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Blast response of curved carbon/epoxy composite panels: Experimental study and finite-element analysis

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Abstract. Experimental and numerical studies were conducted to understand the effect of plate curvature on blast response of carbon/epoxy composite panels. A shock-tube system was utilized to impart controlled shock loading to quasi-isotropic composite panels with differing range of radii of curvatures. A 3D Digital Image Correlation (DIC) technique coupled with high-speed photography was used to obtain out-of-plane deflection and velocity, as well as in-plane strain on the back face of the panels. Macroscopic post-mortem analysis was performed to compare yielding and deformation in these panels. A dynamic computational simulation that integrates fluid-structure interaction was conducted to evaluate the panel response in general purpose finite-element software ABAQUS/Explicit. The obtained numerical results were compared to the experimental data and showed a good correlation.

1. Introduction

The ever expanding applications of composite materials expose them to severe loading and environmental conditions, posing new challenges to the designer. Accidental explosions can cause extreme loading on composites-made structures with both flat and curved geometries. Thus, it is important to understand the effect of curvature of the structure exposed to blast, helping manufacture new structures with better blast resistance. Carbon/epoxy composites, in particular, carbon fibre reinforced polymer (CFRPs) composites are widely used in protective structural applications due to their superior mechanical and physical properties such as durability, high strength-to-weight-ratio, and high stiffness.

There are various studies in the literature related to blast loading of structures [1-6]; only the most relevant studies are mentioned here. Rajendran and Lee [1] conducted a detailed review of the phenomena of air and underwater explosions and their effects on plane plates. They found that of the important shock wave parameters significant for an air blast, were the peak overpressure and the impulse. For an underwater explosion, the peak overpressure, time constant, free-field impulse and energy were recognised to be the four vital parameters for the damage process. Tekalur *et al.* [2] studied the effect of various fibres on the blast response of composite panels. They used two different

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fibre materials: E-glass and carbon, and exposed those composite panels to high strain rates and quasi-static loading. In dynamic loading, the carbon-fibre composites showed catastrophic failure, whereas, E-glass fibre composites exhibited progressive damage behaviour. Arora *et al.* [3] analysed a blast response of glass-fibre sandwich composite panels, fixed at their edges and exposed to real explosives at varying stand-off distances. They used high-speed photography and digital image correlation analysis to characterise the blast response of these panels. Damage was observed to be initiated in the form of a crack in the front skin, giving rise to localised delamination around the cracked region and shear cracking in the core. Interfacial failure between the front skin and the core was also observed. This study also involved a finite-element study to verify experimental observations such as transient boundary conditions. Kumar *et al.* [4] reported the effect of transient boundary conditions in their study where the dynamic response of curved CFRP panels was analysed using high-speed photography, a 3D-DIC technique followed by a post-mortem analysis. They found that curvature had a profound effect on the blast response of the CFRP panels. Ochola *et al.* [5] reported on strain-rate sensitivity of both carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP) composites by testing a single laminate configuration with a strain-rate varying from $10^{-3}\,s^{-1}$ to $450s^{-1}$. The obtained results showed that dynamic material strength for GFRP increased with the increasing strain rate and the strain to failure for both CFRP and GFRP decreased with the increasing strain rate. LeBlanc and Shukla [6] studied an underwater shock loading response of E-glass/vinyl ester curved composite panels. They used a 3D DIC system to measure the transient response during the experiments. They compared experimental results to those obtained in the simulation with the commercial LS-Dyna finite-element code. This comparison showed a high level of correlation based on the Russell error measurement.

In this paper, dynamic response of quasi-isotropic CFRP composite panels with three different radii of curvature exposed to blast loading was studied. A shock tube was employed to impart blast load on these panels to understand the effect of their curvature on the blast mitigation. A real-time analysis was carried out using 3D DIC technique to measure the out-of-plane deflection on the back face of these panels. A finite-element (FE) model of blast response of these panels was developed in ABAQUS 6.11 and was validated using the experimental findings.

2. Experimental details

2.1. Material and specimen

Panels with three different radii of curvature (Fig. 1) were utilized in the experiments: infinite (i.e. flat; Panel A), 304.8 mm (Panel B) and 111.8 mm (Panel C). The specimens were fabricated using ready-to-cure sheets of unidirectional AS4/3501-6 prepreg (fibre volume fraction of 60%) manufactured by the Hercules Corporation of Magna, Utah. The stacking sequence of the composite laminate was selected to have quasi-isotropic properties ($[0^0/90^0/+45^0/-45^0]_{4s}$). The specimens were 203 mm $\times$ 203 mm $\times$ 2 mm in size, made out of 32 layers of carbon fibres. For the curved panels, arc lengths of curved edges correspond to the plate length, i.e. 203 mm. The material properties of this laminate are listed in Table 1.

2.2. Experimental setup

Experimentally, blast loading onto a structure can be imparted using two different methods: using explosives or shock tubes. The use of real explosives is dangerous and produces spherical wave fronts and pressure signatures, which are spatially complex and difficult to measure. On the contrary, a shock tube offers the advantage of planar wave fronts so that the wave parameters can be reasonably easily controlled. Furthermore, the loading conditions are easy to replicate. Therefore, the shock tube was the preferred choice to apply blast loading in our experiments. The shock tube apparatus used in this study and location of pressure transducers is shown in Fig. 2a and b respectively. A complete description of the shock tube and its calibration can be found in [7]. The specimens were clamped on all their four edges.

Table 1. Mechanical properties of AS4/3501-6 UD composite laminate [8]

Elastic modulus	$E_{xx} = 147$ GPa, $E_{yy} = 11$ GPa, $E_{xy} = 5$ GPa
Tensile strength in fiber direction	2004 MPa
Compressive strength in fiber direction	1197 MPa
Tensile strength in transverse direction	53 MPa
Compressive strength in transverse direction	200 MPa
Shear strength	137 MPa

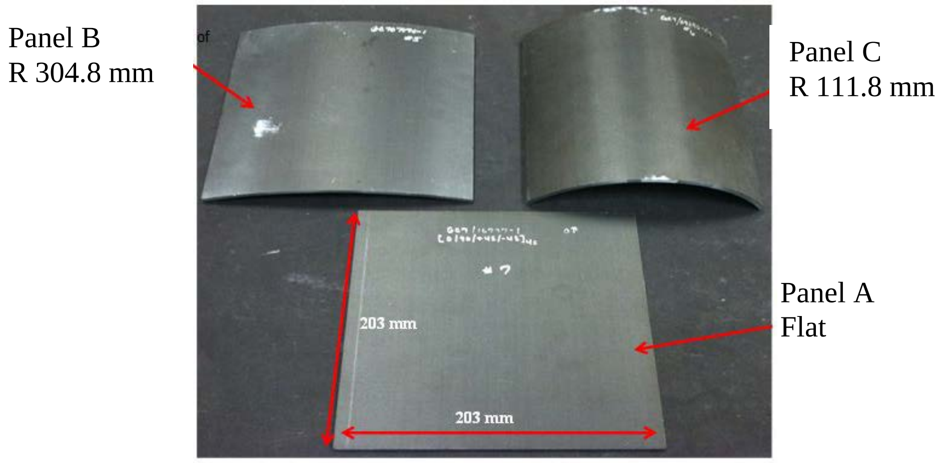
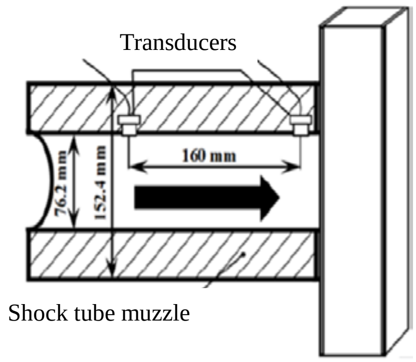


Figure 1. Specimens used in blast study

(a)



(b)

Figure 2 a. Shock tube appartus used in blast study **b.** Shock tube nozzle and location of transducers

The shock tube consisted of a long rigid cylinder divided into a high-pressure driver section and a low pressure driven section separated by a diaphragm. By pressurizing the driver section, a pressure difference was created across the diaphragm. When this pressure differential reached a critical value, the diaphragm ruptured. The subsequent rapid release of gas created a shock wave which travelled down the shock tube to impart shock loading on the specimen at the muzzle end.

The shock tube utilized in the present study had an overall length of 8 m, consisting of driver, driven, converging, and muzzle sections. The diameter of the driver and driven section was 0.15 m. The final muzzle diameter was 0.07 m. Two pressure transducers (Fig. 2b), mounted at the end of the muzzle section measured the incident shock pressure and the reflected shock pressure during the experiment. The pressure transducers were oriented along the horizontal line of symmetry of the specimen. The specimens were clamped on all four edges. Appropriate fixtures were designed and manufactured to hold the specimens. The specimens were blast loaded at three different pressures varying from 3 MPa to 8 MPa. The experiments were repeated three times under same conditions. The pressure profiles obtained at the transducer location closer to the specimen A and B are shown (Fig. 3).

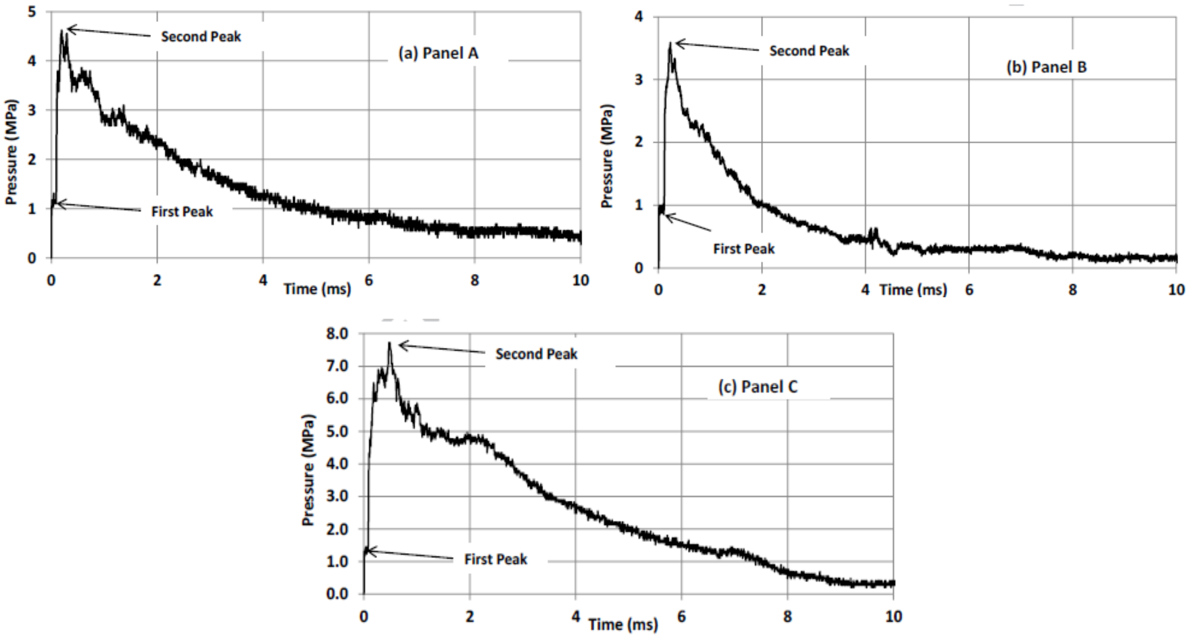


Figure 3. Pressure profiles for studied carbon/epoxy composite panels [9]

2.3. Digital image correlation

Digital Image Correlation (DIC) technique is a non-contact optical method for analysing full-field shape and deformation. Here, DIC technique was employed to measure in-plane strains and out-of-plane deflection at the centre of the back face of all studied specimens. Two high speed digital cameras, Photron SA1s, were positioned behind the shock tube apparatus to capture the real-time deformation and displacement of the panel. The high speed cameras were set to capture synchronized images at 20,000 frames per second (inter-frame time of 50 μs). During the blast loading event, as the panel responds, the cameras record the speckles on the painted back face. The high speed images were analysed using DIC software to correlate the images from the two cameras and generate real-time in-plane strain and out-of-plane deflection/ velocity histories. The further details regarding DIC analysis can be found in [9].

3. Finite-element model

Blast experiments are generally laborious, difficult to repeat under the same conditions and demand plethora of safety precautions. In this regard, a validated FE model can prove to be a valuable tool to estimate the blast performance of underlying materials. Here, a dynamic FE model imitating the mechanical response of curved CFRP panels exposed to the blast was developed in commercial software ABAQUS/EXPLICIT [10]. The details about material modelling, fluid-structure interaction, mesh and boundary conditions are discussed in the next sections.

3.1. Material model

A user-defined 3D damage model (VUMAT) with solid elements was developed and implemented into the finite-element code ABAQUS/EXPLICIT to predict the character and extent of damage through the laminate thickness when exposed to the blast load. Interface cohesive elements were inserted between the plies of the modelled laminate to simulate delamination. The general contact algorithm in ABAQUS/EXPLICIT was used to simulate contact conditions between the shock wave and the composite laminate, and between the layers by defining appropriate contact-pair properties. An element deletion approach [13] was used to represent the laminate degradation based on initiation and evolution of damage in the meshed CFRP elements. The results of numerical simulations were evaluated using comparison with the experimental data.

3.2. Element deletion

The blast load induces large deformation in the CFRP laminate. During the FE modelling, these excessively deformed elements can cause unreasonable increase in the simulation time or premature-termination of the analysis. Hence these elements were removed from the analysis as soon as they satisfied a stress based damage criteria based on the work of Hashin [11] and Puck [12] implemented through VUMAT in Abaqus/explicit. The details can be found in our previous work [13].

3.3. Fluid-structure coupling and shock wave loading

The fluid model consisted of the air inside and outside the shock tube as well as the air surrounding the plate as shown in Fig. 8. The air outside the tube was modelled in an Eulerian domain as a cuboid with a domain size of 400 mm × 400 mm in X-Y plane and 2000 mm along the tube axis. The model had 100 mm of air along the tube axis behind the plate to ensure that the plate remained in air during deformation caused by shock wave loading. The air inside the tube was also modelled in the Eulerian domain with the element size of 3 mm. All the fluid elements were meshed with the Eulerian eight-node, one-integration point hexahedral elements EC3D8R. The acoustic structural coupling between the fluid-mesh acoustic pressure and the CFRP panel structural displacements was accomplished with a surface-based tie constraint at their common surface. The master-slave type of contact was established between the annular surface of the shock tube in contact with the CFRP panel and the top surface of the panel. The surface of the external fluid at the interface was designated as the master surface. This pairing created an internal coupling of the acoustic pressure and structural displacements at 14 the surface nodes of CFRP panel (slave) and coupled the acoustic pressure exerted through the shock tube to the fluid mesh acoustic pressure at the interface. The incident wavefront was assumed to be planar. For a planar wave, which does not decay, two reference points, namely, the standoff point and the source point, were defined, the relative positions of which were used to determine the travel direction of the incident shock wave. The pressure history at the standoff point was used to drive the incident wave. The ‘amplitude’ definition [9] was used specifying the top surface of the CFRP panel to which the incident-wave loading was applied using a pressure-history curve. The entire analysis was divided into two steps pertaining to the wave incidence and reflection where appropriate average shock wave velocity and density was used. Linear fluid mechanics was used. The observed total pressure in the fluid was decomposed into two components: the incident wave itself, which was known, and the wave field excited in the fluid due to reflections at the fluid boundaries and interactions with the solid. The setup of the FE model of the shock loading in the CFRP panel with coupled fluid-structure domain is shown in Fig. 4.

The entire model consisted of about 6.5 million meshed elements. A mesh convergence study was carried out for both fluid and structure domains. The mesh adopted in this FE model represented the refinement level achieved after our mesh-convergence study. The computational time required was approximately 42 hours on 12 Intel Xeon processors (64 bit) using the high performance computing Hydra cluster, available at Loughborough University, UK.

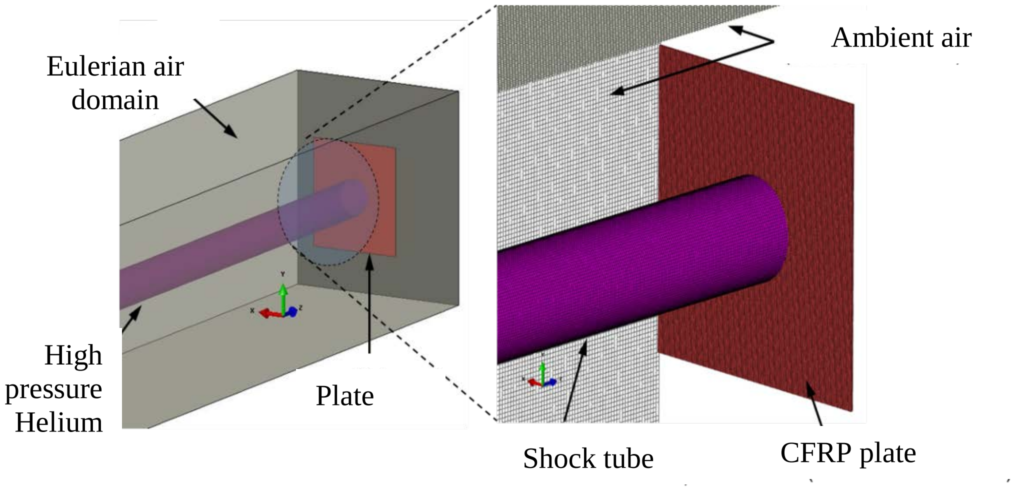


Figure 4. Fluid-structure coupling in FE model

4. Results and discussions

The results of FE model are discussed below. The FE analysis was focussed to determine the out-of plane deflection response of CFRP plates and their energy absorption capacity under blast loading. The local damage at the impacted location was also studied but is not discussed here for the brevity of space.

4.1. Modes of deflection in CFRP panels

From the FE analysis, it was observed that the deflection in the studied CFRP panels was the combined output of two deflection modes, namely, the indentation mode and the flexural mode. It was seen that all the panels started deflecting in the indentation mode. In flat panel (Panel A), the global flexural mode quickly took over and dominated the deflection process. This was also evidenced by the continuous nature of displacement contour that showed monotonic increase in deflection from the edge to the centre of the specimen after t = 200 μs. Deflection of Panel B continued in the indentation mode till about 400 μs after which it snapped into the global flexural deflection mode. These deflection contours showed continuous increase in deflection from the edge to the centre of panel and 16 the transition from elliptical contours back to the circular shape.

In Panel C, the deflection remained in the indentation mode since only the central loading region was affected. In addition to the out-of-plane deflection, velocities and in-plane strain data were also extracted from FE model at the centre point of the back of the studied CFRP panels. Fig. 4 shows that the deflection rate (35 m/s), for the initial 200 μs, was almost same in all the three panels, though Panels A and B attained a higher deflection as compared to Panel C. This showed that the Panel C was stiffer than the other two panels since it sustained higher pressure and had a lower deflection. Panel A and B had similar deflection trend till 1000 μs. At this time, damage was initiated in Panel B which explains the rapid rise in its deflection. The in-plane strain e_{xx} as well as e_{yy} were nearly same for studied panels at the centre point. The lower in-plane strain and out-of-plane deflection in Panel C showed that this panel had higher flexural rigidity. Panel B had higher in-plane shear strain which explained the catastrophic failure in the panel.

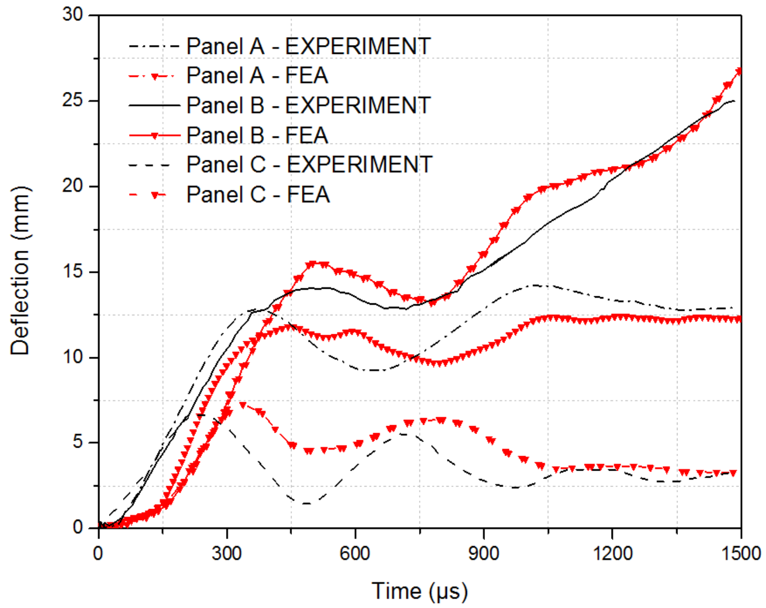


Figure 4. Out-of-plane deflection in CFRP plate: experimental and FE comparison

4.2. Damage dissipation during blast

The incident and remaining energies associated with the shock loading intensities were analysed with the FE model. The damage dissipation energy was obtained numerically. Panel C was subjected to the highest intensity of shock loading and so the incident energy was the highest for this panel, though the damage dissipation energy was the lowest, while it was highest for the Panel B, the Panel A showed intermediate response. The magnitude of the energy dissipated towards damage for studied panels is listed in Table 2.

Table 2. FE results showing magnitude damage dissipation energy for studied CFRP panels

Specimen	Energy dissipated towards damage in specimens (kJ)
Specimen A (Flat)	50
Specimen B (R = 305 mm)	62
Specimen C (R = 112 mm)	27

5. Conclusions

The effect of curvature of CFRP panel on their blast mitigation property was studied using a shock tube. The blast mitigation performance of these panels was characterised in terms of their out-of-plane deflection, in-plain stress. The FE model of blast loading on curved CFRP panels was developed and validated using 3D DIC data coupled with high-speed photography. This model accurately accounted for the interaction between the curved panels, shock tube and the surrounding air. The strain-rate sensitive material model enabled to capture the appropriate mechanical response of these panels under high load rates. The following conclusions were made:

1. There were two preliminary deformation modes with which the studied panels deflected under shock loading: flexural mode and indentation mode. Flexural deformation decreased and indentation deformation increased as the radius of curvature was reduced. Indention mode was found to be more severe since it led to the damage initiation in the panels.
2. The experimental analysis (macroscopic post-mortem analysis and DIC deflection, velocity, and in-plane strain analysis) showed that Panel C was capable of sustaining the highest threshold

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failure load, though further optimisation study using validated FE model revealed the fact that Panel D (76 mm radius of curvature) performed better than Panel C reflecting about 90% of the incident shock energy.

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