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Damage and deformation in composite sandwich panels exposed to multiple and single explosive blasts

H. Arora*[a], P. Del Linz[b], J.P. Dear[c]

[a] Department of Bioengineering, Imperial College London, SW7 2AZ, UK
[b] School of Civil and Environmental Engineering, Nanyang Technological University, 639798, Singapore
[c] Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK

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ABSTRACT

The blast resistance of glass-fibre reinforced polymer (GFRP) sandwich structures has been investigated for increasing shock intensity and for multiple blast exposures. In this study, sandwich panels of 1.6 m x 1.3 m were subjected to 30 kg charges of C4 explosive at stand-off distances from 8 m to 16 m. These targets formed part of two studies presented here: one, to observe the loading of the same geometry of target to an increasing shock intensity; and the second, to observe the response of one target to multiple blast impacts. Experimental data provides detailed data for sandwich panel response, which are often used in civil and military structures, where air-blast loading represents a serious threat. High-speed photography, with digital image correlation (DIC), and laser gauge systems were employed to monitor the deformation of these structures during the blasts. The experimental data provides for the development of analytical and computational models. Initial analysis of the blast experiments are presented alongside a finite element model to establish trends in deformation behaviour. Details of failure mechanisms and the conditions for the onset of failure are also discussed.

1. Introduction

Recent advances in composite manufacturing have occurred predominantly in the aerospace, marine, automotive and related industries. Whereas, formerly, naval vessels were constructed from steel, composites provide a significant weight reduction and increase in stealth characteristics whilst maintaining high strength properties. In a military environment, composite materials can be subjected to increasingly demanding and varied conditions during service. Specifically, blast loading represents the most extreme threat to a structure. Materials testing under blast is now becoming more common in the literature due to the unfortunate rise in use of explosive devices in civilian environments as well as in direct military combat. Materials evaluated in the open literature range from fibre reinforced composites [1,2] to concrete [3] to glazing structures [4,5] amongst others [6–8]. Larger scale blast experimentation open in the public domain tends to be limited to concrete and retro-fitting concrete for increased blast tolerance [9–11].

Numerous investigations have been performed into the dynamic deformation of plates due to explosive blast loading [12–15] with many summarised in [16]. This area remains of key study given the large number of variables at play in blast scenarios that need to be characterised. Menkes and Opat [15] classified the failure modes of structures under impulse loading, from large inelastic deformation to tearing and shear failure at the supports. Neuberger observed the effects of air-blast [17] and buried charges [18] on clamped circular plates and the validity of scaled testing for the comparison of similar blast events using different explosive mass and stand-off distance. This work was extended with the use of image correlation methods to quantify panel distortion during buried [19] and open-air blasts [20]. Nurick et al. [21] further investigated the failures described by Menkes and Opat. Of particular interest to these researchers were the effects of the boundary conditions for the purpose of predicting tearing in steel plates [22]. Many studies have extended this research to the analysis of composite plates under blast loading [23–27].

Given the high costs and space requirements for explosive testing, shock tubes offer a cost-efficient and effective alternative for scaled experiments. Shock tubes of various shapes and sizes are often used to replicate explosive effects [28] on various materials from structural [29,30] to even biological materials [31]. Shock tubes enable a shock load to be produced in a controlled manner. Additionally the experiment can focus solely on the shock wave incident rather than other factors inherent in blast situation, e.g. burning. A shock tube consists of a long cylinder, divided into a high-pressure driver section and a low pressure driven section, which are separated by a diaphragm. To create a shock wave, the driver section is

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[*] Corresponding author.
E-mail address: hari.arora04@imperial.ac.uk (H. Arora).

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pressurised until the pressure difference across the diaphragm causes it to rupture. This rapid release of gas creates a shock wave, which travels down the tube to the test specimen [32]. Studies into the shock loading of composite materials and sandwich panels have been continually developed to great effect [32–37]. Parameters such as the distribution of blast energy during impact [36] and performance of composites subjected to sequential impact and blast loading [35] have been investigated.

The research presented here builds on previous findings focussing on full-scale air-blast experimentation conducted on GFRP sandwich composite panels [20,38,39]. Although sandwich structures remain a significant area of research [40,41], there is a lack of large-scale experimental data, publicly available in this field, for full-scale explosive testing on composite materials. Therefore, large scale data and current, modern approaches applied to data acquisition are an important contribution to this field of research. The experiments were carried out at a specialised test facility, located at RAF Spadeadam, Cumbria,UK. A total of five explosive charges each 30 kg C4 (38.4 kg TNT equivalent) were tested over a range of stand-off distances (8–16 m) against three targets (with repeat blasting of one of the samples). The aim of these air-blast experiments was to capture displacement-time histories of the sandwich composite panels and understand how damage develops during a given blast event. Two methods were employed to obtain these displacement-time histories. High-speed 3D digital image correlation (DIC) was employed to capture full-field displacement plots of the rear surface of the targets. Point displacement measurements were taken during some experiments using a laser gauge arrangement to, firstly, verify the results obtained from the DIC analysis for point measurements, as well as being used as a stand-alone system. The experiments represent the face sheets of a ship's hull present above the waterline, which could be subject to surface or open-air blasts. These experiments provide full-scale data to validate analytical and numerical models of such structures.

1.1. Materials

There was one sample configuration tested, a sandwich composite panel, shown schematically in Fig. 1. Sandwich composite materials were provided by SP Gurit manufactured by P.E. Composites.

All three panels had the same GFRP skins constructed using 2 plies of 0°/90°/± 45° E-glass quadriaxial skins (code: QE1200) on a 40 mm thick styrene acronitrile (SAN) foam core (code: P800). The sandwich constructions were then infused with an epoxy resin (Ampreg 22). A summary of the quasistatic properties of the skin and core materials are given in Table 1. The exposed target area for the air-blast experiments was 1.6 m × 1.3 m. These large panels were designed to represent full-scale face-panels of comparable scale to real naval structures. These targets were bonded into steel frames prior to testing, ready to be secured to the test cubicle (see Section 1.2).

The test samples were designed to withstand a peak (reflected) shock pressure, P^{max}, of 200 kPa without catastrophic failure. Methods used to design these structures involved both analytical and computational methods, as previously outlined in [20,39]. A finite element model was generated in ABAQUS/Explicit 6.10. This model comprised of a continuum shell element model sectioned into the various layers of the sandwich composite (i.e. skin and core) with the material properties (density and Young's modulus) as given in Table 1. This was then subject to a triangular pressure pulse, with zero rise-time to $P_{max} =$ 200 kPa, uniformly distributed over the entire plate with a linear decay time of 5 ms. It was shown that using a simple elastic material model and reducing the load conditions to a uniform pressure pulse with ideal fully clamped boundary conditions that the plates (configuration as illustrated in Fig. 3) would produce a peak central displacement in the region of 45–65 mm for targets with a range of core thicknesses of 30–50 mm (producing strains in the GFRP below their expected failure strains ~1.5%).

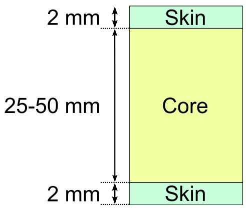

Fig. 1. Schematic diagram of the sample panel design and dimensions.

Table 1
Material properties of the sandwich panel constituent elements [42].

Material property	QE1200	P800
Density (kg/m^3)	1750	155
Tensile modulus (GPa)	17	0.14
Compressive modulus (GPa)	–	0.13
Tensile strength (MPa)	260	2.85
Compressive strength (MPa)	200	2.8
Shear modulus (MPa)	6500	61
Tensile failure strain (%)	1.5	2.2

Based on this model a series of targets were manufactured and various blast scenarios were tested. The charge weight (W) was chosen to simulate moderate to large blast loads in close proximity to naval vessels above the waterline. Here, 30 kg charges of C4 (38.4 kg TNT equivalent) were used for the testing on samples over a range of stand-off distances (R), 8–16 m. The experiments conducted for a 30 kg C4 charge at a 14 m stand-off distance, i.e. an equivalent P^{max} of ~ 200 kPa, were designed in line with the analytical and numerical models. This experiment was used as a reference for a transition from elastic response to visible damage initiation and failure of the targets. Whereas the tests conducted with a 30 kg C4 charge at 8 m was designed with the intent to cause significant visible damage. Explicit damage modelling was beyond the scope of this study but the elastic model showed good correlation with basic deformation characteristics within this test frame for the range of stand-off distances explored here [20].

1.2. Air-blast test design

A test arrangement is given in Fig. 2 featuring all external instrumentation that was used during all air-blast tests. In each case the

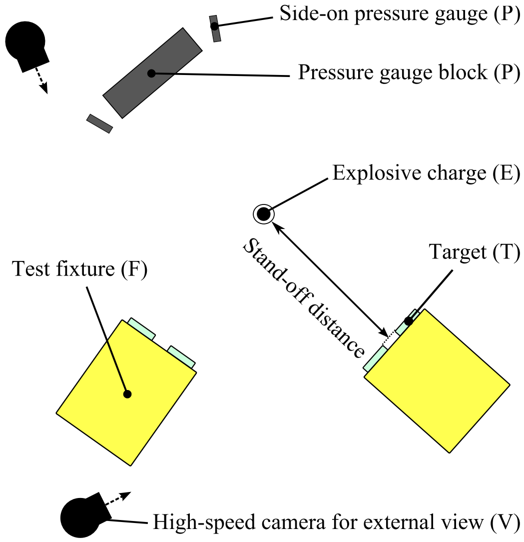

Fig. 2. Blast configurations showing a schematic diagram of the test set-up.