BLAST BEHAVIOUR OF FIBRE-REINFORCED POLYMER COMPOSITE STRUCTURES

Genevieve S. Langdon[1], Christopher J. von Klemperer[2], Sherlyn Gabriel[3] and Richard J. Curry[1]

[1] Department of Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK. Email: genevieve.langdon@sheffield.ac.uk, r.curry@sheffield.ac.uk; https://www.sheffield.ac.uk; Twitter: @genevieve_langd // @SheffieldBlast

[2] Department of Mechanical Engineering, University of Cape Town, Rondebosch 7700, Cape Town, South Africa. Email: chris.vonklemperer@uct.ac.za; www.uct.ac.za

[3] Blast Impact and Survivability Research Unit (BISRU), Department of Mechanical Engineering, University of Cape Town, Rondebosch 7700, Cape Town, South Africa. Email: sherlyn.gabriel@uct.ac.za; https://ebe.uct.ac.za/bisru/about-us/about-bisru

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ABSTRACT

Explosions wreak havoc and cause massive structural damage, whether they are caused by accidents, military action or terrorist activity. Fibre reinforced polymer (FRP) composites are susceptible to many types of damage from blast loading, based on their particular geometric, material and manufacturing characteristics (and, of course, the blast load itself). These composites are important for both defence and civil applications, particularly for structural applications seeking lightweight or tailorable material properties. This paper will discuss some of the “lessons learned” from research into the blast behaviour of FRPs subjected to air-blast loading. It will discuss the influence of fibre type, geometry, loading distribution on the failures observed in FRP laminate composites, including new work on transient behaviour of FRP structures, and comment on the value of computational simulations for advancing the state of the art.

1 INTRODUCTION

Structures comprising fibre reinforced polymer (FRP) composites have become increasingly common, as they offer advantages including high specific strength and stiffness, excellent thermal resistance and the ability to tailor their properties to a required application. Laminate (for example, aircraft) and sandwich (for example, marine vessels) structures are commonly found, especially in transportation.

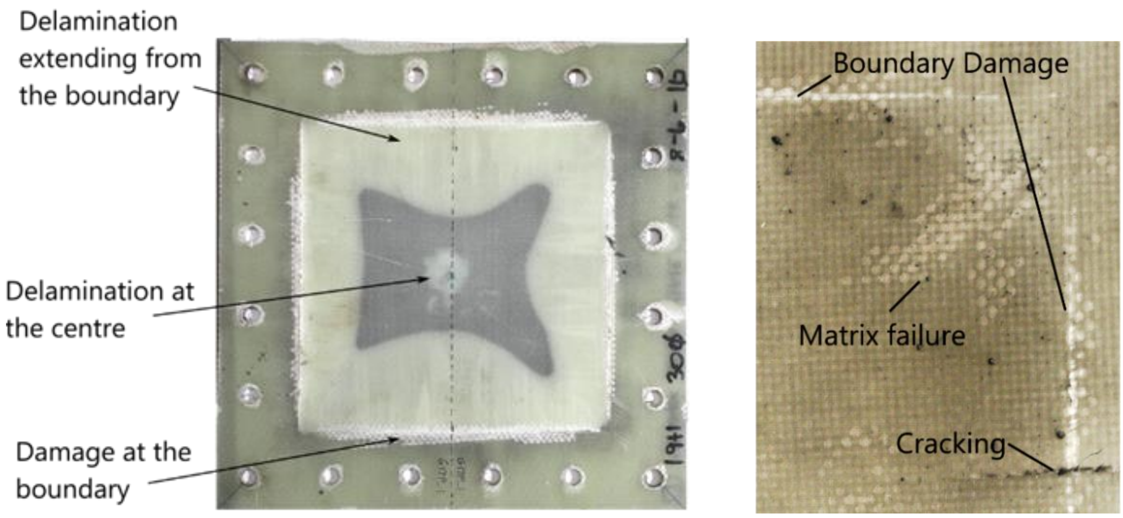
The changing nature of conflict and higher population densities in urban areas have increased the potential threat of explosions to cityscapes [1-2]. Examples such as the 2020 Beirut Port explosion and the bombings in Manchester (2017) and Sri Lanka (2019) remind us that accidents and terrorist activity also pose risks to infrastructure and human lives [3-4]. As transportation hubs are sometimes victims are these devastative events, the performance of FRPs under blast loading conditions is important for both civilian infrastructure and defense applications [5].

The behaviour of FRPs subjected to blast loading is influenced by a wide range of parameters, including the material properties of the FRP (affected by fibre, resin, weave, lay-up and manufacturing process choices), the structural configuration of the FRP (for example, boundary conditions and geometry), and the nature of the explosive event. There are numerous combinations for every factor, leading to a multiplicity of scenarios examined in the open literature.

This paper is an attempt to bring together some of the lessons learnt from research into the behavior of FRPs under blast loading conditions. It will discuss the influence of fibre type, geometry, and loading distribution on the failures observed in FRP laminate composites, including new work on transient behaviour of FRP structures.

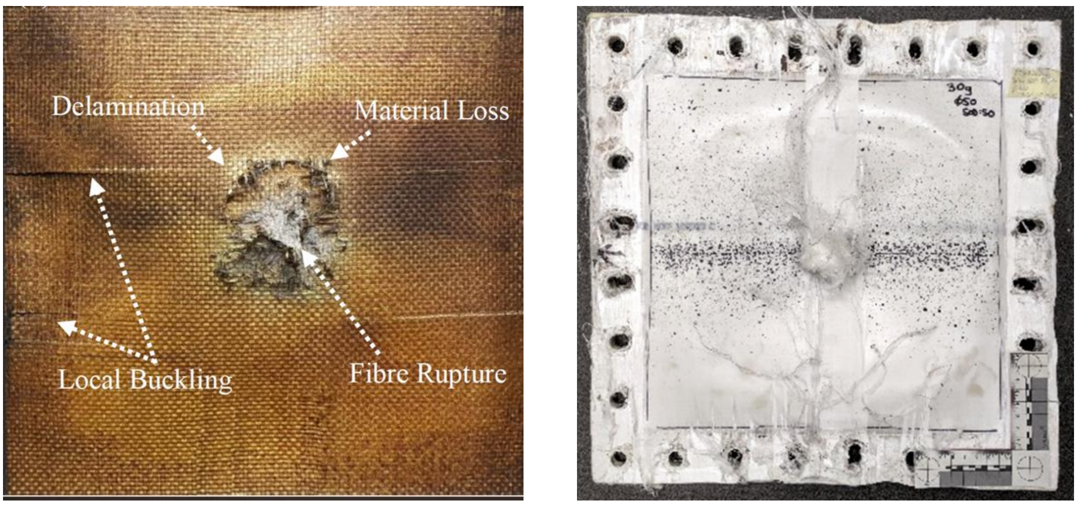
2 TYPICAL FAILURE MODES

Examples of failures observed after blast loading experiments are found in Figures 1 and 2. The typical failure modes exhibited by blast-loaded panels manufactured from FRPs include matrix failure, fibre pull-out, delamination (between layers of FRP), interfacial debonding (when the FRP is bonded to another material), fibre fracture/cracking and penetration/rupture. In-plane plastic displacement and reverse snap-through buckling can also be observed in certain cases (see Figure 2).



(a) (b)

Figure 1: Photographs of glass fibre epoxy panels showing typical failures (a) Delamination (b) close-up of clamped boundary showing matrix failure, cracking and boundary indentations



(a) (b)

Figure 2: Photographs of blast-tested panels (a) S-glass fibre reinforced phenolic resign panel exhibiting rupture and buckling after a localised load (b) Dyneema panel exhibiting rupture, fibre tearing and snap-through buckling after a localized load

3 TRANSIENT BEHAVIOUR

Most FRPs can tolerate very little inelastic deformation, due to their elastic-brittle nature [6-8]. The failure modes exhibited depend upon the spatial distribution of the blast load, the magnitude of the pressures and the thickness of the composite (among other factors discussed below). For example, relatively thin FRP laminates exhibit large transient (elastic) displacements, with peak negative displacements in the opposite direction to the blast [5], while thicker laminates are more prone to delamination and shear failures.

The significant elastic capacity of the FRP makes measuring and predicting the transient response of FRP panels subjected to blast loading conditions critical to their use in conditions where explosions are a realistic threat. Examples of transient displacement curves obtained from blast tests on glass fibre reinforced polymer laminate panels are evident in Figure 3. After large initial peak displacements, the displacement history resembles an underdamped vibration, with almost no permanent displacement (indicated by the dotted lines in Figure 3) visible in the panels after testing.

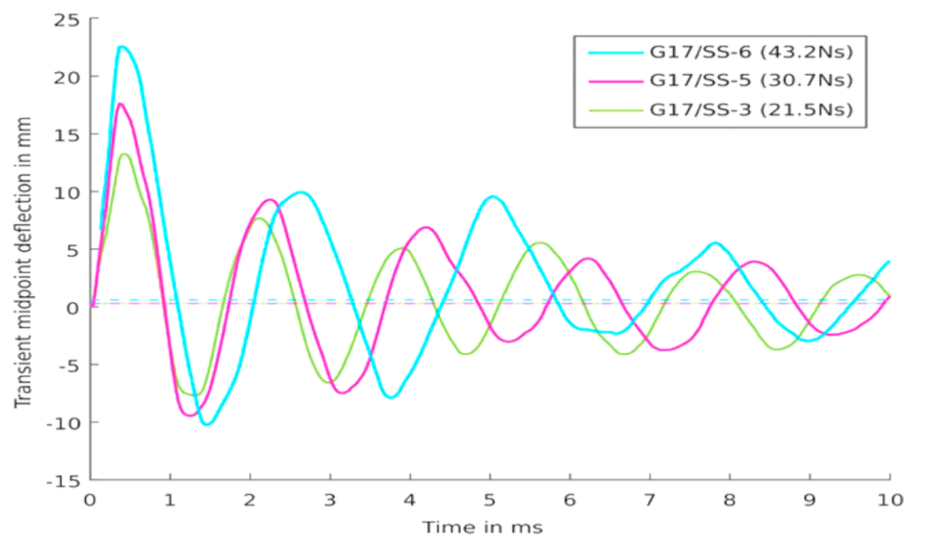


Figure 3: Graph of mid-point displacement versus time for blast-tested glass fibre epoxy panels subjected to different charge masses (and applied impulses)

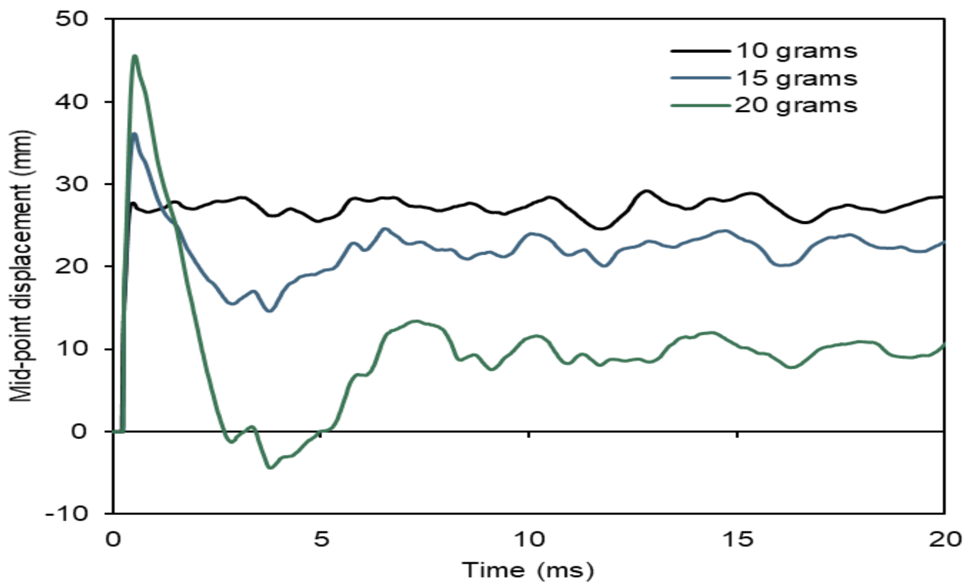


Figure 4: Graph of mid-point displacement versus time for S-glass fibre panels subjected to localized blast loading at different charge masses

Figure 4 shows the interesting case of panels with significant permanent displacement due to delamination and local buckling (see Figure 2a). Reverse snap-through buckling is also evident in the response, where increasing charge mass results in higher peak displacement in the loaded direction, but upon elastic rebound the permanent displacement decreases with increasing charge mass (Figure 4).

4 LESSONS LEARNED: INFLUENCE ON FRP STRUCTURAL RESPONSE TO BLAST

4.1 Blast load distribution

Results from blast loading experiments, where the spatial distribution of the blast pressure has been varied, show that FRP composite panels perform better when the load is uniformly distributed [9]. Uniformly distributed loads were tolerated without rupture, while localised loading near the plate centre caused cracking and panel rupture at lower charge masses. Similar sensitivity has been observed in metal plates, but the effect is exaggerated in FRP composites as they have lower shear resistance. Hence, FRP composites are likely to perform poorly (if panel rupture must be prevented) for contact charge detonations or in circumstances where the stand-off distance is small. Due to elasticity of the panels, rupture can be difficult to identify because the hole can close up after testing, see for example the ruptured Dyneema panel in figure 2b where it is difficult (if not impossible) to see the hole in the image.

4.2 Fibre and resin choice

Natural fibres are derived from sources including plants, animals and agricultural waste. They have often been limited to applications where structural rigidity and strength were of secondary importance, as their impact performance, ductility and tensile strengths tend to be much lower than synthetic commercial alternatives, so they are used less often in load-bearing applications. However, they offer the advantages of being more sustainable and are continually improving, so may be used more frequently in future [10-11]. This has implications for the blast resilience of future FRPs, as natural FRPs exhibit more cracking and brittle failures and less delamination than glass or carbon fibre systems [8, 12]. We recently blast-tested equivalent mass Flax, Jute and glass fibre epoxy panels. Some typical responses are shown in Figure 5; the natural FRP were inferior to glass FRPs, with far lower rupture thresholds and higher levels of fragmentation.

(a) (b) (c)

Figure 5: Photographs of blast-tested panels containing different fibre types (a) glass fibre, 25g PE4 (b) Flax fibre, 11g PE4 (c) Jute fibre, 1g PE4

Traditional synthetic fibres such as aramids, carbon and glass are in widespread use. Kevlar has excellent ballistic impact resistance due to friction, but performs poorly under blast conditions. The choice between carbon and glass is more controversial [6], with some studies favouring carbon fibre (for example, see [13]) while others concluding the opposite [14-15]. It may depend on the exact nature of the manufacturing process, resin choice and degree of compaction and studies seldom compare exactly equivalent systems (or have the same criteria for good performance). However, our own tests have shown that glass appears to offer superior blast resistance, probably due to its greater ductility. Failure tends to progress from matrix damage at low charge masses to delamination followed by cracking and/or fragmentation at high charge masses.

The focus on the fibre system is usually justified as the dominating factor in determining the strength and blast resistance of a FRP composite. However, the resin system influences bond strength and hence the likelihood of delamination failures in the panels. Gargano et al. [14] showed experimentally that the vinyl ester resins performed slightly better than equivalent polyester ones because delamination was initiated at higher impulses and was less widespread. The bond between the matrix and the fibre system was key to this improvement in blast resistance. Furthermore, we found that resin choice had a greater influence on the blast performance on weaker fibre systems (i.e. natural fibres) compared to those reinforced with glass fibre. However, the fibre system remains a more significant influence on blast performance overall, with resin systems being a secondary (but significant) consideration.

Newer fibre systems offer intriguing possibilities. For example, Dyneema, based on ultra-high molecular weight polyethylene has shown excellent ballistic impact properties [16] and good penetration resistance under blast loads [17-18].

4.3 Boundary conditions

Metal plates subjected to pressure loads are well known to be sensitive to boundary conditions, with fully-fixed plates developing membrane action that reduces its out of plane displacement. Simply supported plates undergo larger deformations during blast loading, while fully-fixed plates tend to fail due to rupture along the boundary. When the panels are manufactured from FRPs, more complex failure patterns are achieved, with delamination, matrix failure and rupture along a built-in boundary. This is also influence by the geometry of the joint, for example, if the panel is clamped then indentations of the FRP surface by the clamped edge can lead to premature rupture.

Practical FRP composite structures deployed in real life tend to have complex boundary conditions, meaning that the joints cannot be idealised as either simply supported or fully built-in, making closed form predictions of their behaviour difficult, even when failure is not considered.

4.4 Geometry: laminate or sandwich, woven or uni-directional?

Sandwich structures, with FRP laminate face sheets and a lightweight core increase structural rigidity by increasing the second moment of area due to the core. Thus, in simple quasi-static bending, the sandwich is an efficient structural form. However, the overall strength of the sandwich is sometimes limited by the strength of core, and the thin face sheets may result in a weak sandwich panel, especially in impact and blast applications. Results from laboratory scale experiments suggest that sandwich constructions are inferior, on an equivalent mass basis, to FRP laminate panels under blast loading conditions [9]. The thin FRP face sheet layers rupture, allowing the explosive products to damage the relatively weak inner core. Unequal face sheet thicknesses, with the thicker sheet on the side facing the explosion could partially address this (if the explosion threat is known to be from only one side), but it is questionable whether this would be entirely beneficial [19].

Uni-directional FRPs are used when there is a known directionality to the loading, for example, in slender components. For panel structures where the blast load would be applied perpendicular to the face, the loading within the panel is similar in each direction if the boundary conditions are the same along each edge. In this case, for symmetrical structures, woven FRPs appear to offer better damage tolerance than unidirectional or cross ply laminates to blast loading [6], with fewer delamination failures and a higher rupture threshold. This is attributed to their superior toughness.

4.5 Sustainability

The global heating crisis is encouraging industry and society to seek out “eco-friendly” sustainable alternatives to synthetic FRPs, with the goal of lowering environmental impact, reducing fossil fuel consumption and dependence on oil, and improving human health [10-11, 20]. There are two common approaches relevant to FRPs: (a) using resins generated from renewable resources such as plant oils [8-9, 19] and (b) to using natural fibre reinforcements.

Natural fibres, such as jute and flax, have been discussed above and are currently unsuitable for structures where blast resilience is an importance function. However, replacing marine grade synthetic epoxy resin with a version containing bio-based raw materials has been shown to make little difference to the overall blast resistance of a glass fibre epoxy composite panel [8]. The Super Sap (bio) resin showed a small degradation in the blast performance of the panels when compared to a traditional Epoxy (Prime 20/27), but not significantly so. We also showed that these results are consistent with quasi-static flexural and Mode I interlaminar toughness test results on the same two composite systems. This is a small but potentially significant step to improving the sustainability of FRP composites in the future, taking advantage of the fact panel response is dominated by the fibre choice rather than the resin system. More work is needed in this area.

5 THE RELATIONSHIPS BETWEEN SIMULATION AND EXPERIMENTS

For many years, the state-of-the-art of computational modelling has far exceeded our experimental capability in explosion testing of FRP composites. I am pleased to say that recent experimental developments such as ultra-high speed stereo imaging, digital image correlation and virtual fields methods are being adapted or have already been used in explosion testing to help close the divide. The ability to capture transient response measurements for materials with significant elastic capacity creates a new opportunity for closer collaboration, something seen in other parts of the composites world but not used in blast resistances with any confidence.

However, numerical modelling of FRP composite behaviour under blast loading conditions still faces significant challenges [7]. Firstly, it is critical that simulations use the correct degree of fidelity that offers a cost-effective but accurate solution. Incorporating failure and response modes, proper interface formulations, and correctly modelling contact are all important – but these can become challenging when the geometry of the FRP structure is curved or the boundary conditions cannot be idealised. Secondly, materials formulations and proper characterisation of material parameters (covering rate dependent plastic hardening, temperature-dependent behaviour and damage) is difficult, especially at high rates of loading. Much of this conference concerns this topic. Thirdly, simulation of blast loading itself is important for FRPs as they exhibit great sensitivity to the spatial distribution of the loading.

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