



Transitioning to low carbon construction: A review of blast and fragmentation impact research related to terrorist threats

A. Laycock^{a,*}, A. Helliker^b, R. Critchley^a, R. Hazael^a

^a Cranfield Forensic Institute, Cranfield Defence and Security - Cranfield University, Defence Academy of the UK, Shrivenham SN6 8LA, United Kingdom

^b Centre for Defence Engineering, Cranfield Defence and Security - Cranfield University, Defence Academy of the UK, Shrivenham SN6 8LA, United Kingdom

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ABSTRACT

As countries tackle climate change by aiming to reach net-zero carbon, the construction industry faces a substantial challenge to reduce carbon emissions in infrastructure, whilst maintaining safety standards. This review initially explores the sustainability targets and the evolving terrorist threat landscape and trends. A systematic search identifies research publications around blast and ballistic/fragmentation impact testing of materials. It then focusses on low carbon material variants, 'carbon sink' products and materials where design efficiency can reduce carbon content. Whilst this review shows that blast, ballistic and impact performance research of low carbon construction materials is a growing topic, currently the testing of products against relevant threats lags implementation. Design and test standards for these materials are still limited, resulting in difficulties for building owners to assess the risk and implement an adequate safety plan against terrorist threats. The greatest area where research and test standards are lacking is around cladding, especially for modular or off-site buildings which have a wide variety of material options. This review concludes with suggestions for further research to understand the vulnerabilities of these building materials against terrorist threats.

1. Introduction

Terrorist attacks continue to cause death and destruction around the globe with the lethality of attacks increasing by 22 % in 2023 according to the Global Terrorism Index Briefing [1]. Over the last 50 years, bombs or Improvised Explosive Devices (IEDs) have been a popular weapon for terrorists to cause fear, injury, death and destruction to infrastructure [2,3]. As building technology changes [4] and countries set carbon reduction targets [5] there is a risk that the susceptibility of buildings to terrorist attacks is forgotten as priorities change. New threats such as the use of drones is evolving [6] and vulnerabilities of using alternative lower carbon materials is a growing area of research interest [7–11]. This review looks at the existing blast and fragmentation impact performance and test standards for materials with lower embodied carbon emissions [12] than traditional materials. It starts with a focus on Western Europe with particular emphasis on the UK's challenge of balancing the net zero carbon challenge with domestic security.

2. Sustainability and protection requirements

2.1. Net zero carbon

At the UN Climate Change Conference (COP21) in Paris in 2015, 196 parties adopted a legally binding international treaty on climate change called the Paris Agreement [13]. As a result, many countries have established net zero carbon strategies and targets which have an impact on the construction sector. In the UK, the Climate Change Act [14] and 2050 Target Amendment Order [15] sets the legislative basis for action on climate change. More recent publications include the Net Zero Strategy [16] in 2021 and the Net Zero Growth Plan [17] in 2023, which set out policies and commitments to reach net zero by 2050. As the UK has some of the most stringent legislation and ambitious plans, it will be used in this research. In the year 2022, buildings accounted for 17 % of UK emissions [18] and in the UK strategy, the heat and buildings sector is one which is targeted to have a large reduction in emissions [16].

2.1.1. Carbon management

For the construction industry, there is a growing requirement to consider carbon management and conduct whole life carbon

* Corresponding author.

E-mail address: ange.laycock@cranfield.ac.uk (A. Laycock).

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assessments (methodology found in [12]). In 2020, the London Energy Transformation Initiative (LETI) produced the LETI Climate Emergency Design Guide to support the design of new buildings to meet the UK's climate change targets [19]. The guidance clearly defines Whole Life Carbon (WLC) as the sum of 'Operational Carbon' plus 'Embodied Carbon' with the definitions below:

"Operational carbon (kgCO₂e): The carbon dioxide and equivalent global warming potential (GWP) of other gases associated with the in-use operation of the building. This usually includes carbon emissions associated with heating, hot water, cooling, ventilation, and lighting systems..." [19]

Embodied carbon (EC): The carbon emissions associated with the extraction and processing of materials and the energy and water consumption used by the factory in producing products and constructing the building. It also includes the 'in-use' stage (maintenance, replacement, and emissions associated with refrigerant leakage) and 'end of life' stage (demolition, disassembly, and disposal of any parts of product or building) and any transportation relating to the above." [19]

The vision from the World Green Building Council [20] was to reduce embodied carbon in new buildings by 40 % by 2030. An example of the embodied carbon breakdown for a UK school is in Fig. 1 [19] showing how material choice is an important factor in achieving the reduction of upfront carbon.

Over the past 5 years a number of standards have been developed to support carbon reduction including: 'PAS 2080:2023. Carbon management in buildings and infrastructure' [21] which contains good practice standards to be used by asset owners, designers, constructors and material suppliers. Updates to the Building Regulations 2010 [22] introduced new standards for ventilation, energy efficiency performance targets and overheating (Approved Documents F, L and O). The construction industry has also proposed a Part Z for Whole Life Carbon [23] which looks to enforce reporting requirements and add limits to carbon intensity. The most recent publication is the UK Net Zero Carbon Building Standard pilot document which also sets embodied carbon limits [24].

2.1.2. Low carbon construction materials

A comprehensive definition of a 'low carbon' material has not been found in academic literature or policy. 'Carbon sink' building materials are described as being sourced from harvested wood products and biomass materials which have sequestered carbon; and 'low carbon' building materials are ones which have minimised carbon emissions during production and usage [25]. Typically, these products have a lower carbon content than the traditional material due to the use of recycled materials (for example low-carbon bricks, concrete and

recycled steel) [26]. Novel plant-based materials using hemp, straw, grass, etc are also entering the construction market [27] to reduce embodied carbon. A comparison of two types of modular timber frame housing and a traditional masonry house suggested a 34 % reduction in embodied carbon can be achieved using the lighter timber frame and timber clad house scenario. Leaner design can also reduce embodied carbon [28] but this review will specifically focus on material options.

Whole life carbon calculations look at the full range of carbon emissions over the life cycle of a building. Fig. 2 shows the modules used in a WLC assessment [29] and the embodied carbon percentages from the school example in Fig. 1 are overlayed in the centre. It shows that material selection is important as the product stage emissions (A1-3) make up the greatest proportion of embodied carbon.

The in-use stages (B1-5) have the next largest impact on embodied carbon and can also be a significant factor in material choice. Durable materials that are easy to maintain and repair can help reduce carbon [30] compared to a material which requires more frequent painting, treatment or replacement. Operational carbon (B6-7) can also be reduced by using materials with better insulating properties to lower heating and cooling requirements. However, as heating becomes increasingly electrified by the installation of heat pumps and electric boilers, and electricity production continues to be decarbonised, operational carbon is likely to decrease making the embodied carbon modules even more dominant [20,31].

To help compare materials, manufacturers produce Environmental Product Declarations (EPDs) [32] which give values of environmental impacts over the modules. Until a project location and material suppliers are known, only modules A1-3 can be directly compared using generic material databases [33,34] or potential/similar product EPDs [35,36]. Embodied carbon is reported using a declared or functional unit, which is typically a mass (kg) or a volume (m³) for most construction materials [32]. Most designers will use an embodied carbon calculator or life cycle assessment tool to calculate the totals once dimensions, weights and volumes are inputted (examples include: The structural carbon tool [33] or One Click LCA [37]). It is typical for embodied carbon to be reported using units relevant to the project type, with most buildings using kgCO₂e/m² floor area either Gross Floor Area (GFA) or Gross/Net Internal Area (GIA/NIA) and industrial/storage units using kgCO₂e/m³ of internal building volume [38]. For direct comparison of cladding materials, kgCO₂e/m² wall area is a useful measure [39].

2.2. Terrorism (Protection of Premises) Act 2025

Previously in the UK, there has been no legislative requirement for organisations or owners of publicly accessible spaces to employ security measures. Following the Manchester Arena attack in 2017, a victim's mother campaigned for improvements in protective security for the public, leading to the development of: The Terrorism (Protection of

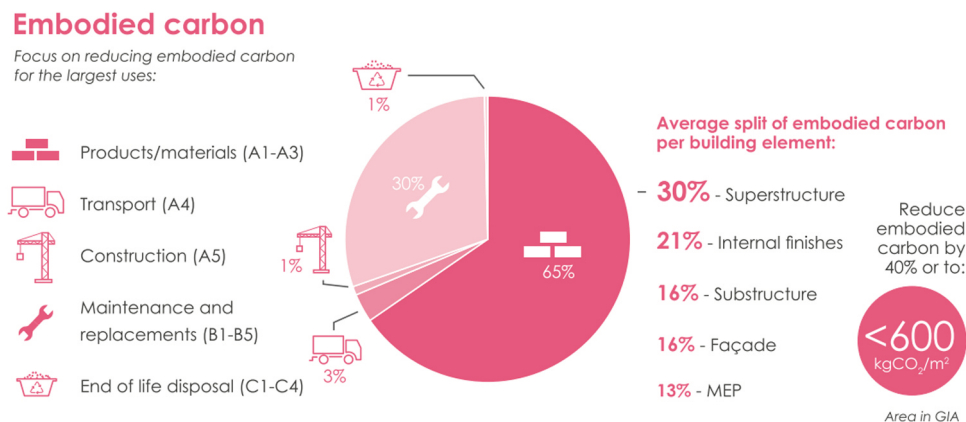


Fig. 1. Embodied carbon breakdown by building element for a typical school design [19].

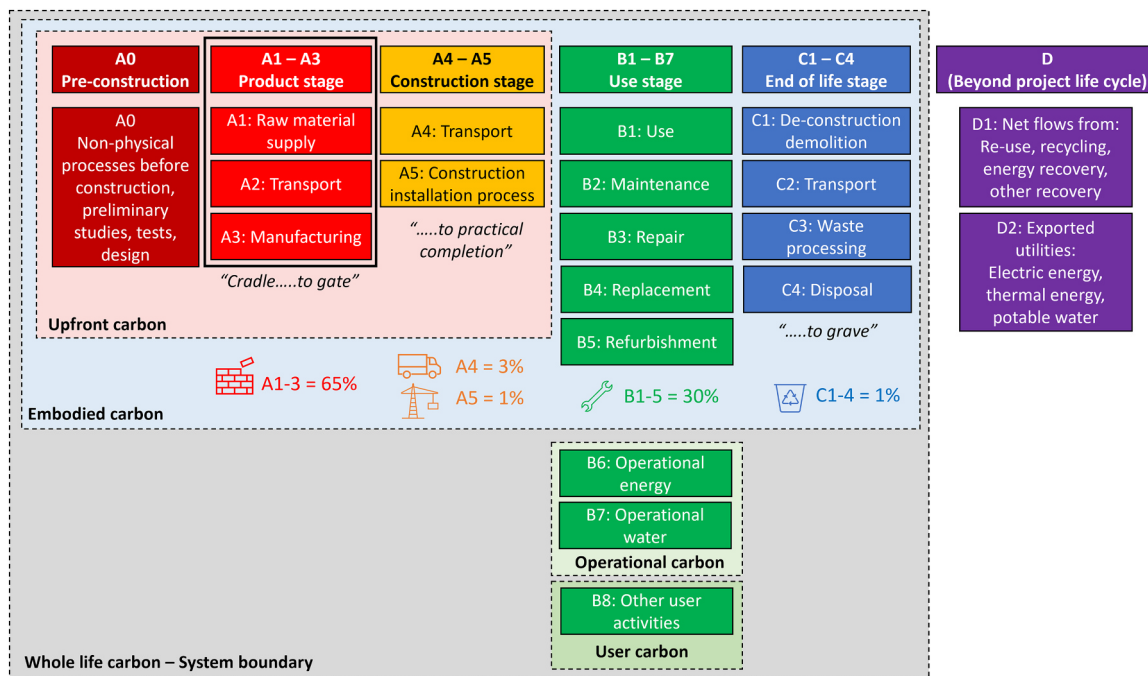


Fig. 2. Whole life carbon modules with embodied carbon figures from the school example in Fig. 1 adapted from Sturgis et al. [29].

Premises) Act 2025 [40] which is also known as Martyn’s Law. The Act requires those responsible for publicly accessible venues and events to have in place appropriate (reasonably practicable) protection procedures that are expected to reduce the risk of harm in the event of an attack [41]. For venues with capacity of over 800 people, enhanced tier requirements must be met which include the provision of public protection procedures and measures. One of the procedures is ‘invacuation’ which is the process of bringing people into safer parts of the premises [42].

To enable venue owners to select appropriate protection procedures and measures, they must understand the strengths and vulnerabilities of their building structure against potential threats. Without adequate building resilience and understanding of material performance, incorrect safety advice could be given as seen in the Grenfell fire disaster [43].

2.3. Security and carbon trade-off

Over the next few decades, both the private and public sector will need to balance the increasing demand for net zero carbon design and construction against the evolving security threat from terrorist activity. Lower carbon and more thermally efficient materials will be used which may increase a building’s vulnerability to an explosive event nearby. For example, lightweight cladding and framing systems may also be easily perforated by primary fragmentation from an explosive device [44] and the building materials may also pose a secondary fragmentation risk if they are damaged by blast. Many of the new and evolving building products will not have been tested against blast or fragmentation unless specifically requested by clients. To ensure the appropriate risk assessments can be completed, a basic understanding of the protection levels of the latest building materials and construction methods is required. This paper aims to identify gaps in the current research and testing associated with the security vs net zero carbon trade-off.

3. Terrorist methodology

3.1. Terrorist threat analysis

Terrorist attacks have come in many forms over time, from explosive devices to firearms, bladed weapons to vehicle ramming [45]. As

weapons have evolved, protective security designs and guidance have been adapted to reduce the risk of attack [46–50]. The Global Terrorism Database (GTD) has collated information from 1970 to 2020 covering over 200,000 cases [51]. Data from 1993 is missing due to the loss of the original data cards [51] and 2021 data is downloadable separately. However, the resource is still an extremely comprehensive database that is useful for analysing strategic trends in terrorist incidents across the globe.

3.1.1. Large explosive events

Large blast devices typically in the form of Vehicle Borne IEDs (VBIEDs) with over 100 kg of explosives were used to attack both high-profile infrastructure and people for many years [52]. Examples over the last 50 years include: Embassies in Beirut (1983), Istanbul (2003) and Jakarta (2004), the World Trade Centre (1993) and the Manchester shopping area (1996) [53]. Large VBIED attacks have been the most devastating to buildings and fatality numbers were reduced if a bomb warning was given to allow evacuation [54]. Incidents such as these have influenced protective security design alongside advances in design rules for robustness to prevent disproportionate collapse following accidents such as the Ronan Point collapse [55]. Other passive mitigation measures such as Hostile Vehicle Mitigation (HVM), main entry point design and active methods including searching and screening have all assisted in reducing the effects by providing more stand-off. An example of this was seen in the Glasgow Airport attack in 2007, where metal bollards prevented the explosively laden vehicle from entering the crowded check-in hall [56].

3.1.2. Smaller explosive events

Throughout the terrorist bombing campaigns of the late twentieth century, groups such as the Provisional Irish Republican Army (PIRA) and radicalised individuals used improvised mortars or smaller (less than 10 kg) IEDs [57]. As protective security measures around key targets improved, the threats evolved to aerial mortars [58] or small concealed devices like the Brighton Hotel bomb in 1984 [59] and Boston marathon bombs in 2013 [60]. The use of suicide Personnel Borne IEDs (PBIEDs) has also increased as terrorists moved from targeting infrastructure to injuring people in publicly accessible spaces like in the

London July bombings in 2005 and Manchester Arena bomb in 2017 [60]. While smaller devices placed outside may reduce the risk of building collapse, lethality has been increased by the addition of fragmentation such as nails, nuts, bolts or ball bearings [61]. These could potentially perforate lightweight cladding, causing injury to occupants who may have thought they were safe inside a building. The building components may also become secondary fragmentation injuring people within close proximity to the building [62].

3.1.3. Explosive hazard trend

Research by the National Academies [53] suggests that restricting the availability of explosive pre-cursor chemicals used to make Home Made Explosives (HME) has led to a decrease in main charge size. Collett et al. [63] highlighted that HME is most often used when the organisation does not have access to reliable commercial or military explosives. To test this, an analysis of the GTD database was conducted using the 'Explosives' weapon filter and extracting approximate charge size data from the 'Weapon detail' free text box. This was supplemented by data from the National Academies paper [53] and used to produce the plot in Fig. 3 which shows the maximum charge size for each region by year.

Whilst the majority of regions show decreasing charge size trends indicated by the arrows in the legend, Sub-Saharan Africa, South America, South & Central Asia show steady increases. These regions are linked to ongoing conflicts where there is better access to munitions, explosives and pre-cursor chemicals to produce large devices [64].

Regions which have regulations or codes of practice limiting pre-cursor chemicals such as Europe, North America and Australasia have seen a reduction in charge size over the past decade (Fig. 4). The US Ammonium Nitrate Security Program, amendment to the Homeland Security Act of 2002 in 2008 [53], Canadian Explosives Regulations 2013 [65], Australian National Code of Practice for Chemicals of Security Concern [66] and EU Regulation 98/2013 (repealed by EU 2019/1148 [67]) control the use of ammonium nitrate or restricted common explosive pre-cursors such as: hydrogen peroxide, nitromethane, nitric acid, potassium chlorate, potassium perchlorate, sodium chlorate and sodium perchlorate [68]. These are also shown on Fig. 4 and charge size has remained at a very low level since the implementation of such rulings.

One exception to the general decline in the 21st century is shown by the 2021 spike in Western Europe in Fig. 4. This represents the Oslo bombing where Anders Breivik purchased ammonium nitrate under the guise of using it legitimately as fertilizer [69]. He combined it with fuel oil to create a huge VBIED killing eight people and injuring over two hundred others [60]. The explosion destroyed all nearby glazing, damaged masonry walls and a concrete roof [70]. However, the 1958 reinforced concrete H-block pictured in Fig. 5 [71] survived the blast despite having exposed lower columns. With the recent introduction of low carbon concrete variants, it raises the question whether blast performance is comparable. The damaged high-rise building was retained and refurbished as part of the construction of the new Government Quarter [72].

In the last 10 years, until the GTD ceased to be updated in 2021; the focussed graph of Western Europe continues to show a downwards trend (Fig. 6). Analysis of the data from the GTD suggests that since 2015, car bombs containing over 50 kg of HME based on ammonium nitrate have been replaced by PBIEDs carried in suitcases, backpacks or as suicide vests [51]. Triacetone triperoxide (TATP) was used as the main charge in the Paris suicide vests, Brussels suitcase bombs and Manchester Arena backpack bomb [53]. Use of this chemical has become prevalent as the precursor materials are readily available and inexpensive [73].

The data shows that the current main charge size has stabilised to around 10 kg, targeting crowded places or specific individuals, rather than having the aim of destroying entire buildings as seen in the late 1990s. Most of these devices can be carried right up to buildings before searching and screening takes place, therefore our building external

envelope designs should consider close-in damage and fragmentation.

3.1.4. Fragmenting devices

The GTD has free text details on the weapon, including descriptions of additional fragmentation and container type. This detail is limited for attacks prior to the early 1990s, but since then the addition of: nails, nuts, bolts and ball bearings has become widespread [51]. Fragmentation increases the lethality of smaller IEDs as the fragment density drops off with range slower than that of blast as shown in Fig. 7 [74,75]. The requirement to understand fragmentation was emphasised by Price et al. [61], then Sielicki et al. [76] in a paper on irregular steel debris from PBIEDs, where blast driven hex nuts were used in a field test and probabilistic analysis was used to establish casualty risks. The research found that the serious injury zone with an explosive charge size of only a few kilograms was likely to be a maximum of 20–30 m.

Fragmentation can also penetrate building materials, especially in the case of lightweight sandwich panel cladding as shown in the study by Studziński [44]. As building designs are aiming to become more efficient to reduce construction materials and embodied carbon; lightweight cladding materials which resemble stone, brick or metal panels are becoming more popular. Brick slips of just 7–20 mm thickness are available and they can be adhered directly to insulation or retained in mechanical rails, but both look identical to full bricks. Reducing the mass and density of these walls may increase the risk of device fragments passing straight through them. This could cause injuries to building occupants, who may have thought they were safe behind a solid wall.

3.2. Future threats

Predicting future terrorist threats is a research topic in itself, but the latest battlefield technology can easily be adapted for terrorist use. The weaponisation of commercial drones to poses a significant threat to target crowds or damage infrastructure [6,77]. Drones can carry a variety of explosive payloads dependent on their size including fragmenting devices or they can be used as one-way suicide drones [78,79]. Whilst the blast and fragmentation terminal effects of the explosive device will be the same, the drone can bypass obstacles which would normally have provided stand-off or enter buildings via windows and doors. Due to the complex nature of internal blast, this will remain out of scope of the paper. Cyber, chemical, biological, radiological and nuclear threats will also not be covered.

3.3. Threat analysis summary

Whilst a large blast event may remain as the most dangerous terrorist threat to buildings it is unlikely to materialise in countries with significant legislation and strong security enforcement able to interdict early suspicious activity. The increased use of hostile vehicle mitigation around iconic buildings and built-up areas also makes them a less attractive target. The current most plausible explosive event is a small personnel borne or drone dropped IED which can function close to a building. The blast from the device may damage building frontages and fragmentation could perforate lightweight cladding causing injury to occupants who thought they would be safe inside. Regardless of the future threat, it is likely that blast and fragmentation penetration risk will remain present during the 50 + years design life of most buildings.

4. Research trend analysis

A systematic literature review into blast and ballistic effects on buildings using Scopus was conducted, resulting in 2734 research items from journals and conference papers from 1970 to 2024. The process and search terms are shown in Fig. 8 and inclusion/exclusion criteria were used to obtain items relevant to construction materials.

From the search results, the plot shown in Fig. 9 was created by normalising the research items per year along with the sum of terrorist

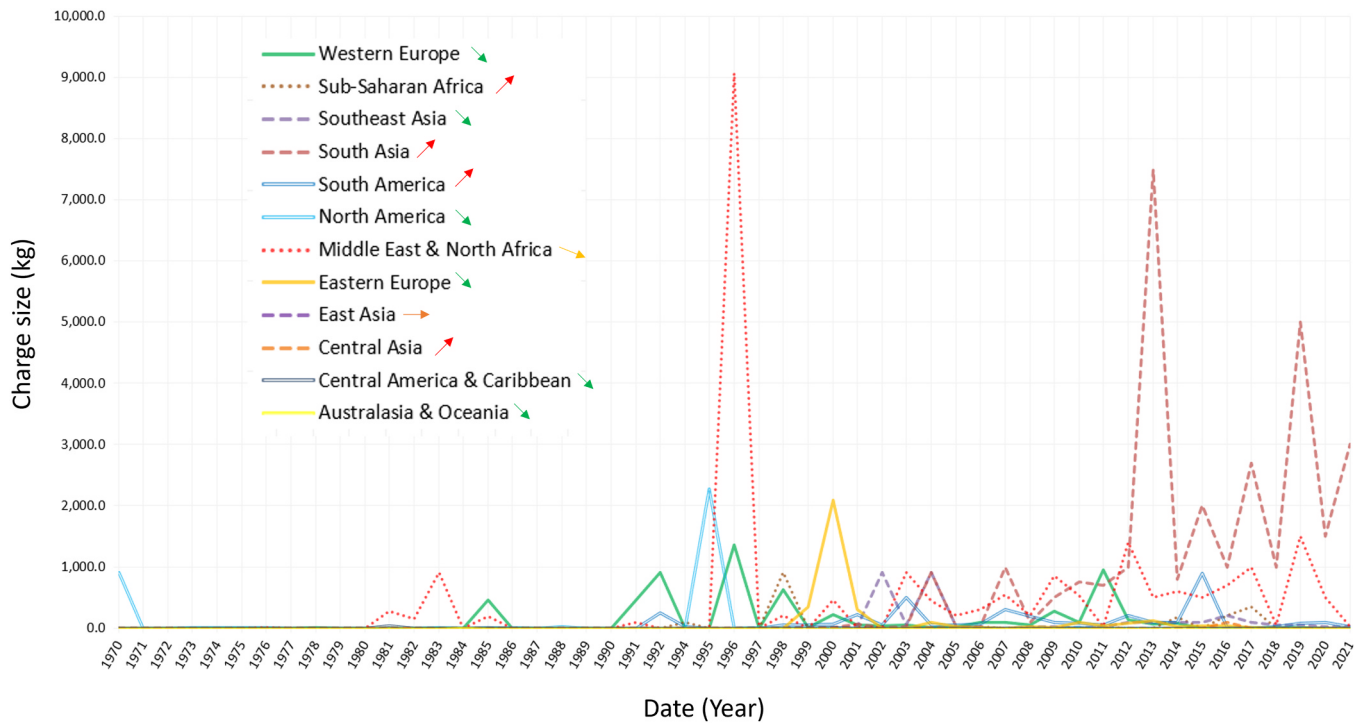


Fig. 3. Maximum charge size vs year per region with arrows indicating general trend of charge size over the time period.

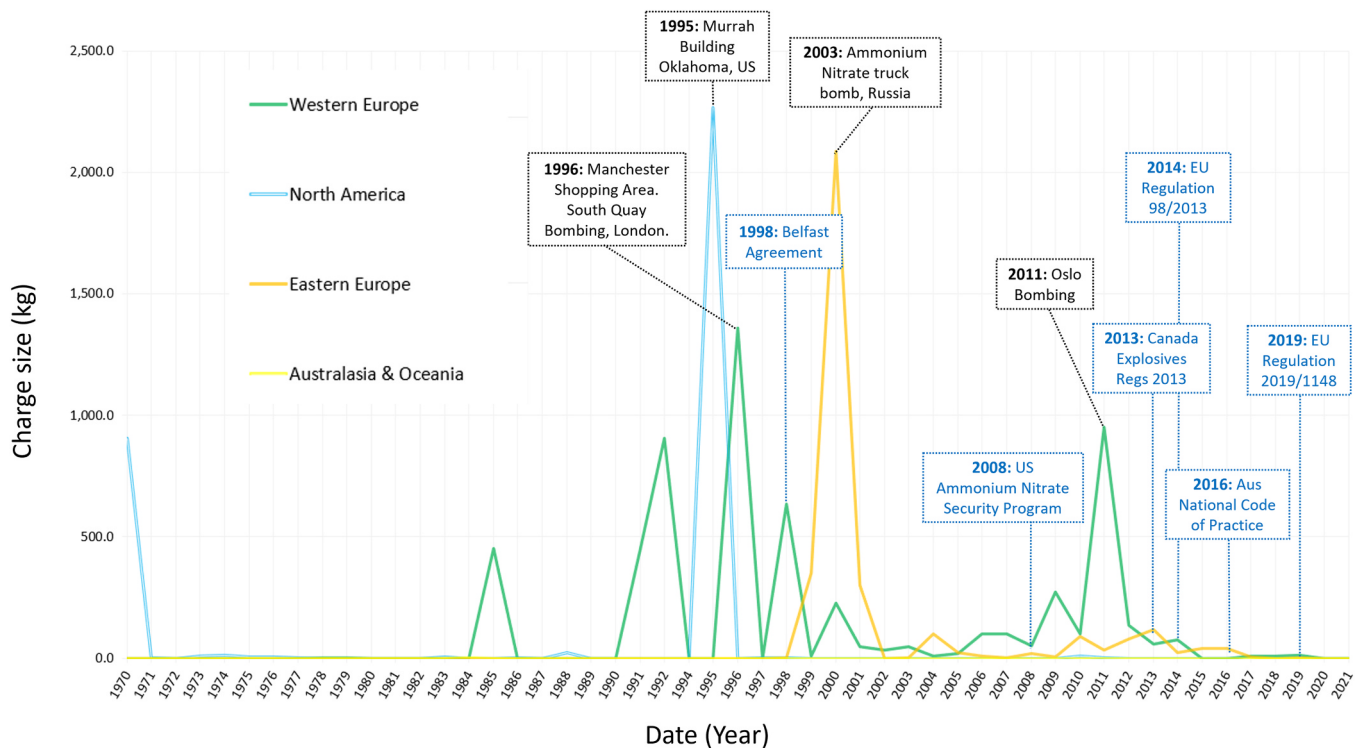


Fig. 4. Maximum charge size vs year (four selected regions) with annotations of specific events in black and control measures in blue.

attack fatalities each year from the GTD [51]. The data shows that research in weapon effects on building structures started to increase in the early 1990s, around the time that large charges became more common as previously shown in Fig. 3. The graph in Fig. 9 shows a general increase in research correlating with rising terrorist attacks and fatalities.

The research ranged from papers analysing attack damage (examples

include [80,81]), to examining retrofit [5,82] and protection options [83–94]. Papers included research on accidental explosions [95] or blast protection requirements in industries such as petrochemical, mining, storage and manufacturing [96,97]. Whilst the general rise in research is likely due to the increase in journals, digital content and more stringent safety requirements, there are spikes in the research typically 2–5 years after high-profile attacks that are highlighted in Fig. 9. This lag is



Fig. 5. “The world according to Bannon and Trump” by A Davey is licenced under CC BY-NC-ND 2.0.

conflicts in Eastern Europe and the Middle East are likely to continue to drive terrorism bringing new threats and technology.

5. Material testing research

The primary objective of the systematic search was to identify what blast and penetration resistance testing research had been conducted on building materials in general. As there is no single definition of a ‘low carbon material’, down-selecting using search terms relating to carbon and sustainability did not yield meaningful results. Therefore, articles were manually selected if they covered materials that are either: advertised as low carbon variants (e.g. low carbon concrete); carbon sink/biogenic products (e.g. timber products, bamboo) and materials with a range of carbon content options (masonry, glazing, cladding and modular construction). Another online tool called ResearchRabbit¹ [98] was used to identify similar papers and explore other research by the authors of the most relevant papers. For blast research articles, loading is described using scaled distance (Z), where possible. This is the Hopkinson-Cranz or Cube root scaling law [99] as shown in Equation (5-1), where R is range (m), and W is charge mass (kg) in TNT.

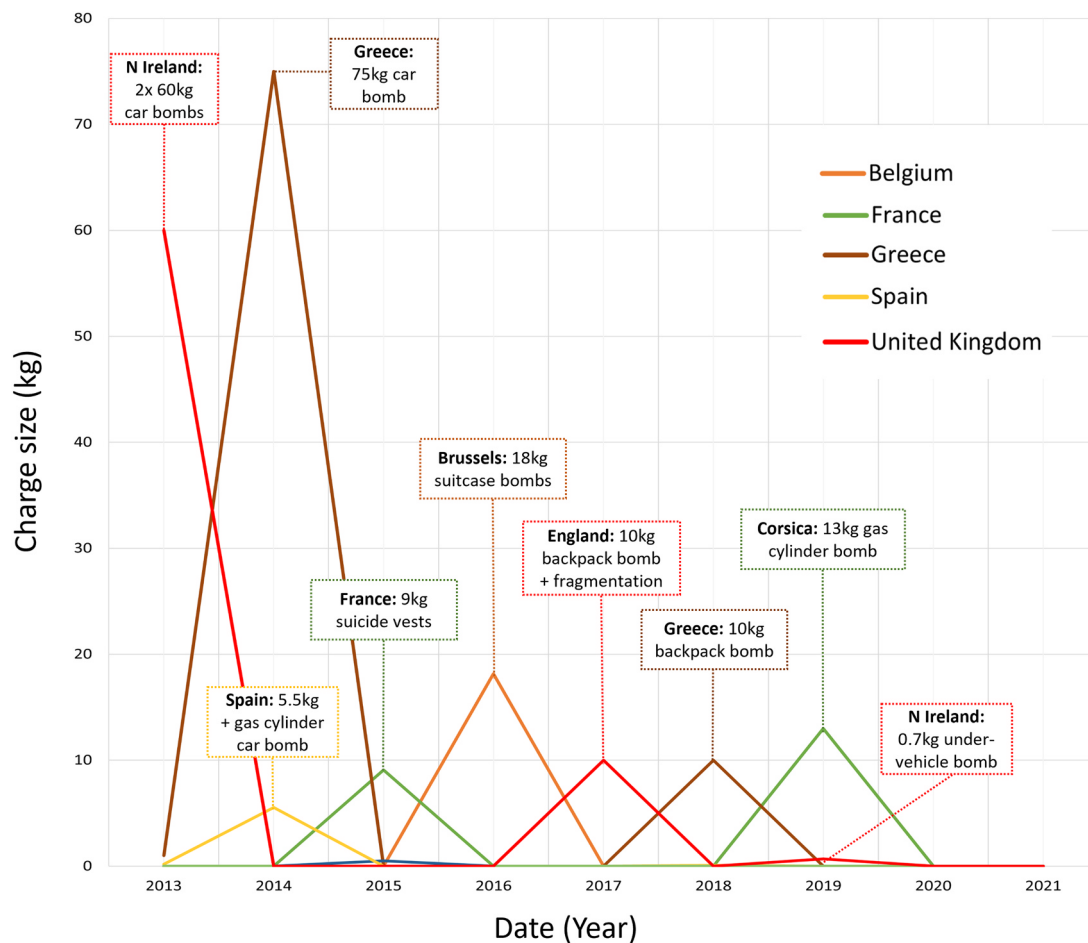


Fig. 6. Western Europe 10-year maximum charge size vs year with events and countries annotated.

potentially due to a delay in obtaining funding and time taken to publish the findings.

Despite a decrease in fatalities and attacks, research interest continues to rise due to the continuing threat and evolution of weapons, development of building materials and increasing safety requirements in modern industries. Traditional threat actors such as the IRA and ISIS may have reduced the scale and frequency of their attacks, but ongoing

$$Z = R/W^{1/3} \text{ (m/kg}^{1/3}\text{)} \quad (5-1)$$

It is acknowledged that grey literature was not directly obtained

¹ <https://www.researchrabbit.ai/>

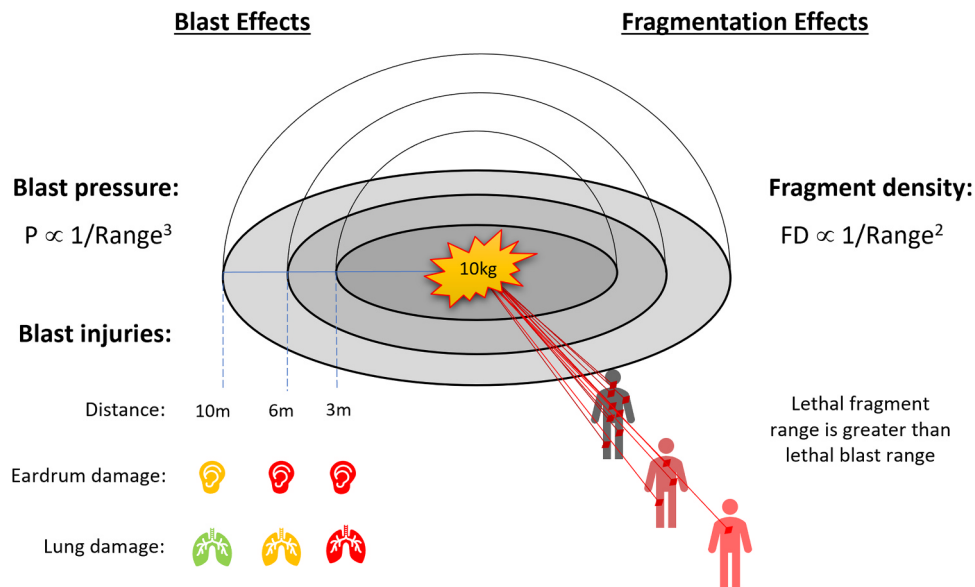


Fig. 7. Lethality of blast and fragmentation adapted and enhanced from references [74,75].

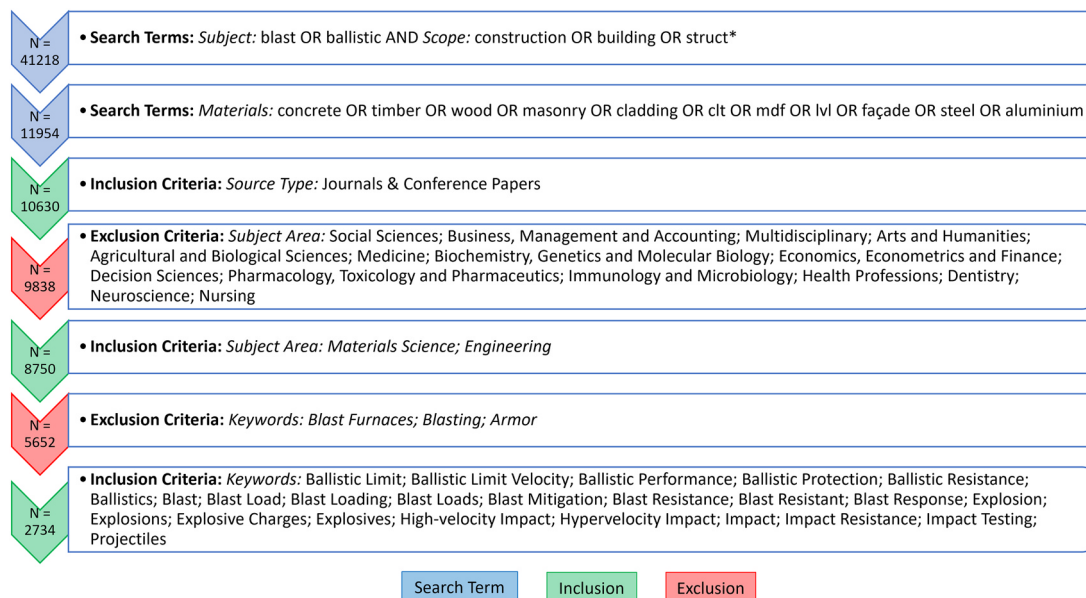


Fig. 8. Systematic literature review search terms, inclusion, exclusion criteria and results.

from the systematic search. However, some policy items were found by following citations and authors who have specialised in blast research (e.g. [45,100,101]). This selection gave a wide enough range to understand the research trends and in the field of low carbon construction and identify any research gaps.

5.1. Concrete

There have been numerous studies on the protective properties of many concrete variants as it has been a popular building material that has been the victim of large blast events [102]. In a review paper, Hao et al. [103] summarises much of the field and laboratory testing, numerical modelling techniques and design approaches. Concrete has also been used in the design of protective infrastructure and as a result, many tests and analyses of performance have been conducted, especially by military research establishments. Much of this information is not available in the public domain but would have been used to create

design guidance such as the Unified Facilities Criteria (UFC) 3-340-01: Design and analysis of hardened structures to conventional weapons effects [104].

Concrete technology has also been moving towards the use of Ultra High-Performance Concrete (UHPC) and various fibre reinforcements. A state-of-the-art review into the blast and ballistic perspective of UHPC summarised decades of research on blast and ballistic effects on various types of concrete. Das et al. [105] concluded that UHPC and Ultra High-Performance Fibre Reinforced Concrete (UHPFRC) performs well in resisting penetration of projectiles and showed reduced blast damage compared to normal and high strength reinforced concrete. However, the research into UHPC does not address the issue of embodied carbon or sustainability.

There are also several papers on reinforcing or protecting concrete structures against blast loading and a state-of-the-art review by Draganić et al. [82] summarises 20 years' worth of experimental studies researching blast improvement of structural elements. Protection

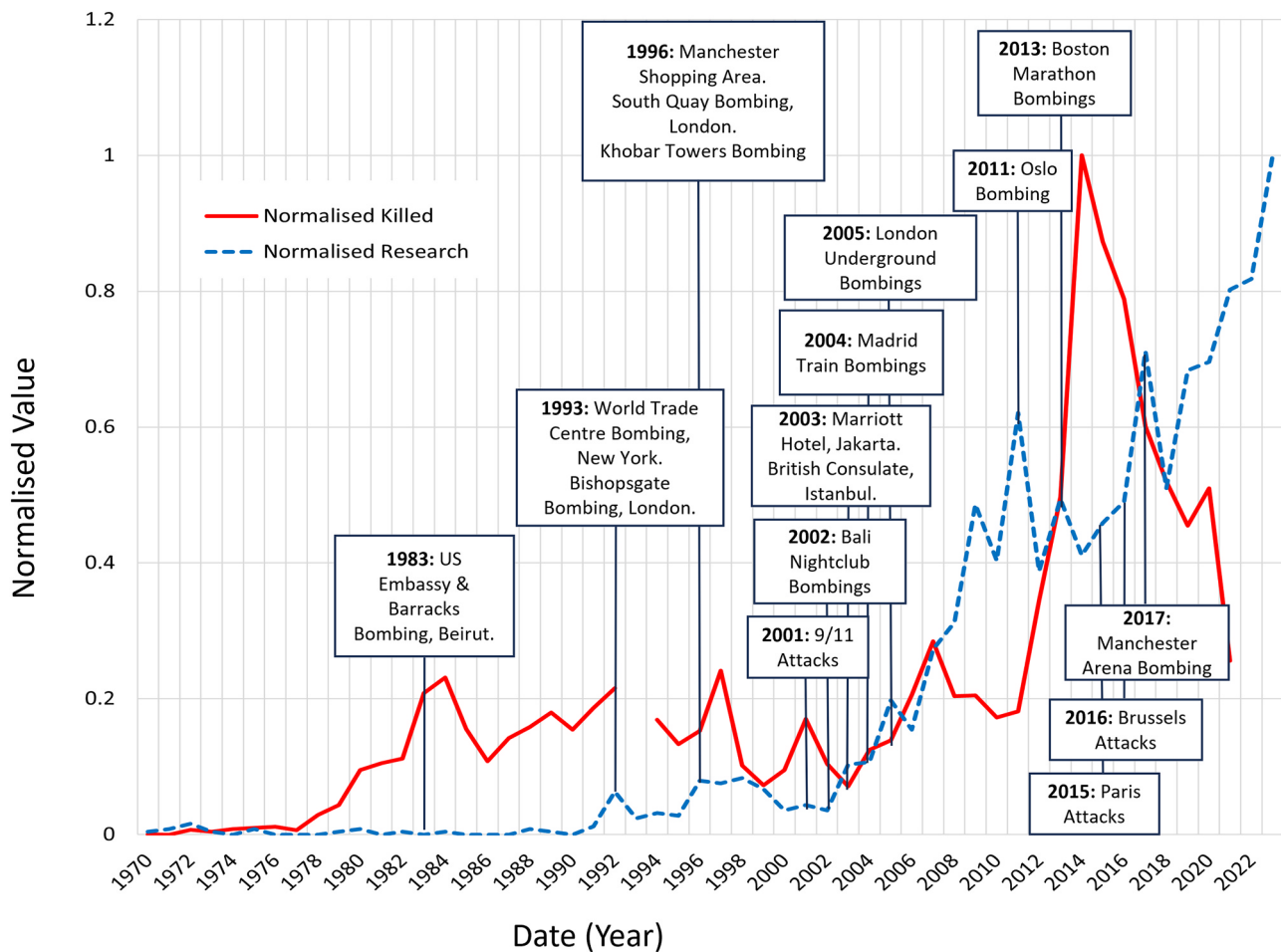


Fig. 9. Normalised values of research papers (blue), attack fatalities (red) and number of attacks (grey) vs year.

methods that have been analysed range from steel or resin panel jacking [90] to aluminium foam [94,106] and sacrificial cladding with hybrid-multi cell tubes [93]. The materials used in these types of retrofits were typically metallic foams or tubes which increase the embodied carbon content. However, reinforcing an existing building could potentially be a more sustainable option than demolition and re-build, but that is out of scope for this research due to the variability of building scenarios.

5.1.1. Sustainable concrete blast research

During this literature review there were only two papers identified that addressed both the protective properties of concrete and sustainability challenges. A paper which discussed sustainable design of concrete and blast-resistance was presented at the Structures Congress 2023 [10]. The paper performed Life Cycle Assessments (LCAs) on three case studies to evaluate the embodied carbon for each version of the 3-storey reinforced concrete structures. The first was a base-line design; the second, an enhanced building with protective design elements; and the third was a sustainable alternative to the enhanced design. The paper concluded that a more sustainable protective structure could be achieved by selecting a low carbon concrete alternative and low embodied carbon glazing. However, the paper assumed that the low carbon alternatives perform similarly to the original materials in a blast scenario. The second paper presented at the same conference [8] acknowledged that low-carbon alternatives required field testing to test the assumptions. This remains an aspect of blast research that is not being widely addressed.

5.1.2. Sustainable concrete penetration research

The only paper which specifically addressed low carbon concrete protection performance was a paper written by Norwegian researcher Jacobsen et al. [9]. It questioned whether low-carbon concrete variants were comparable to standard concrete against ballistic impact loading. His research evaluated the ballistic perforation resistance of two commercially available low-carbon C75 strength concretes and standard C75 concrete against ogive steel projectiles. He used modules A1-A3 from EPDs as a way of assessing and comparing Global Warming Potential (GWP). The paper concluded that there was no significant difference in ballistic perforation resistance between the concrete variants which is reassuring for the design of low carbon concrete protective structures. It also shows that there is interest in the topic of verifying that low-carbon alternatives perform comparably to the traditional materials that they are replacing. His research continues to look at ballistic resistance using other projectile shapes and the modelling of projectiles into concrete.

5.2. Timber

Across the world, there has been a resurgence of timber usage. This is due to both advances in timber construction technology and to support net-zero carbon commitments as timber and bamboo can be considered as carbon sink materials [25]. Developments in engineered wood products such as: Glued Laminated Timber (glulam), Cross Laminated Timber (CLT), Nail Laminated Timber (NLT) and Dowel Laminated Timber (DLT); has meant that load bearing capacities and achievable spans are now much greater. This has now opened the possibilities of high-rise buildings (currently up to twenty-five storeys) and large

residential or multi-use structures [107].

5.2.1. Timber blast research

In the case of timber, researchers have been proactively looking at the blast performance properties of timber for over 10 years. Two papers were found which concisely summarised this research, the first being: 'Lessons learned from a decade of research on wood assemblies under blast loading' [7]; the second being: 'State of the art review into timber research' [108]. Professor Doudak and his colleagues at the University of Ottawa in Canada have extensively researched structural timber subject to blast loading with a range of experiments [109], modelling [110] and analysis of light-framed walls, glulam, CLT, timber connections [111] and retrofit solutions. The research has also resulted in the development of the 'Proposed design methods for timber members subjected to blast loads' [112]. This paper suggests design parameters such as: Strength Increase Factors (SIFs), Dynamic Increase Factors (DIFs) and load factors for different wood products based on analysis of a range of experiments. However, the author acknowledges that close-in and contact explosions were out of scope.

The variety of timber blast research is covered well in the Mourão et al. [108] review where they summarised the research with scaled distance ranging from $Z = 3.4\text{--}35 \text{ kg/m}^{1/3}$. He acknowledged that test standards are lacking for timber products and that design codes are still under-developed. This is especially true for different species of timber where properties may vary, and species-specific parameters are required. He also highlighted the lack of research on close-in blast as most studies concentrate on far-field detonations.

5.2.2. Timber penetration research

Historically, wood has been used as a protective material for hundreds of years, especially in the maritime environment where ship builders designed wooden hulls against ramming and canon fire [113]. Early fortifications and castles were also constructed from wood and overhead protection from indirect fire could be made using thin tree trunks. More recently, research on bullet penetration into wooden targets was conducted due to interest in forensic reconstruction and urban military operations. Using 9 mm projectiles, Keone et al. [114] observed penetration into a variety of types of wood using Poncelet and Robins-Euler models to analyse the experimental data. They concluded that the Robins-Euler model could describe penetration into most types of wood and the Poncelet equation was suitable for softer wooden targets. They also found that Janka hardness had a linear relationship with the apparent dynamic strength of the target material. This methodology was repeated on plywood where the Poncelet model worked better than Euler-Robins [115]. This experimental methodology and analysis using those models could be suitable for testing some softer low carbon materials including some types of rainscreen cladding.

5.2.3. CLT Blast research

Full scale blast loading on CLT was conducted in the US against three CLT structures as part of a project to demonstrate the capability of mass timber systems [116,117]. The research project also covered quasi-static panel testing and shock tube testing for NLT. Three single-bay, two storey structures were built to test three different grades of CLT. Three explosive tests were conducted ($Z = 5.095\text{--}9.37 \text{ kg/m}^{1/3}$) to firstly test the panels to their elastic limit displacements and finally to test a structure to 1.5 times over the elastic limit. The structures all maintained load carrying ability and the testing concluded that the rebound response due to the negative phase must be considered in design, and that a Single Degree of Freedom (SDOF) dynamic analysis only gave approximate displacements in panels without openings. Sanborn built on this research by using the field data to validate a CLT blast analysis tool using Mathcad. She concluded that the tool needed further work testing in the plastic regime, negative phase parameters, rolling shear and dynamic increase factors [118].

5.2.4. CLT penetration research

Sanborn [118] also conducted ballistic research with CLT by experimenting with small-arms projectiles, a $\frac{1}{2}$ inch sphere penetrator and $\frac{1}{2}$ inch Fragment Simulating Projectiles (FSP). Initially she compared the results to the equation for timber in the design guidance: 'Unified Facilities Criteria (UFC) 4-023-07, Design to Resist Direct Fire Weapons Effects' [119] which showed poor correlation as the CLT outperformed traditional timber. She then went on to calibrate this model and evaluate the following models: Euler-Robins, Poncelet, Resal, Force law, THOR and a calibrated THOR. She concluded that the Force Law model was the best fitting model.

Sanborn continued research into CLT by introducing a non-wood material between laminates to create an 'Enhanced CLT' [118]. She conducted experiments on the following enhancing layers: perforated steel plate; expanded metal plate; aramid epoxy panel; mild steel plate; high-hard steel plate; ultra-high-molecular-weight polyethylene (UHMWPE); Fiberglass fabric (4-ply consolidated) and Fiberglass fabric (separated 4-ply). This chapter concluded by subjectively determining a ballistic resistance ranking based on the penetration data and a benefit cost ratio. The benefit cost ratio was then expanded to include ease of production and transportation cost and the inclusion of weightings. This methodology could easily be adapted to add the embodied carbon value and the thermal resistance to compare WLC between the materials.

Following on from Sanborn's work, Lo Ricco et al. [120] conducted research to determine whether a CLT layout could be established that is comparable to the thickness and cost of protective designs made from reinforced concrete or steel. They tested eight different combinations of seven layers of wood using variations of softwood, hardwood, thin and thick steel plate reinforcement, fine and coarse steel mesh reinforcement. Three types of NATO ball ammunition were tested: 7.62 mm (M80); 5.56 mm (M193); 5.56 mm (M855) and results were given as pass (captured all bullets) or fail (one or more exited back face). For the tests which had full penetration, residual velocity was measured and plotted against impact velocity. Residual and absorbed kinetic energy was calculated and the layouts were ranked in cost order. In the final accomplishment report covering this research, Weaver et al. [121] concluded that the addition of steel plates was the most cost-effective way of improving performance. However, a carbon comparison of the products was not conducted.

Swinea et al. has continued the work on enhanced-CLT by developing an analytical model and cost benefit analysis [122]. She has also continued to build understanding around CLT by examining the effect of thermal modification on ballistic performance [123]. In this work she continued to build on the ballistic penetration data for coastal western hemlock and concluded that thermal modification did not significantly alter the penetration performance.

5.3. Medium density fibreboard

Medium Density Fibreboard (MDF) is a popular building material that is cheap and easy to manufacture into a variety of shapes and sizes to make furniture, fixtures, fittings, partitions and flooring [124]. It is found in almost every room in modern buildings and could pose a secondary blast injury threat or be presumed by the general public to provide ballistic/fragmentation protection comparable to solid timber products. Some blast and ballistic research was found to understand the behaviour of MDF.

5.3.1. Medium density fibreboard blast research

The air-blast response of MDF was investigated by small scale blast tests ($Z = 0.928\text{--}1.1 \text{ kg/m}^{1/3}$) using a blast tube [125]. Material properties were determined using quasi-static 3-point flexural tests, tensile testing and compression testing. Modelling was completed using LS-DYNA to determine suitable explosive arrangements. The researchers concluded that MDF was very brittle and displayed poor blast resistance and the failures caused fragmentation which could increase the risk of

secondary blast damage. This type of small-scale blast experimentation could be used to observe failure mechanisms and fragmentation hazard of other materials such as cladding.

5.3.2. Medium density fibreboard penetration research

The ballistic properties of MDF were explored by Koene et al. [126] using 9 mm projectiles. They used Janka hardness measurements and the Robins-Euler and Poncelet models to analyse the experimental data as in their previous research on wooden targets [114]. For MDF the Poncelet model worked better to predict projectile penetration in the MDF that was tested.

5.4. Bamboo

Engineering and materials science research into bamboo has doubled over the last 10 years according to a Scopus search for the term 'bamboo'. Articles on bamboo in the 'Journal of Construction and Building Materials' have grown by around fifty per year since 2021. In a review by Adier et al. [127], China produced 46 % of studies, Brazil 11 % and the UK 9 %. Although there is regional dominance in Asia there is an increased interest in the use of bamboo as a widely available, low carbon material which is much faster growing than most other timber species.

5.4.1. Bamboo blast research

A recent article on bamboo and blast, investigated two kinds of bamboo composite plates: Parallel Bamboo Strand Lumbar (PBSL) and Cross Laminated Bamboo (CLB) [128]. Quasi-static three-point bending tests were carried out to establish the bending strength and stiffness, and to compare strength anisotropy coefficients with other bamboo products. The blast testing comprised 22 tests with scaled distances from $Z = 0-2.714 \text{ m/kg}^{1/3}$ (standoff 0–1 m and 50–400 g TNT). Pressures, displacements, strains and damage patterns were all recorded during the testing. They established critical scaled distances based on the damage criteria from the testing and concluded that CLB had superior protective properties against blast over PBSL due to the cross-laminated structure. This methodology to establish a critical scaled distance could be used to establish a performance metric for other low carbon materials.

5.4.2. Bamboo penetration research

Koene & van der Worp [129] continued work on engineered wood products by testing bamboo, Oriented Strand Board (OSB) and Low-Density Fibreboard (LDF). The research followed the same format of the previous work on wood and MDF. In this research, they concluded that the Poncelet model fitted better for all materials with Robins-Euler also working for bamboo.

5.5. Masonry

Blast effects on masonry were well understood following analysis of bomb damage data in London during World War II [130]. A simple search in Scopus using terms: "blast OR ballistic AND masonry" brought 609 documents (as of Mar 2024) and many of the papers were around: modelling using a variety of software, retrofitting to improve performance, or comparison of performance of different products. Masonry can come in various forms from brick to blocks, solid to aerated, each with a different WLC cost [131]. Another way of reducing embodied carbon whilst maintaining the appearance of bricks is by using brick slips. These are popular in the offsite/modular construction industry where 15–50 mm thick bricks slips are either adhered or mechanically fixed to the wall system. They offer a lower embodied carbon design over a traditional brick wall as they are lighter weight and can be fitted to modules in the factory without requiring a bricklayer or scaffolding. Currently no publicly available research into the performance of brick slips was found.

The most relevant paper found on the comparison of masonry

product performance was by Czech researchers Rolc et al. [132], who conducted ballistic impact and blast testing on walls using five types of bricks. The ballistic testing was according to STANAG 2280 categories A1-A4 (5.56–14.5 mm Armour Piercing (AP)). The blast testing used a 2.4 m x 2.5 m high wall against 10 and 20 kg TNT charges at distances of 1.5m-5m away from the wall ($Z = 0.55-2.32 \text{ kg/m}^{1/3}$). Modelling was conducted using LS-DYNA and the results correlated well with experimental results. They were also able to reinforce the wall using basalt and ceramic plates to improve the ballistic performance. This ballistic and blast testing methodology could be used to test low carbon walling solutions to give a protection ranking which can be compared with a carbon ranking.

5.6. Glazing and glazed façades

Blast and ballistic research on glazing has been a popular area of research since the 1960s, from looking at the effects, injuries, designing blast resistant glazing units and ways of modelling glass and glazed façades. Two papers were identified which addressed both security and sustainability of glazing products. One looking at: security, energy and embodied carbon in glazing design [133] and the other: sustainable façade design in a blast resilient urban environment [11]. In the first paper, Harijanto et al. [133] highlighted three attributes to explore sustainability in glazing design: blast-resistance, thermal performance (R-value) and embodied carbon, establishing methods of analysing performance for each. These were then compared in diagrams of normalised embodied carbon or R-value vs blast capacity to aid material selection. This approach could be useful to compare cladding materials where the R-values would impact operational carbon (from heating and cooling) and therefore be a beneficial measure of material performance.

Lori et al [11] looked at optimising protection against blast waves. They concluded that for the most efficient design, it needed to be balanced considering the interaction between the different system elements. This research was further developed by a case study that showed that use of efficient calculation could reduce façade depth by around a third [134]. Although neither paper addressed carbon content, they showed that accurate modelling is essential for efficient design which in turn improves the sustainability credentials of a construction project.

5.7. Cladding and curtain walling

Choice of cladding can significantly affect the WLC of a building from both an embodied carbon perspective [39] and operational carbon depending on the thermal resistance of the material. Low carbon cladding can be in the form of timber products or new materials with lower carbon than solid products (e.g rainscreen cladding). An overview of the blast performance research of cladding found evaluations or analysis of a variety of types of protective materials: sacrificial cladding [84,85], foam filled panels [88,91,92,135,136], blast absorbing panels [137]; near field blast [83]; and connections [138,139]. Brewer et al. [140] conducted full-scale field testing and modelling of a blast-resistant, steel stud curtain wall with granite cladding and glazing against a large VBIED.

The research that was most applicable to the potential threat of a PBIED with fragmentation as described in Section 3.1.4 was a recent paper from Poznan University of Technology [44]. The team conducted testing and analysis of wall cladding sandwich panels subjected to a simultaneous blast load and accelerated fragments using a cylinder of TNT ($Z = 2.02 \text{ m/kg}^{1/3}$) and six 8 mm diameter ball bearings. The pre and post impact velocities of the ball bearings were recorded, and the panels provided very little resistance to penetration posing a hazard to building occupants. The deflection of the panels was measured during the testing and compared to the Ultimate and Serviceability Limit States (ULS and SLS). Numerical modelling was also completed using finite element modelling which was validated with the field test results. This methodology could be used to assess the combined blast and

fragmentation resistance of a variety of cladding types.

No publications were found around the performance of cladding panels used in standard (non-protective design) situations, except for an article on impact resistance to gravel [141]. With many new rainscreen cladding options and lightweight systems coming to market with a variety of carbon and environmental credentials (e.g. [142,143]) there is a potential gap in research around the blast and ballistic performance of such products.

5.8. Modular/offsite construction

At the turn of the century, modular, offsite, prefabricated or modern

methods of construction (MMC) started to increase in popularity, especially for large scale repetitive residential buildings such as hotels, apartments and accommodation blocks [144]. Building the modules offsite can save both time and cost as much of the artisan trade work can be done inside the factory without being impacted by the weather, access or other construction work. Embodied carbon can also be reduced using MMC as shown in an early LCA comparison to a standard masonry cavity wall construction [145].

The research on blast effects on modular buildings seems to be limited to the design of blast resistant buildings for industrial uses [96, 97,146]. These buildings are specifically designed to be protective structures and are typically constructed from steel. Blast and ballistic

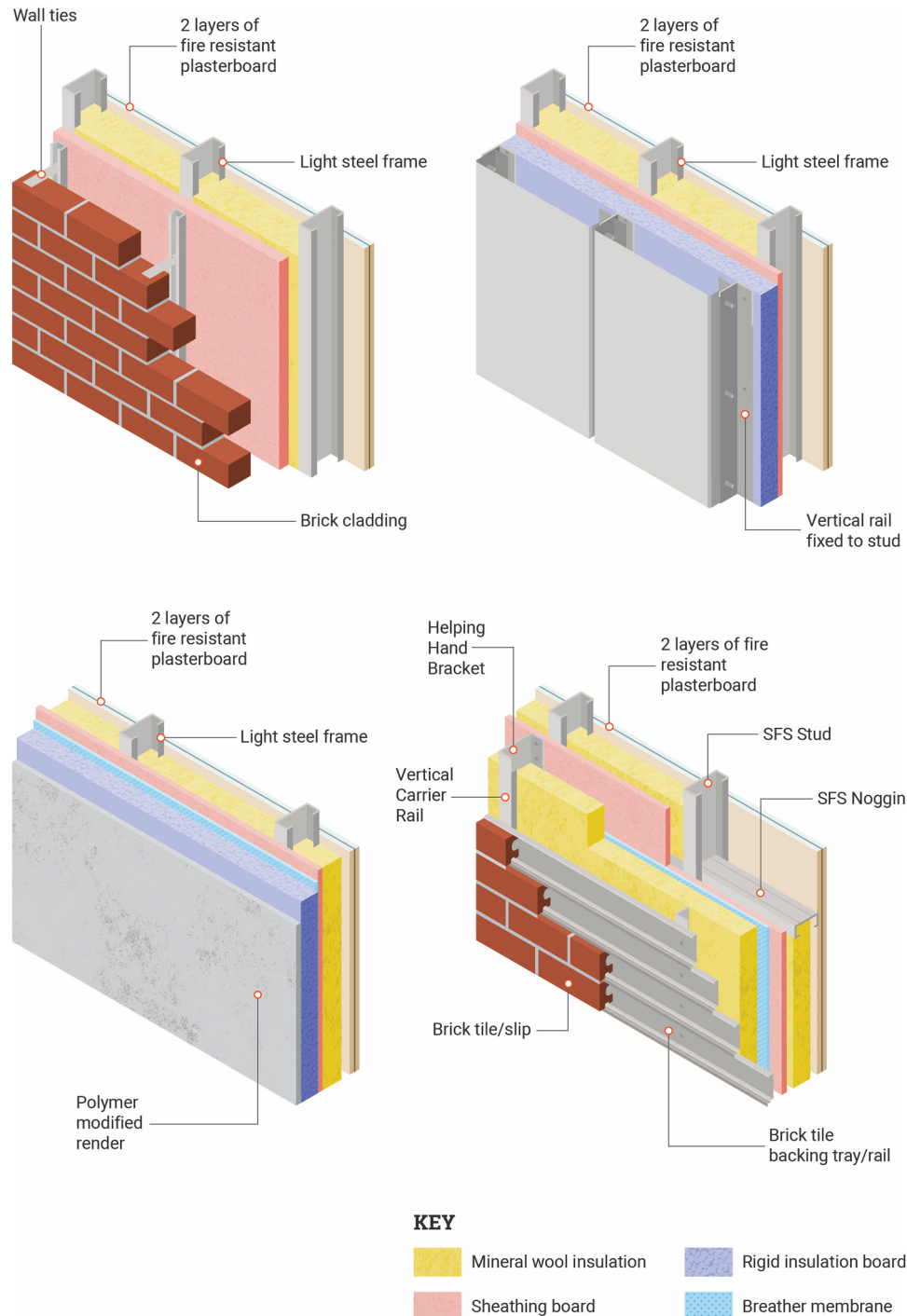


Fig. 10. Modular cladding options: brick, rainscreen cladding, render and brick slip system.

protective modular buildings are commercially available with a range of protection levels [147,148], but these buildings are not driven by a low carbon requirement as protection is the priority. Lacey et al [149] also highlight the limited number of published qualitative studies on blast loading, especially for mid to high-rise modular buildings. Research into the progressive collapse of non-blast resistant modular buildings is still quite limited to static analysis and the notional removal of elements and modules [150–152] with Alembagheri et al. [153] investigating dynamic progressive collapse simulations.

Modular buildings can also accommodate several different cladding options including: standard brickwork, a variety of rain-screen cladding materials, insulated render or brick slips [154]. Fig. 10 shows some of the options on light steel frames or a Steel Frame System (SFS). This makes them a popular choice as they can both visually replicate existing masonry buildings or have a unique external appearance. The performance of this wide range of cladding systems are likely to behave very differently in blast and penetration resistance and research on the testing of different cladding types has not yet been found in publicly available literature.

5.9. Summary of material testing research

A summary of the blast and ballistic/penetration research is shown in Table 1 with reference to whether the product is classed as low carbon and if carbon comparisons have been completed. The majority of the research is based around conventional weapons or relatively large FSPs. Some CLT research completed a cost/benefit analysis and a carbon comparison using EPDs could easily be added to this research, if carbon was a driver for material choice. The table shows that whilst some materials that are classed as low carbon are being tested, the only research directly comparing the performance of low carbon variants is

the paper on low carbon concrete by Jacobsen et al. [9].

6. Security vs sustainability

Of the research material found from both the systematic Scopus search in Section 4 and by following relevant references and authors, very few papers addressed both carbon and protective security. They have already been described in the relevant material section and are summarised in Table 2. The first four were written by protective design consultancies and they included theoretical design comparisons and carbon accounting of existing material options against low carbon alternatives. All four papers were presented in the ‘Blast and Impact’ section at the 2023 Structures Congress, showing that there was an interest in low carbon protection at that conference. The first paper [8] states low embodied carbon variants must be field tested to prove performance and the second paper [10] assumes low carbon concrete performs as well as standard concrete in blast. The third paper [133] directly compares embodied carbon, thermal resistance and security of specific types of glazing using EPDs and WINGUARD analysis. The fourth [155] is a direct comparison of carbon cost for different designs of Hostile Vehicle Mitigation, rather than low carbon material variants.

The final paper of interest [9] was the only one which included experimental testing of low-carbon alternative materials. This suggests that researchers are only just starting to enter the domain of experimental testing, modelling and comparisons of lower carbon materials against extreme loading criteria such as blast and impact resistance.

7. Current design and test standards

There are no international standards for blast and ballistic design, so a range of design and test standards readily available in Europe, the US

Table 1
Comparison of blast and ballistic/penetration research on various materials.

Material	Lower carbon	Blast	Z (m/kg ^{1/3})	Ballistic/Penetration	Penetrator type
UHPC Concrete [105] (Review Paper)	No	Unreinforced UHPC slabs showed less damage to both far-field blasts and contact explosions than the normal reinforced concrete	0–0.578	UHPC can resist projectile penetration at different impact energy depending on the fibre type, compressive and flexural strength	Various
Low carbon concrete [9] (Testing)	Yes - comparison using EPDs	N/A	N/A	No significant difference in ballistic perforation resistance when using low-carbon concrete	Ogival steel projectiles
Timber (General) [5,7,108–112]	Yes - timber products, no comparison	Failure modes, connections and design methods researched Close range detonation researching is lacking. Species specific design criteria are under-developed	Various CLT: 3.4–35; Light-frame: 5.9–33.7; GLULAM: 5.7–33.5; SIP: 5.9–15.6	N/A	N/A
Cross Laminated Timber	Yes - timber product, no comparison	CLT structures maintained load carrying ability against large scale blast testing [116–118]	9.37, 7.32, 5.095	Empirical models required calibration to fit CLT penetration test data [118]	0.50-cal FSP, 1/2" sphere
Enhanced CLT	Dependent on enhancement layer - no comparisons	N/A		Benefit/cost ratio was established [118,120–122]	0.50-cal FSP, 1/2" sphere, 7.62 mm (M80), 5.56 mm (M193), 5.56 mm (M855)
MDF	Yes - timber product, no comparison	Poor blast resistance and failure caused fragmentation [125]	0.928–1.1	Poncelet model was used to predict penetration [126]	9 mm @20 m, different velocities
Bamboo	Yes - timber product, no comparison	Cross Laminated Bamboo had superior protective properties against blast over Parallel Bamboo Strand Lumbar [128]	0–2.714	Poncelet and Robins-Euler model fitted penetration data [129]	9 mm @20 m, various velocities
Oriented Strand Board & Low-Density Fibre Board	Yes - timber product, no comparison	N/A	N/A	Poncelet model was used to predict penetration [129]	9 mm @20 m, various velocities
Masonry	No, no comparison	Comparison of different types of masonry wall [132]	0.55–2.32	Ballistic testing from 5.56 mm to 14.5 mm AP rounds	5.56–14.5 mm AP various velocities
Cladding/glazed facades (less sacrificial cladding)	No, no comparison	Large free-field blast against steel stud curtain wall [140]	Not specified	N/A	N/A

Table 2

Summary of research papers addressing both protection and carbon.

Source	Materials	Blast	Ballistic/ Fragmentation	Carbon	Conclusions/Recommendations
Protective design and sustainability - Synergies and conflicts [8]	General construction material low-embodied carbon options	General protective security considerations and description of impact to strength/physical properties for low-embodied carbon options. Theoretical study only without confirmatory testing.			Low carbon cladding and concrete blocks = Minimal impact on strength. Concrete and brick specification = Medium impact. Field testing of products recommended
Effectiveness of sustainable design for blast-resistant concrete structures [10]	Concrete (& low carbon concretes), masonry, metals, glazing	Comparison of blast enhanced design with non-protective and low carbon design	N/A	Carbon compared using LCAs - GWP values	Blast hardened buildings can have a reduced carbon footprint using low carbon material alternatives (Note: assumed low carbon materials performance the same as original)
Security, energy, embodied carbon: balancing envelope performance goals in glazing design [133]	Glazed façades – comparison of security glazing layouts	Comparison of products using: WINGARD analysis	N/A	Carbon comparison using: EPD Modules A1-A3, Comparison of R-values (thermal performance)	No single glazing layout excelled in thermal and security performance whilst minimising embodied carbon.
Hostile Vehicle Mitigation (HVM) carbon cost comparison [155]	HVM – RC wall and bollard comparison	N/A	N/A	Comparison of LCAs - Modules A1-A3 vs crash impact kinetic energy	Foundation depth and footprint effect carbon score (Low carbon material variants not discussed)
Sustainable shielding: Ballistic performance of low-carbon concrete [9]	Low carbon concrete (C75) Normal, –28 %, –58 % CO _{2e}	N/A	Experimental: 48 impact tests- Ogive nosed projectiles	Carbon measured using EPDs - Modules A1-A3	No significant difference in ballistic perforation resistance found between concrete variants

and Canada have been identified and discussed.

7.1. Design standards

The Eurocode standards only cover blast in terms of explosions in EN 1991–1-7: Eurocode 1 – Actions on Structures: Part 1–7: General Actions – Accidental actions [156]. It is predominantly based around internal gas, vapour or dust explosions and the requirement is that structures are designed to resist progressive collapse. There are no international standards covering blast or design with regards to terrorism [157] but there are some national standards, books and various design guides available in different countries. Some well-known examples include:

- Design and assessment of buildings subjected to blast loads, S850-12 [158].
- Blast protection of buildings: ASCE/SEI 59–11 [159].
- Unified Facilities Criteria (UFC) 3–340-02: Structures to resist the effects of accidental explosions [160].
- UFC 4–010-01: Department of Defense (DoD) Minimum Antiterrorism Standards for Buildings [161].
- Reference manual to mitigate potential terrorist attacks against buildings, FEMA-426/BIPS-06 [162].
- Blast effects on buildings [163].
- Aviation Security in Airport Development [164].
- Security in the design of stations [47].

The most relevant design standard for protection against terrorist threats is the UFC 4–010-01 Minimum Antiterrorism Standards for Buildings [161]. Although it is only applicable to US DoD buildings, other designers often use it. It contains stand-off distances for different building types including lightweight sheathing, brick veneer, concrete, masonry, etc, suggesting that some testing or modelling has been conducted, however that data is likely classified and held by the DoD.

Following the blast research conducted in the US [116], analysis guidance for CLT construction was written by the US Army Corps of Engineers (USACE) [165] to allow the use of SDOF dynamic analysis models. This was also based on the work conducted by the University of Ottawa who also proposed design methods for timber members including stud walls, glulam and CLT [112].

In terms of glazing, it is more common for designers to specify a glazing type which has been tested in accordance with standards discussed next in Para 7.2. The requirement of a standardised procedure for

the numerical modelling of glazing is discussed in the Larcher et al. paper [166]. He highlights the complexities of modelling glazing and suggests further work on model validation.

7.2. Test standards

In 2014, the European Reference Network for Critical Infrastructure Protection (ERNICIP) thematic group conducted a review report on testing standards [101] and a comparison of existing standards for testing blast-resistant glazing and windows [167]. The standards are predominantly European Standards (EN)/British Standards (BS), International Organization for Standardization (ISO) documents and US standards.

The current standards that have been discussed in previously cited studies are summarised in Table 3. The latest curtain walling standards written by the National Protective Security Authority (NPSA) addressed the issue that other standards only tested relatively small windows and not large panes and framing systems [168]. There are currently no standards for cladding systems, however the NPSA curtain walling standard could potentially be adapted to test cladding.

8. Conclusions

The building sector is coming under increasing pressure to reduce carbon in infrastructure by using efficient structural design and low carbon material alternatives. However, to date, research into the protective security of lower carbon construction materials subject to terrorist threats has been largely theoretical comparisons of products. Most papers assumed that the low carbon alternative performed in the same way as the material that it was replacing, with the exception being the comparison of low carbon concrete ballistic performance by Jacobsen et al. [9].

The experimental testing of ‘carbon sink’ materials has been predominantly mass timber products conducted in the US and Canada, but currently no research on native European timber has been found. An area of research could be to validate the proposed CLT design methods and modelling are applicable to timber species grown in Europe or similarly elsewhere in the world. Many researchers have also noted that there is a gap in research on timber subject to close-in blast and contact explosions. This is important as smaller charge sizes used in PBIEDs, or drone dropped IEDs can be taken much closer to buildings than VBIEDs which can be kept at greater stand-off distances using hostile vehicle

Table 3

Blast standard summary.

Standard name	Title	Material	Test (loading)	Region
BS EN 13123–1:2001 [169]	Explosion resistance - Requirements and classification - Part 1: Shock tube	Windows, doors and shutters	Blast - Shock tube (Large charge VBIED)	Europe
BS EN 13123–2:2004 [170]	Explosion resistance - Requirements and classification - Part 2: Range test	Windows, doors and shutters	Blast - Free field (Small charge PBIED)	Europe
BS EN 13124–1:2001 [171]	Explosion resistance - Test method - Part 1: Shock tube	Windows, doors and shutters	Blast - Shock tube (Large charge VBIED)	Europe
BS EN 13124–2:2004 [172]	Explosion resistance - Test method - Part 2: Range test	Windows, doors and shutters	Blast - Free field (Small charge PBIED)	Europe
BS EN 13541:2012 [173]	Glass in building - Security glazing - Testing and classification of resistance against explosion pressure	Glazing	Blast - Shock tube or similar (Large charge VBIED)	Europe
ISO 16933:2007[174]	Explosion - resistant security glazing - Test and classification for arena air-blast loading	Glazing	Blast - Free field (Small PBIED and large charge VBIED)	International
ISO 16934:2007[175]	Glass in building - Explosion-resistant security glazing - Test and classification by shock-tube loading	Glazing	Blast - Shock tube (Large charge VBIED)	International
ASTM F1642[176]	Standard test method for glazing and glazing systems subject to air-blast loadings	Glazing and glazing systems	Blast (Small PBIED and large charge VBIED)	United States
GSA-TS01–2003[177]	Standard test method for glazing and window systems subject to dynamic overpressure loadings	Glazing and window systems	Blast - Free field or Shock tube (Large charge VBIED)	United States
NPSA Test Standard [168]	Explosion resistance of windows and curtain walling. Part 1: Requirements and classification	Windows and curtain walling	Blast - Free field (Large charge VBIED)	United Kingdom
NPSA Test Standard [178]	Explosion resistance of windows and curtain walling. Part 2: Test method	Windows and curtain walling	Blast - Free field (Large charge VBIED)	United Kingdom

mitigation methods.

Most of the research on building cladding was protective sacrificial cladding and creating shock absorbing panels or connections. The most relevant research to model the PBIED threat was by Studziński et al. [44]. This research analysed the blast and fragmentation effects of a small PBIED on a standard sandwich panel. It showed how little protection the panels provided against the fragmentation, highlighting a significant risk to occupants of structures with lightweight cladding panels. There is a lack of research on the blast and fragmentation impact performance of cladding options for modular/offsite buildings where cost, carbon and aesthetics are the drivers for material choice.

This review shows there is an increasing demand and requirement for research into lower carbon construction materials and building techniques. Designers are likely to use carbon calculators and tools to select the lower carbon alternatives without considering protective performance unless it is specified by the client. The understanding of the blast and fragmentation impact performance of lower carbon materials is paramount to enable accurate risk assessments and security plans to ensure the safety of building occupants in the event of a close-by terrorist threat.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Laycock, Angela; Helliker, Aimee; Critchley, Richard; Hazael, Rachael

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