness	Coefficients	Normal TPU roll
1 mm	a	3.222

	b	-70.73
2 mm	a	2.226
	b	-57.75
3 mm	a	10.17
	b	-50.49

$$1 \text{ mm} \quad f(t) = 3.222e^{(-70.73t)} \quad (7-23)$$

$$2 \text{ mm} \quad f(t) = 2.226e^{(-57.75t)} \quad (7-24)$$

$$3 \text{ mm} \quad f(t) = 10.17e^{(-0.03212t)} \quad (7-25)$$

7.5.2 Discussion for the TPU Origami Capsule “Roller” Module Embedded Structure

This part of the study deals with the structural analysis of rolled TPU in simple and DCB beam structure. From the results, it is notable that rolled member shows resistance on stresses by releasing energy. These internal stresses are induced into the structure due to increased load applied to test the beam’s response. Besides, the response of these internal stresses also changes with the secondary parameters, such as geometrical design, dimensions, and materials used. In the research work, it is evident that the graphical representation of strain energy vs time for both TPU roll and embedded DCB with TPU produces an exponential decay curve. The generalized equation of the curve is indicated in Equation (7-2), which shows the inclusion of time and coefficients as a and b .

Table 7-7, Table 7-8 and Table 7-9 for both embedded and non-embedded beams, the value of a increases and the value of b decreases with increasing thickness for both the TPU roll and the embedded DCB with TPU roll.

Given the difference in trends of the TPU rolled and the embedded DCB with TPU roll structure, it is evident from Figure 7-8 that the magnitude of strain energy in the TPU roll increases with the thickness of the beam, since 3 mm showed the greatest and 2 mm showed the least responsiveness over time. Upon comparing this with the trend in Figure 7-9, it can be seen that the 3 mm thickness has the

greatest and 2 *mm* has the least response to strain energy. It is notable that 2 *mm* thickness produces a similar response to the TPU roll in terms of TPU roll and embedded DCB, showing the lowest strain energy. Overall, the embedded DCB with TPU roll showed the highest strain energy as compared to the simple TPU roll over. However, the time taken for decay is consistent (i.e., 100 *s*) for all three thicknesses in the TPU roll, whereas in the embedded structure, each thickness of the beam decayed at a specific interval. For instance, 1 *mm* decayed at 110 *s*, 2 *mm* decayed at 100 *s*, and 3 *mm* decayed at 120 *s*. The governing equation and its correlative parameters, as indicated in Table 7-9, show higher R-squared value (i.e., above 90%), which shows that the model equations are extremely accurate. Notably, this shows that strain energy was more slowly dissipated in the TPU rolled beam than in the embedded DCB with a TPU rolled structure. Therefore, to include the healing mechanism in structures where high strain energy is required, embedded DCB with TPU seems to be a reasonable option unlike the simple TPU roll.

To further study the healing rate in the DCB roll, the research assessed the strain energy release due to crack propagation over time for different thicknesses (Figure 7-10). The results indicate that as the beam thickness increased, the strain energy release due to crack increases and the time needed to observe that propagation decreases. The study further analyses strain energy versus force for different thicknesses of DCB roll (Figure 7-11). It is clear that a thicker beam structure tends to yield higher strain energy than do low thickness values for the beam. Since the strain energy release is dependent on how much cracking has propagated, so the higher strain release from the DCB TPU roll contributes to the rate at which crack propagation extends.

7.6 Conclusion

The research has sought to determine the behaviour of self-healing beams under the elastic and plastic loads for TPU cross and TPU roller materials. The study calculated the strain via strain energy and strain release for beams with and without origami capsules. Origami capsules were made in the shape of a cross

with the four small beams comprising the arms, folded or elastically deformed and embedded in the main beam structure. For crack propagation in the main beam, once the strain is released due to the crack the small beams comprising the origami capsules open in the direction of the crack path and increase the crack resistance of the structure. When ABS transparent was used as the beam and TPU as the embedded capsule it was found that the capsule worked as a self-healing mechanism, healing the crack before it occurred at a force of 24 *N*. From the results it is evident that the properties of the TPU allowed deformation to remain flexible, which is why it was considered a suitable material for a novel self-healing mechanism that can be triggered by crack propagation due to strain release in a structure. Structural analysis has shown that greater the beam thickness, the greater force required to attain the plastic region. The delamination tests showed the presence of a capsule suppressed the high compressive stresses induced by the bending moment in the vicinity of the crack-tip and prevented the specimen from breaking and allowing crack propagation. The results show the potential of origami capsules as a novel self-healing mechanism to extend existing practice which is primarily based on external healing agents.

8 ANALYSIS DEVELOPED OF SELF-HEALING CAPABILITY IN EMBEDDED STRUCTURE

8.1 Introduction

This chapter investigated the effect of self-healing capability in embedded structures for different types of materials to confirm its workability, which achieved the fourth objective indicated in section 1.3. The efficacy of the mechanism on real application scenarios was tested with the TPE "cross" capsules in the specimen. However, to retain the continuity of the validation, it was decided to provide the details of with and without the origami capsule inside the embedded structure.

8.2 Bending Moment of TPE “Cross” Origami Capsule Tests Results

The TPE material beam displacement response was tested for different thicknesses at variable loads applied at the free end of the capsule, as indicated in Figure 8-1. Theoretically, the deflection of the TPE “cross” origami capsule is directly proportional to the applied force and inversely proportional to the capsule thickness, which is evident in Figure 8-1. The highest deflection is observed for the capsule at more increased thickness, whereas the shaft for lower thickness tends to show an elastic region almost the half magnitude of the force. It is also evident that the maximum pressure at a 1 mm beam is 0.15 N and the deflection is 21 mm; at 2 mm beam thickness, it is almost 0.23 N and 24 mm; and at 3 mm thickness, the deflection is 25 mm at 0.35 N force. The elastic region plastic region of the beam consolidates at higher beam thicknesses. Based on Equation (5-5).

The graphically plotted values of force and deflection can be utilized to calculate the strain energy of the beam. It is ascertained that the total amount of the stress applied on the beam is wholly converted into strain energy as shown in Equation (5-6):

Maximum strain energy beam at 1 mm capsule thickness

$$= \frac{4.709^2}{2 \cdot (14)} * 5 * 25 = 98.986 \text{ Nmm}$$

Maximum strain energy beam at 2 mm capsule thickness

$$= \frac{1.912^2}{2 \cdot (14)} * 10 * 25 = 32.674 \text{ Nmm}$$

Maximum strain energy beam at 3 mm capsule thickness

$$= \frac{1.177^2}{2 \cdot (14)} * 15 * 25 = 18.560 \text{ Nmm}$$

The calculated values show that the strain energy for 1 mm capsule thickness is the highest, almost 98.986 Nmm; for 2 mm capsule thickness, it is 32.674 Nmm, and it is the least for 3 mm capsule thickness, which is 18.560 Nmm. This shows that higher values of capsule thickness produce the minimum amount of strain energy, and lower values of beam thickness produce the maximum amount of strain energy.

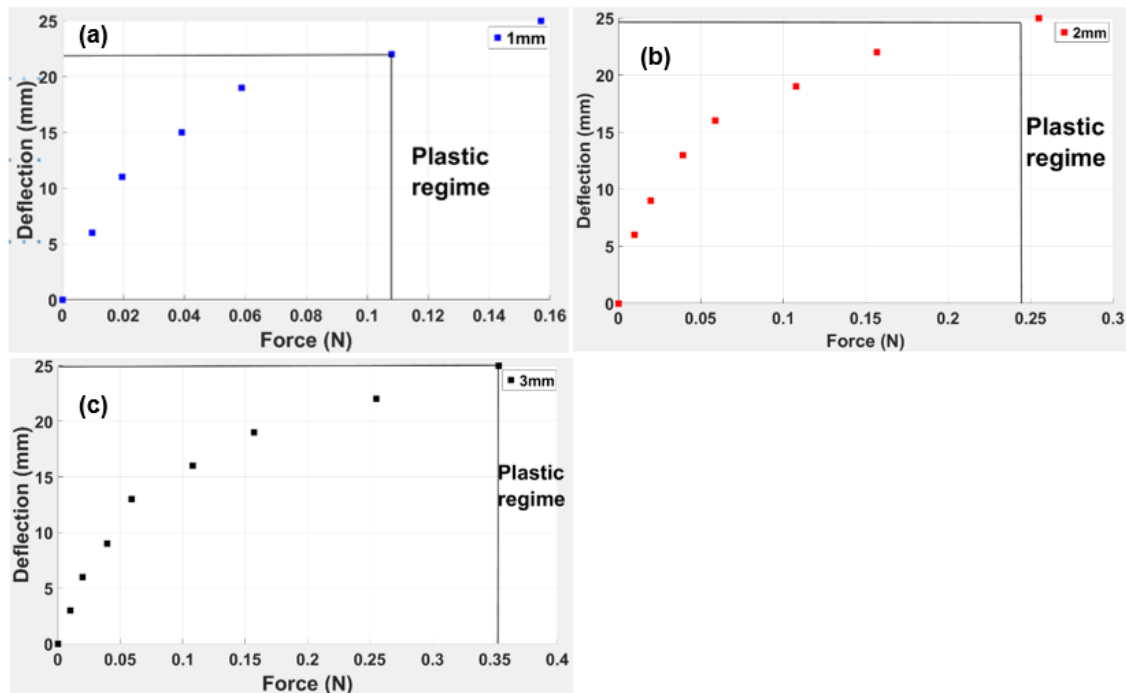


Figure 8-1 Deflection of end loaded simple TPE capsule at various thickness (a) 1 mm, (b) 2 mm, and (c) 3 mm

The vertical lines in the force and deflection graph show the initiation of the plastic regime and the end of the elastic region. At higher thickness, the beam could sustain a high-force magnitude and show maximum deflection before entering the plastic region. However, for the minimum thickness of the 1 *mm* beam, the elastic region only sustained a 0.11 *N* load. This is because TPE “cross” is already a flexible rubber-like material; at a minimum beam thickness, the overall load-bearing capacity of the beam reduces. Hence the beam can withstand minimum deflection before entering the plastic region.

With the obtained data for the maximum deflection applied at different loads, there is a further need to assess different parameters affecting the beam. A 3D graph was plotted to correlate the behaviour of the beam due to the action of deflection, force, and position, as indicated in Figure 8-2.

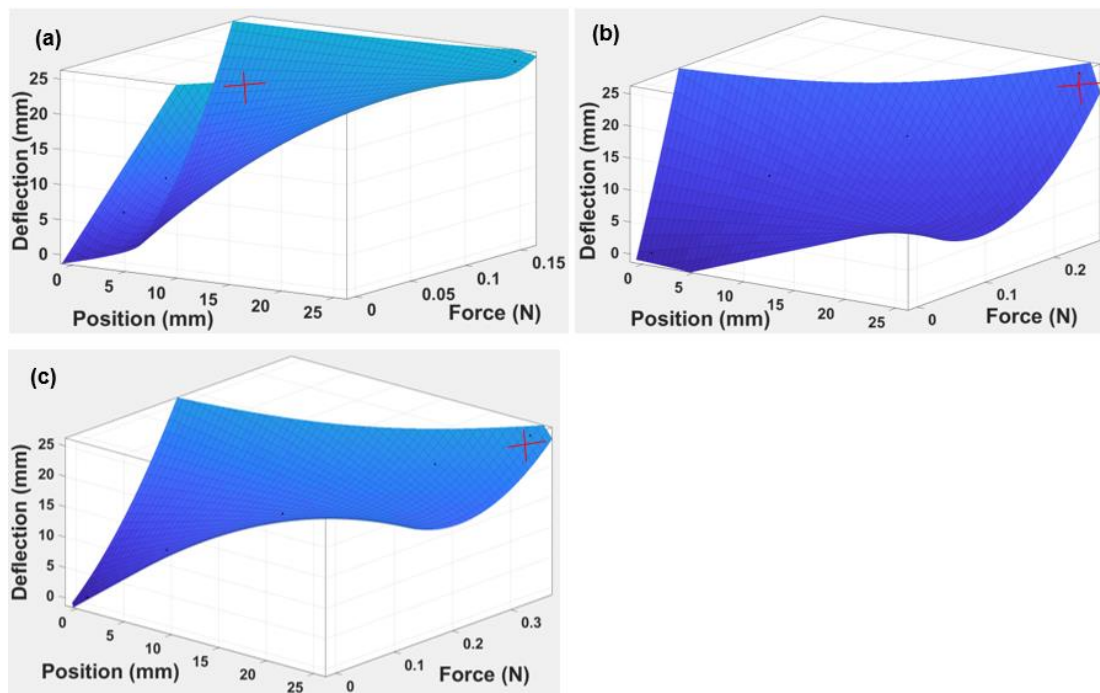


Figure 8-2 3D-gradient graph of TPE “cross” capsule showing the relationship between applied force (*N*), Position (*mm*), and Deflection (*mm*) for three capsule thicknesses: (a) 1 *mm*, (b) 2 *mm*, (c) 3 *mm*

The estimation is performed using 3D-surface graph, as indicated in Figure 8-2. The three variable graph shows parametric relationship between force, position,

and deflection of the beam. The changes for the maximum deflection of the beam were calculated for different values of loads. It is confirmed from the gradient that as the thickness of the beam increases from 1 to 3 mm, the beam tends to deflect at its maximum position.

For the 3D-graph surfaces, the approximate polynomial Equation is given as:

$$\begin{aligned} \text{Deflection of the beam } (f = \text{Force}, y = \text{position at any point}) \\ = T_{00} + T_{10}f + T_{01}y + T_{20}f^2 + T_{11}fy \end{aligned} \quad (8-1)$$

where, $T_{00}, T_{01}, T_{10}, T_{20}$ and T_{11} are the coefficients of the polynomial.

Table 8-1 Different values of coefficients at simple TPE “cross” origami capsules of different thicknesses.

Thickness (mm)	T_{00}	T_{10}	T_{01}	T_{20}	T_{11}	R-square
1 mm	0.2492	-137	2.373	2086	-16.41	0.9991
2 mm	0.7806	389.9	0.3744	513.1	-18.49	0.994
3 mm	0.6838	86.07	1.134	329.1	-8.55	0.9965

By substituting the coefficients in Equation (8-1), the polynomial equation for each capsule thickness can easily be found.

$$1.0 \text{ mm} \quad f(f, y) = 0.2492 - 137f + 2.373y + 2086f^2 - 16.41fy \quad (8-2)$$

$$2.0 \text{ mm} \quad f(f, y) = 0.7806 + 389.9f + 0.3744y + 513.1f^2 - 18.49fy \quad (8-3)$$

$$3.0 \text{ mm} \quad f(f, y) = 0.6838 + 86.07f + 1.134y + 329.1f^2 - 8.55fy \quad (8-4)$$

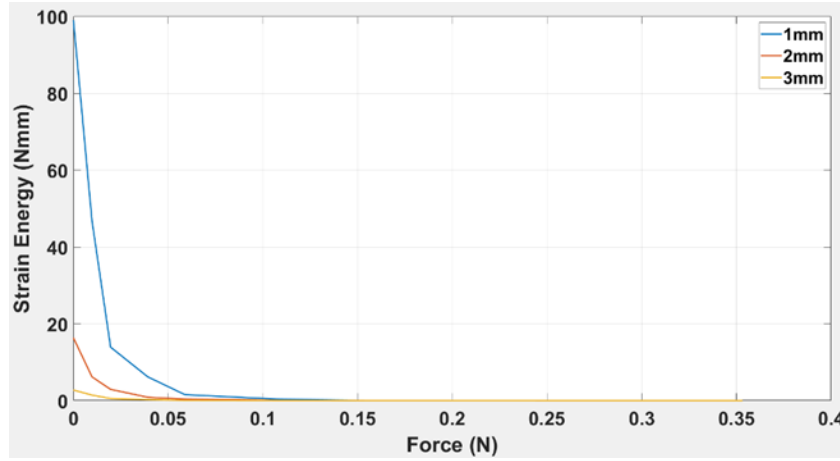


Figure 8-3 Strain energy vs applied force for simple TPE “cross” origami capsule of variable thicknesses 1 mm, 2 mm, and 3 mm

The curves, as indicated in Figure 8-3, are plotted for strain energy (Nmm) as a function of force (N) applied on a single TPE “cross” origami capsule for a) 1 mm, b) 2 mm, and c) 3 mm thickness. The legend marks in the top right corner indicate that the maximum strain value for 1 mm capsule thickness was 98.98 Nmm ; for 2 mm thickness, it is 16.33 Nmm ; for 3 mm thickness, it is 2.749 Nmm , respectively. This shows that the higher the capsule thickness value, the higher strain energy and decay will be over time. Notably, at higher value of beam thickness takes longer time for strain energy to decay with the action of force, as 1 mm beam thickness as the highest value of strain energy, and it shows reaction till 0.07 N force. Meanwhile, 2 mm and 3 mm capsules already decayed at 0.04 N force. The governing equation for the trendlines for various thicknesses is given below:

$$f(t) = ae^{bt} \quad (8-5)$$

$$1.0 \text{ mm} \quad f(t) = 196.5e^{-70.73t} \quad (8-6)$$

$$2.0 \text{ mm} \quad f(t) = 35.68e^{-81.59t} \quad (8-7)$$

$$3.0 \text{ mm} \quad f(t) = 4.77e^{-57.75t} \quad (8-8)$$

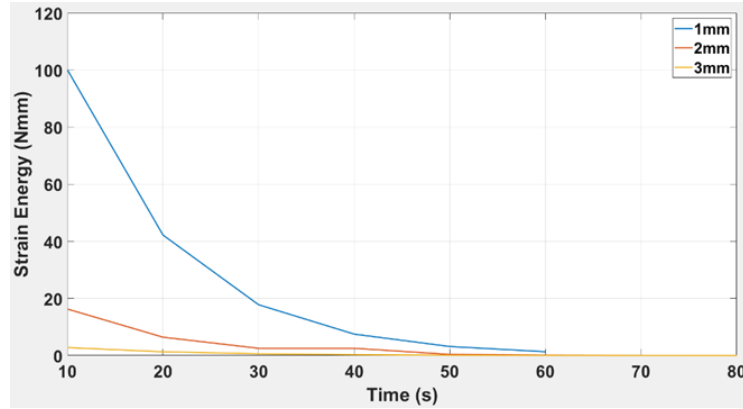


Figure 8-4 Strain energy vs Time for simple TPE capsule of variable thicknesses 1 mm, 2 mm, and 3 mm

Figure 8-4 indicates the strain energy over the period for various capsule thicknesses (i.e., 1 mm, 2 mm, and 3 mm). From the graph, it is evident that the strain energy for the 1 mm thickness is much higher than the strain energy for the 3 mm capsule thickness. However, the decay rate of strain energy is significantly less for 1 mm as compared to 3 mm TPE capsule thickness. The governing equation for the trendlines for various thicknesses is given below:

$$f(t) = ae^{bt} \quad (8-9)$$

$$1.0 \text{ mm} \quad f(t) = 237.4e^{-0.08637t} \quad (8-10)$$

$$2.0 \text{ mm} \quad f(t) = 41.33e^{-0.09308t} \quad (8-11)$$

$$3.0 \text{ mm} \quad f(t) = 5.926e^{-0.07551t} \quad (8-12)$$

From the above-indicated Table 8-1, it is mentioned that as the value of thickness increases, the absolute value of coefficient increases. This is why the 1mm beam thickness has the most negligible value of coefficients and the highest value of R-squared (0.9991) and vice versa. To simplify the variables, a curve has been plotted between coefficients and beam thickness (see Figure 8-5).

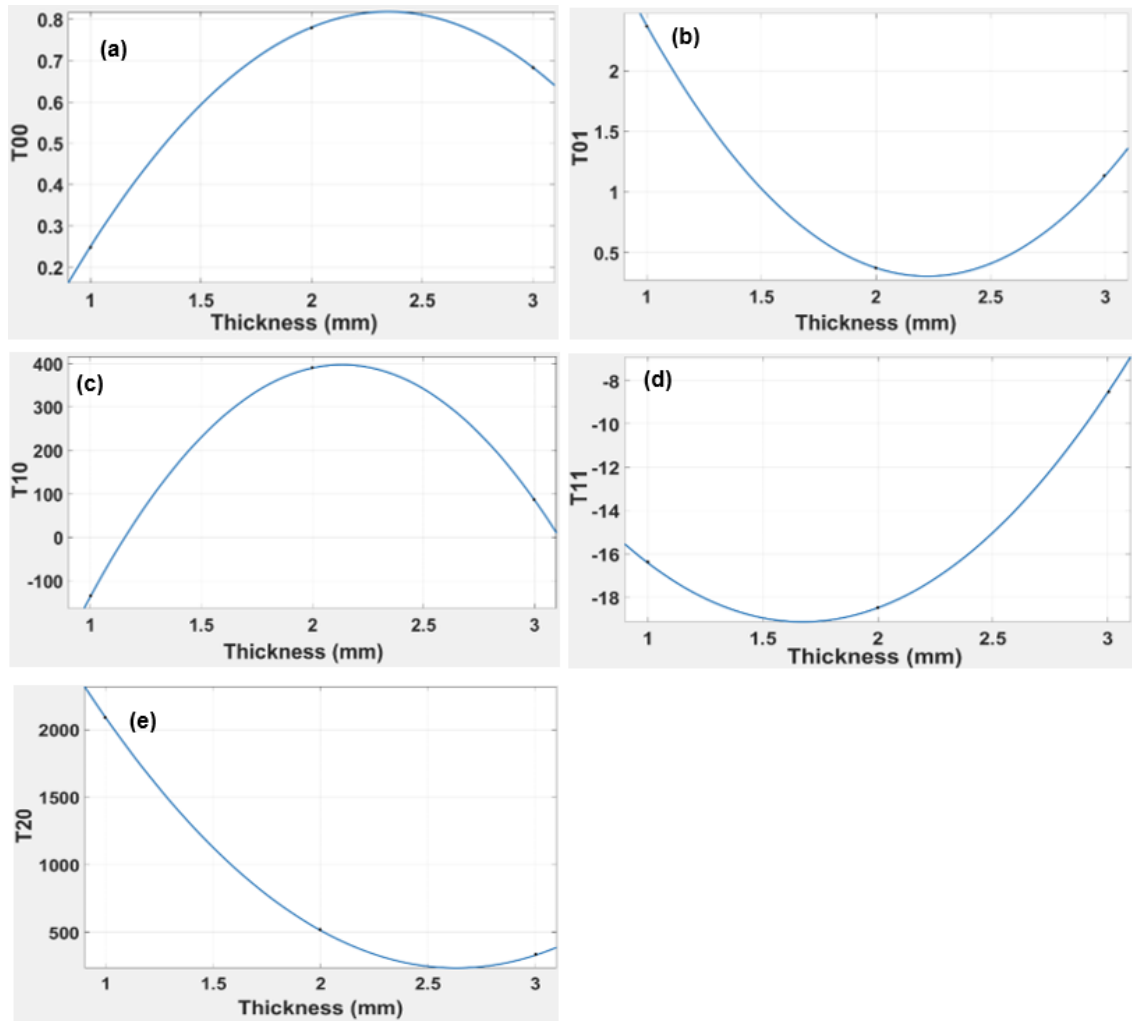


Figure 8-5 Graphical plots showing the correlation of TPE capsule thickness versus the correlation coefficient for a) T00, b) T01, c) T10, d) T11, and e) T20.

Each graph in Figure 8-5 was fitted with second-degree polynomial, so the generalized equation becomes:

$$f(x = \text{thickness}) = e_1x^2 + e_2x + e_3 \quad (8-13)$$

Table 8-2 Values of linear equation coefficients for all thicknesses TPE "cross" origami capsule

Coefficient	e_1	e_2	e_3	R-squared
T ₀₀	-0.3141	1.474	-0.9104	1.00

T_{01}	1.379	-6.136	7.13	1.00
T_{10}	-415.4	1773	-1495	1.00
T_{11}	6.01	-20.11	-2.31	1.00
T_{20}	694.5	-3656	5048	1.00

By substituting the values of the coefficient in Equation (8-13), the generalized equations become:

$$T_{00} \quad f(x) = -0.3141x^2 + 1.474x - 0.9104 \quad (8-14)$$

$$T_{01} \quad f(x) = 1.379x^2 - 6.136x + 7.13 \quad (8-15)$$

$$T_{10} \quad f(x) = -415.4x^2 + 1773x - 1495 \quad (8-16)$$

$$T_{11} \quad f(x) = 6.01x^2 - 20.11x - 2.31 \quad (8-17)$$

$$T_{20} \quad f(x) = 694.5x^2 - 3656x + 5048 \quad (8-18)$$

The R-squared value of four different coefficients, as indicated in Table 8-2, was 1.0.

8.2.1 Discussion of the TPE “Cross” Origami Capsule’s Behaviour

The research is based on analysing the self-healing properties of the TPE material. The objective is to present an origami-based star design made of TPE material, which is further embedded into the beam to assess self-healing behaviour. From the material point of view, it is shown that the strain rate will increase the modulus of TPE as the material is highly compressible. It is also evident from Figure 8-1 that the plastic region for the 1 *mm* beam thickness occurs at the median position. The plastic region starts at the end for the 2 *mm* and 3 *mm* thicknesses. Although studies on the moment of inertia and the elastic modulus are not tested, from the strain energy, it can be asserted that both parameters depend on dimensions and individual material properties.

TPE is characterised using the study's extended research work and scope. The analytical process was similar to that of ABS and TPU, which involves the capsule deflection at different thicknesses, which is 1-3 *mm* in our case. From the analysis of 3D curves, as indicated in Figure 8-2, it is evident that the plastic regime achieves the maximum value of the applied load at 2 *mm* and 3 *mm*. The R-squared value for each thickness was 0.9973 for 1 *mm* TPE, 0.9859 for 2 *mm* TPE, and 0.9931 for 3 *mm* TPE. After plotting the strain energy vs force in Figure 8-3 for all three capsules, it is proved that the strain energy is maximum at a higher capsule thickness value and decays gradually compared to the capsule with less thicknesses. The R-squared values are 0.9973, 0.9822, and 0.9956 for 1 *mm*, 2 *mm*, and 3 *mm* thickness, which further explains the model's validity. The graphical representation of strain energy over the period shows that the decay rate of strain energy is significantly less at higher beam thickness than the smaller beam thickness (Figure 8-4). Here, the model has R-squared values of 0.9944, 0.9989, and 0.9958 for 1 *mm*, 2 *mm*, and 3 *mm* thicknesses.

To simplify the correlation results, the variable coefficients obtained from the model equations T_{00} , T_{01} , T_{10} , T_{11} , and T_{20} were graphed against the thickness values, as indicated in Table 8-2. The R-squared values for these graphs were 1.0, indicating an accurate fit of the data points in the model equations (Equation (8-14)-(8-18)). Furthermore, from the experimental results, it is observed that the modulus value of TPE “cross origami capsule increases with the strain rate. The experimental results correlate with the material properties that define TPE as a flexible material with more flexible filaments than ABS and TPU. The TPE is less hard than ABS and TPU, due to which the beam surface was more like a rubbery texture [167]. This is why the maximum strain energy of TPE is only 100 *Nmm*, whereas, for TPU and ABS, it was 180 *Nmm* and 8000 *Nmm*, respectively. Therefore, TPE polymer can be utilized in origami capsules for self-healing a low rigidity structure.

8.3 Embedded Structure of TPE Origami Capsule Inside DCB

By analysing the responses from the DCB model, the behaviour of the star origami in self-healing beams can be studied. During this process, analytical process helps in estimating the amount of stress released when the beam is deflected with the action of force. From the results, it can be ascertained that the force applied on the beam is dependent on the strain release. The response of the applied force vs displacement for the TPE embedded DCB is shown in Figure 8-7. For the DCB structure, one end of the beam was trimmed down, as indicated in Figure 8-6. The HD camera was applied by recording the video of the experimental process. The entire setup comprises of taking a picture after every 10 s, which is used to evaluate the position of the crack from the tip to the point where the star origami is placed.

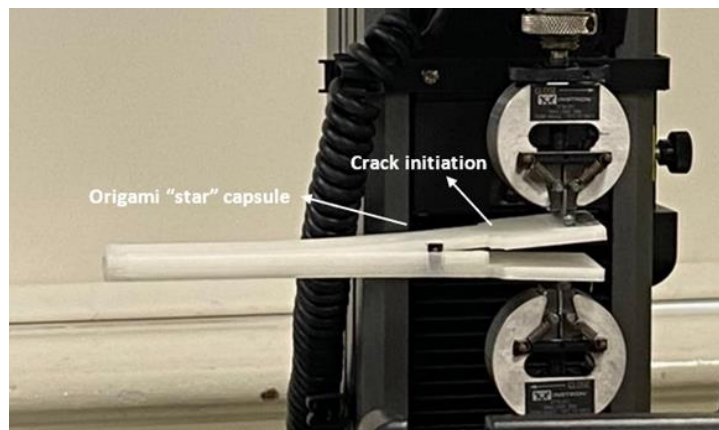


Figure 8-6 Measuring DCB crack length and displacement during the test

The load-displacement graphs obtained from the beam embedded with the star origami structure are shown in Figure 8-7. The observation shows that there are some non-linearities in the load-displacement for the specimen. As indicated in Figure 8-7 (a), (b), (c), and (d), the graphical relationships are non-linear. In Figure 8-7 (a), the maximum amount of force is 25 N for the specimen with origami. In Figure 8-7 (b), the maximum resisted force for specimen without origami is 17 N with a displacement of 22 mm. Noticeably, there is a substantial drop in force magnitude in both cases – with and without origami capsules. For the specimen with star origami, the force was dropped from 25 to 9 N. In contrast,

the drop without origami shows 16 to 6 N. Theoretically, the sudden failure is the highest to the lowest magnitude of the force that causes jerk in the beam, which can lead to significant damage and even collapse of the DCB. Since the DCB with Origami has a gradual decline in the force compared to without origami; therefore, it is evident that the inclusion of star shaped Origami into DCB can help reduce the sudden jerk due to force, which can reduce the chances of structural damage.

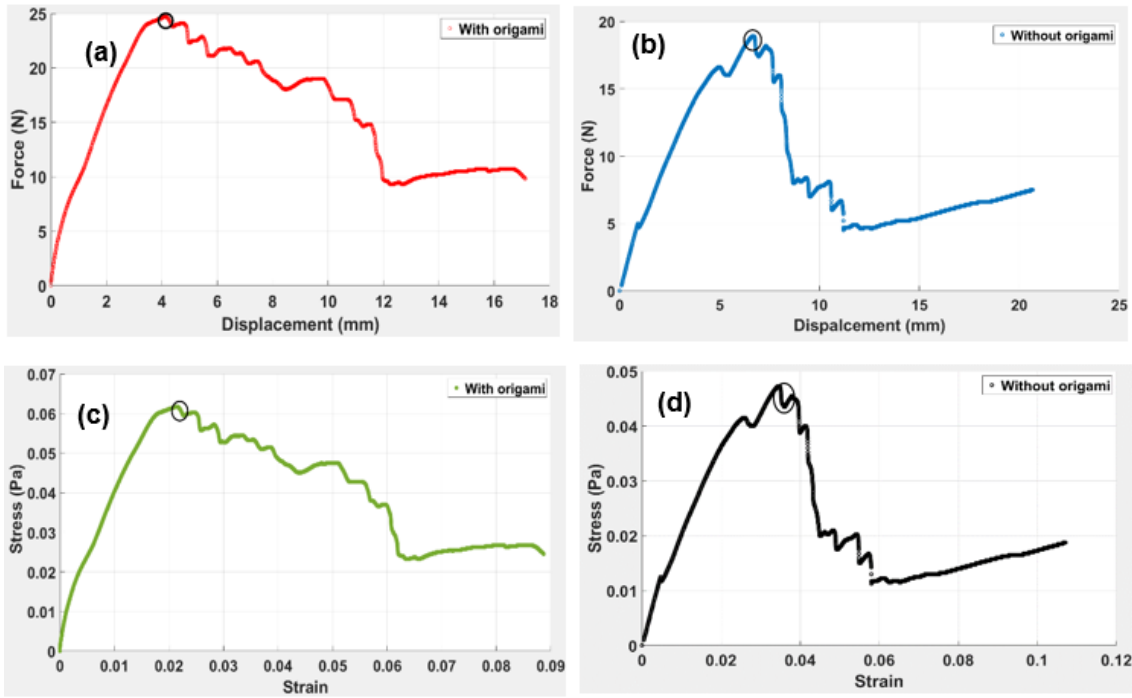


Figure 8-7 Crack length in DCB under the quasi-static conditions

Utilizing the parameters, such as time taken by the beam and strain released, research can calculate the percentage error deviation between DCB with Origami and without origami using the formula:

$$\text{Strain release due to crack } (U) = \frac{\sigma^2}{2E} B \pi a^2 \quad (8-19)$$

where σ represents the stress applied (N/m^2), E is the elastic modulus of the materials (N/m^2), B is the area length (mm), π is the area from middle DCB until the open area, and a indicates the length of the beam (mm).

**Table 8-3 Experimental and theoretical value of strain energy release of the beam
a) with origami, b) without origami**

	With origami (5 mm)	Without origami (5 mm)
The experimental value of strain release	$\epsilon = 3.831$	$\epsilon = 2.555$
Theoretical model value of strain release	$\epsilon = 3.238$	$\epsilon = 2.072$
Percent Deviation in strain release	$\Delta\epsilon = 0.183$ (18.31%)	$\Delta\epsilon = 0.233$ (23.3%)

Table 8-3 indicates the theoretical and experimental values for the strain release during the testing of the beam, both with star and without star origami. The results show that the difference for origami is 0.183 and 0.233, which makes 18.31% and 23.3%, respectively. From these values, it is clear that the strain release without origami is greater than with origami. Therefore, the response of TPE in Origami can help dampen the appreciable amount of strain release, preventing the beam from collapsing or being damaged.

Figure 8-8 indicates the maximum amount of strain energy release for DCB of different thicknesses over a period of time, as shown in Equation (8-24 to (8-27). The maximum strain energy release was 18.2 *Nmm*, 28.7 *Nmm*, and 40 *Nmm* for 1 mm, 2 mm, and 3 mm thickness, respectively. Similarly, the time at which the maximum strain release occurred was 30 s, 40 s, and 45 s respectively.

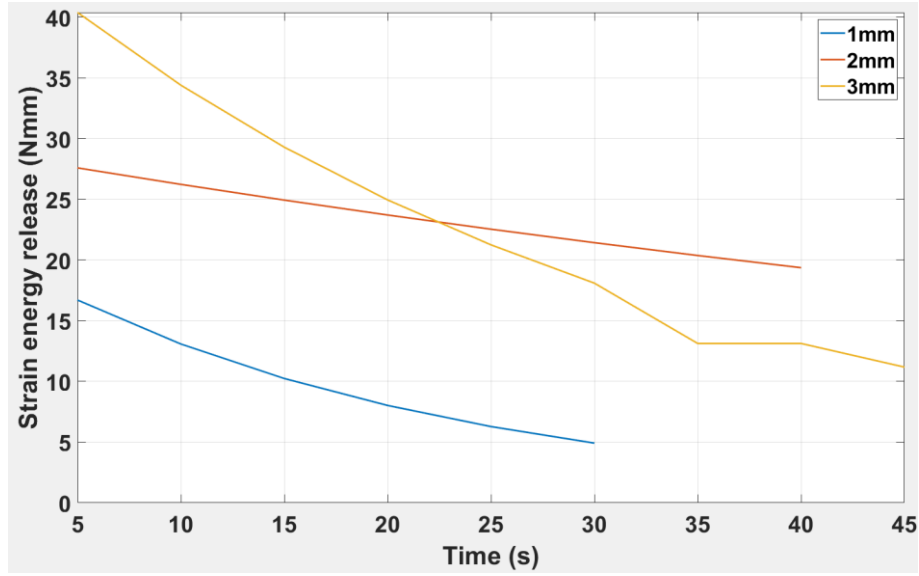


Figure 8-8 Strain energy release versus time for DCB, 1 mm, 2 mm, and (c) 3 mm

The governing equation for the trendlines for various thicknesses is given below: it is clearly indicated that as the beam thickness increases, the maximum strain release time is reduced. The capability to retain maximum strain value also increases.

$$f(x) = v_1x^4 + v_2x^3 + v_3 + v_4x + v_5 \quad (8-20)$$

$$1.0 \text{ mm } f(x) = -3.59 * 10^{-8}x^4 + 3.78 * 10^{-6}x^3 - 0.00013x^2 + 0.0018x - 0.0032 \quad (8-21)$$

$$2.0 \text{ mm } f(x) = -6.259 * 10^{-5}x^4 + 0.0065x^3 - 0.248x^2 + 4.306x - 7.94 \quad (8-22)$$

$$3.0 \text{ mm } f(x) = -0.00054x^3 + 0.0023x^2 + 1.431x - 1.658 \quad (8-23)$$

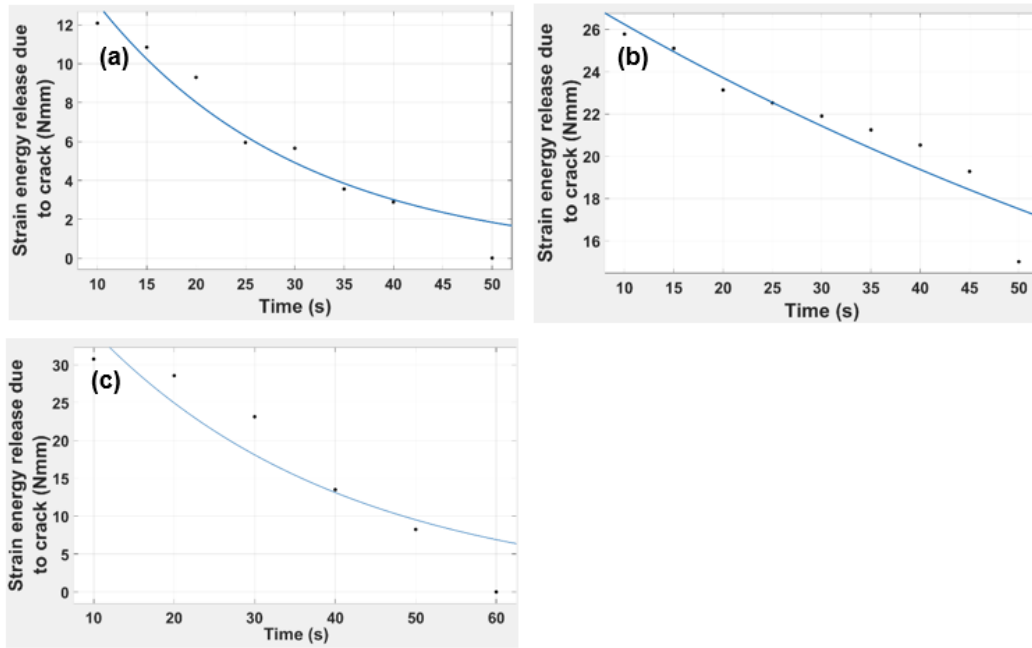


Figure 8-9 Graphical representation of DCB strain energy release due to crack vs time for DCB a) 1 mm, b) 2 mm, and c) 3 mm

Figure 8-9 indicates the strain energy release due to the crack propagation versus time for 1 mm, 2 mm, and 3 mm beam thickness. It is clear from the graphical trends that the value of strain release due to crack increases as the thickness increases, even the time to reach the zero value of strain release was also extended for the higher thickness. The governing equation for the trendlines for various thicknesses is given below:

$$f(t) = ae^{bt} \quad (8-24)$$

$$1.0 \text{ mm} \quad f(t) = 21.33e^{-0.04892t} \quad (8-25)$$

$$2.0 \text{ mm} \quad f(t) = 29.02e^{-0.01011t} \quad (8-26)$$

$$3.0 \text{ mm} \quad f(t) = 47.43e^{-0.03212t} \quad (8-27)$$

8.3.1 Discussion of TPE Origami Capsule Inside Embedded Structure

The research analyses the behaviour of the star-shaped origami embedded in the DCB structure using TPE material. The method of testing DCB is based on an Instron testing machine with displacement rates from 0.05 to 0.10 *mm/s*. The configuration from the energy release rates was also calculated using 15 printing parameters for different specimens. The results indicate that TPE star-origami is more reliable and robust in withstanding greater fluctuations than the beam without star origami. Besides, a mathematical analysis using force vs displacement and stress-strain curves can help assess whether the hypothesis and research arrangement were true.

From the experimental results, it is found that two sets of graphs were obtained for the two arrangements with origami and without origami Figure 8-7 (a) (b) (c) (d). As indicated (see Figure 8-7 (a)) with the origami capsule, the graph proceeded with almost a straight line from 0 *N* to the maximum force of 25 *N*, attaining a total displacement of 4.8 *mm*. This denotes that the beam's elastic limit and the resistance are indicated at the maximum load. At this point, the DCB continues to bend, and the displacement increases from the origin, reaching the maximum displacement of 17.5 *mm*; this is the plastic region of the beam. For the specimen without origami, as indicated in Figure 8-7 (b), it is clear that the maximum force is resisted at 16 *N* at a total displacement of 6.5 *mm*. It is noticeable that there is a substantial drop in the force from 16 *N* to 6 *N*, and after this failure, the beam collapsed. Therefore, it is evident that DCB with Origami withstands the greater amount of force upon maximum force, gradually releasing strain without damaging the beam. Experimental results theoretically support the previous [167] results, where the research work critically analyses the load vs displacement test on the specimen. There was a clear difference in the lamination length for the two specimens with the sudden drop in load without origami.

These results indicate that the beam with the origami capsule has better resistance from the failure of the beam without the capsule. As per observation,

the dimension of the beam critically plays an important role in defining the material's strength. As per the study [27] different material observes different resistance toward multi-directional layups from crack propagation. The delamination resistance observed from the DCB test depends on the fibre orientation of the TPE. It is also indicated in Figure 8-7 (c) and (d) that the capsule presented the maximum stress with origami at 0.06 Pa and without origami was 0.048 Pa . In Figure 8-8, it is evident that as the beam thickness increases, the time at which the maximum strain release occurred was reduced, also the capability to retain maximum strain value also increases. The R-squared values are 0.927, 0.946, and 0.9041 for 1 mm, 2 mm, and 3 mm thickness, which further explains the model's validity. Notably, upon further study of the effect of beam thickness, it is shown in Figure 8-9 that as the thickness of the beam and strain energy release due to crack are directly proportional to each other,

The stress-strain relation of TPE in high-density stitched beams is discussed in the study [168], Upon comparing the results from the research paper and our experimental results, it is evident that the load increases linearly with the displacement. Still, as the maximum force was reached, the stitches were broken, and the crack was initiated, causing a sudden load drop. The obtained results are similar to the research study by [169], which tested the crack propagation in the DCB made from polymeric composite materials [169]. The load fluctuations are also steady, indicating a high tensile strength to bear the increased load during the crack propagation.

In conclusion, the proposed TPE “star” origami capsule tends to absorb more fluctuation of load and displacement; however, upon comparing with TPU and ABS, the results of TPE are ideal for less rigid material. The results for TPU and ABS are more ideal for high-stress application, but TPE is ideal for structures where even a small stress can lead to structural damage. Therefore, the hypothesis is that specimens made of TPE origami can propagate the self-healing properties when the load is axially supported. On the other hand, DCB structures tested without origami pose less resilience and have low material tensile strength.

8.4 Discussion on Error in Predictions of ABS, TPU and TPE

Once the beam modelling is completed, the validation is performed by adjusting the 3d surface graphs in model approximation and prediction. This enables us to choose the optimum model equation for different materials. As mentioned earlier, the initial process is to assess the model values with the points of the experimental design. The criteria used to test the model fit between different observations and predictions on the deflection, force, and displacement are used. Notably, during the MATLAB plot, the role of determination involved both R^2 and adjusted R^2 , followed by Root Mean Square Error (RMSE).

For the research study, it is questionable what the probable difference between the points obtained from the predicted model versus the experimental design is. Since the number of simulations is not restricted, evaluation of Absolute Error and Root Mean Square Error (RMSE) can be considered for validation. The MSE values obtained for ABS, TPU and TPE are indicated in Figure 8-10, Figure 8-11 and Figure 8-12, respectively.

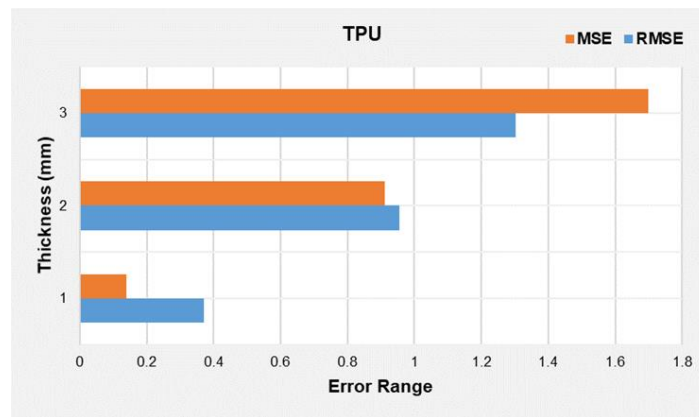


Figure 8-10 Thickness versus error ranges for MSE and RMSE for TPU capsule.

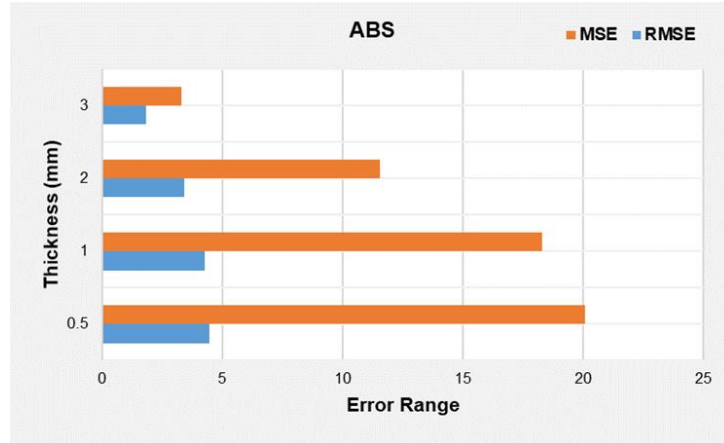


Figure 8-11 Thickness versus error ranges for MSE and RMSE for ABS beam.

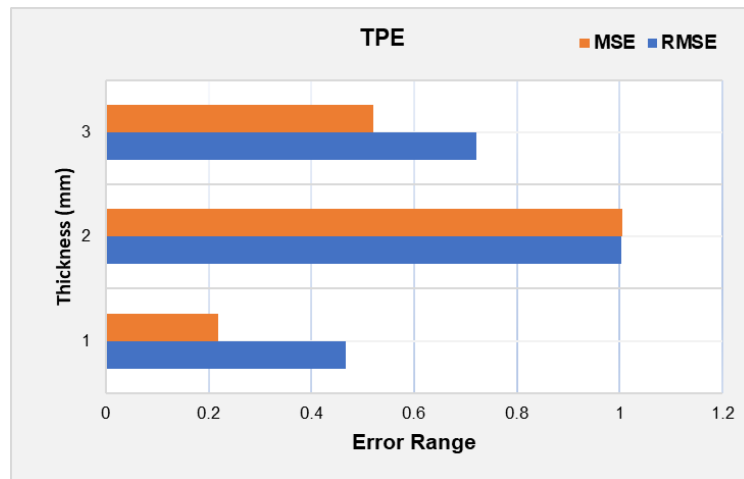


Figure 8-12 Thickness versus error ranges for MSE and RMSE for TPE capsule

The above-indicated Figure 8-10, Figure 8-11 and Figure 8-12 show the thickness versus error ranges for MSE and RMSE for TPU, ABS and TPE, respectively. The highest error range is obtained for ABS, and the lowest is noted for TPE. This is due to the presence of the lowest degree polynomials in ABS model equations and higher in TPE. The MATLAB simulation converts the polynomial equation into an algebraic equation and then carries out the calculations. Therefore, neglecting a higher degree in a calculation in any algebraic equation reduces the model's accuracy. The only method to reduce error difference is to conduct an experimental research study with precision, as it will reduce analytical and experimental differences.

Theoretically, the proposed numerical model converts the continuous function into a piece-wise function by dividing the domain of the graph into discrete elements. Within this phenomenon, when research try to approximate the continuous function to discrete function, this leads to the generation of error, which generally accounts for a numerical error, in the case of surface graphs, which involve the modelling of the continuous system through discrete elements. With this inherited error, MATLAB does simulate the solution known as a numerically converged solution. However, there also exists a solution that is numerically uncovered since MATLAB has ignored the inherited error, so the difference between numerically converged and unconverged produces a differential error [170]. Specific to the model equations research proposed, it is presumed the error leading to MSE is the differential error.

9 CONCLUSIONS

This research investigated a self-healing mechanism based on origami capsules in 3D printed composite structures under different loads. Also, investigated were elastic and inelastic regimes and strain release behaviour of beams made of ABS, with TPU and TPE origami capsules inserted along their lengths. The results are analysed with corresponding experimental validation using crack opening based tensile loads.

The aim and objectives of Section 1.3 were accomplished, and novel contributions to knowledge are summarized below.

9.1 Achievement of Aim and Objectives

Aim – “The aim of this thesis is to develop a self-healing mechanism based on origami capsules in 3D printed composite structures.”

Objective 1- Design and develop strain driven origami-inspired capsules. (Achieved in Chapters 4, 5 and 6).

Origami capsules of different shapes were designed using Inventor Software to test the workability of different origami-inspired capsules whose geometrical features remained confined under initial pre-stressed conditions. The research also proposed design conceptualization methods depending on a combined analytical and experimental approach. Firstly, a simple beam design was developed for use with the origami capsules. Suitable experimental setups were designed and built, and procedures developed, to test the performance of the capsules.

Objective 2- Investigate the designed capsules' workability under different values of strain release. (Achieved in Chapter 6).

The research programme tested the samples, beginning with the selection of four beam thicknesses and mounting two strain gauges on each specimen. The experiments used an ABS simple beam with TPU origami capsule and were

designed to investigate the effects of applied bending loads. The obtained experimental data were validated by comparison with empirical models.

Objective 3- Characterize the mechanical strength and workability of a product (structure/ component) after healing. (Achieved in Chapters 7 and 8).

The experiments were tests of the mechanical strength of a beam with embedded capsules. The experiments were performed following the experimental scheme described. This scheme provided a comprehensive mapping between measured mechanical and material properties and applied loading values obtained during the experiments. Also, the workability observed in videos and other recordings and the healing obtained, as derived from mechanical strength measurements were, investigated under the delamination test. After comprehensive investigation, it was observed that the delamination tests confirmed that the presence of a capsule suppressed the high compressive stresses induced by the bending moment in the vicinity of the crack-tip, preventing crack propagation and the specimen from breaking. The results show the potential of origami capsules as a novel self-healing mechanism.

It was observed that the two beams attained maximum strain release at 40 and 3.5 *sec*, with the larger value corresponding to the beam with the origami insert, meaning a crack will not propagate so fast because there is self-healing present. Because strain release depends on how far the crack has propagated, the strain released due to the presence of the origami capsule acts to resist the crack's propagation.

Objective 4- Analyse the workability of the developed healing capsules with different material types and shapes. (Achieved in Chapter 8).

To attain this objective required carrying out experiments to validate the performance and response of the developed smart self-healing devices/capsules under different external loads and environmental conditions and applying the designed self-healing mechanism (origami capsule) to different polymers to confirm its workability. The efficacy of the mechanism in real application

scenarios tested the capsules with the specimens made of TPE. The printing times were calculated for the printed products with and without origami capsules. Furthermore, different polymers have different physical characteristics, notably their degree of elasticity, therefore testing different materials was necessary. The beam would also be affected by its loading. As a result, various loading arrangements were investigated.

9.2 Contributions to Knowledge

The most promising contribution to the field of damage mechanics is the development of smart capsule dynamics at the micro-level which can allow the added material to unfold in the same direction when the strain is removed or substantially reduced due to crack initiation or propagation. No external intervention or initiation is required in the proposed self-healing system. In academic terms, this has importance for the currently published methods, and will, therefore, contribute significantly to the advancement of knowledge.

9.2.1 Elastic-Plastic of ABS Simple Beam Behaviour

- The research extends knowledge of the elastic and inelastic behaviour of ABS and TPU materials under different strain release rates. The experiments and possible correlations can take strain release or stress values and provide us with information about how the beams behaved.
- The research studied how origami capsules can usefully be included into the beam. And the research investigated elastic and inelastic regimes, strain release behaviour of beams composed of ABS with TPU crosses along their lengths.

9.2.2 Origami Capsule of Elastic and Plastic Behaviour

- Development of strain release and deformation empirical correlations for 3D printed polymeric beams structures.
- The dynamics of the developed capsule at micro level enabling it to unfold in the direction of crack propagation or crack birth to reduce and/or remove the strain.

- A method has been developed which can optimise the thickness of TPE origami capsule embedded inside a structure.
- The increase in the structural strength due to insertion of origami capsules as protection against crack propagation.
- The self-healing mechanism of TPU and TPE origami capsules has been demonstrated and reported for the first time. These materials achieved a good balance of mechanical strength and self-healing ability. The self-healing mechanism proposed for these materials can contribute to the design of self-healing mechanism in the future.
- This research proposed an analytical approach to determine the bending response of a cracked 3D printed ABS simple beam and TPU origami capsule under different loads.

9.2.3 Embedding the Capsule Inside a Polymeric Structure Composite

- The study also investigated how printing parameters (such as orientation and layer thickness) and different loads affected the bending crack life of the embedded structure beam during delamination tests.
- The study also investigated the workability of origami capsules in embedded structures to resist crack propagation.
- The fundamental assumption of damage mechanics is based on energy release during crack initiation and propagation. The main actuation mechanism of the proposed self-healing capsules is based on strain energy release within the subsurface. The design and development of the capsules involved analytical efforts to quantify the relation in between the strain energy removal required for unfolding the origami inspired capsules. This promising contribution in the field of damage mechanics will help the development of the capsule dynamics at the micro level which can allow it to unfold in the required direction to remove strain due to crack birth or propagation.
- This research will assist the revolutionary development of creating materials with mechanical self-healing ability. 3D printing allows the

deposition of layers for the manufacturing of a component or a part, and origami-inspired capsules can be deposited within the layers to counter any void or damage initiation.

9.3 Proposed Future Works

Due to a lack of time, different tests, experiments, and adaptations have been left for the future. Future work could focus on a more in-depth investigation of certain mechanisms or new proposals to try different methods.

TPU and TPE were confirmed to be capable of self-healing, and this should be developed for practical engineering applications. However, the next step in the research is to develop the relationship between the self-healing mechanism and a numerical model.

Future research should focus on crack growth in beams under different bending loads based on the experimental relationship between pre-stressed conditions at the crack tip and dynamic load. Furthermore, future research should consider studying the influence of different parameters on the crack propagation rate in the structure. This could be investigated numerically. Also, same approach could be used for establishing quantitative relations between the motion of each stretchable fold and the value of relaxation in pre-stressed conditions required for this motion. ABS as a polymer sustained a load to 4.02 N for a 3.0 mm thick beam, indicating that the load sustainability of the designed polymeric beam is suitable for further research work. Additionally, the crack propagation in other polymeric composites under different loads should also be evaluated in the future.

Computer simulations are also an open window of opportunities to design innovative self-healing nano-systems and should provide an effective direction for the efforts of research and scientists for the fabrication of self-repairing systems.

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