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Composite Sandwich and Laminate Materials against Blast Loads

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Abstract

Large-scale blast testing has proved that full-field displacement and in-plane strain data can be reliably obtained for composite sandwich panels secured around their edge during explosive events. Detailed deformation maps were obtained using digital image correlation (DIC) under extreme shock loading conditions and have been validated by point measurements using a laser gauge system. The DIC technique is now being adopted by other research groups for similar blast experiments. Important in this researchwas the support arrangement for the composite sandwich panels and how it influenced, as a design consideration, the mode and location of failure. Several studies were conducted which showed a number of real scenarios for naval structures, such as multiple blast impacts as well as a number of different blast impacts on a number of different constructions. Each of these studies has shown that the modes of failure are front-face dominated compared to the underwater blasts, which involved both front- and back-face failures being observed.

1. Introduction

The primary aim of this study was to improve the understanding behind the mechanical performance of traditional fibre reinforced polymer composite sandwich and laminatematerials against blast loads and evaluate them with respect to their suitability for futuremarine applications. The main deliverable of this study was full-scale blast data referringto the deformation processes that occur during an air and underwater blast. A seriesof 16 air and underwater blasts were conducted. There were 13 air-blast targets (12composite sandwich constructions). The sandwich panel targets were 1.3 m × 1.6 m in area of variable skin/core configurations and were subject to charges 38.4-100 kg TNT equivalent at stand-off distances of 8-16 m. There were 18 underwater-blast targets tested.Four sandwich panel targets 0.4 m × 0.5 m area of variable skin/core configurations and14 tubular laminates 44 mm diameter, 0.3 m long with laminate thickness of 2 mm weresubject to charges 0.64-1.28 kg TNT equivalent at stand-off distances of 1-2 m. All testswere conducted at RAF Spade dam. The extent and nature of damage incurred was identified for each target. A number of support and blast parameters were investigatedsuch as: the influence of support uid on target response to underwater blast; and the effect of an increased degree of freedom around certain edges of a target during airblast tests. A transition in behavior was identified between air- and underwater-blastconditions, particularly in the sandwich material where damage mechanisms changedfrom shear cracking (during air blasts) to through-thickness crushing (during underwaterblasts).

A series of finite element simulations were used as both a predictive and reflectivetool for evaluating the response of the targets to a given blast. The complexity of blast load conditions is significant and various aspects are being investigated every day with the aim of improving computational simulations and hence the design process for marine structures. This investigation highlighted the mechanisms of failure observed within commercially available naval materials under blast conditions with full-scale explosive experiments (reinforced with numerical simulations). This built on the understanding behind the sequence of events responsible for damage development under such extreme load conditions.

2. Blast experimentation

2.1. Underwater-blast loading of composite tubular laminates

The first of three types of blast test conducted. The test set-up was established for underwater-blast testing of tubular structures. Conventional (strain gauges) strain monitoring techniques were employed to monitor the deformation of the targets during the blasts. A set of preliminary trials highlighted various improvements with regard to quality and interpretability of data. This lead to a series of full-scale explosive tests being conducted on a number of GFRP tubular laminates. Various aspects of blast events have been highlighted by these studies such as yield and effectiveness of the blasts, the damage that can be sustained and the damage development process as well as how boundary conditions can affect the outcome in terms of the damage sustained. Tube structures were tested and the effect off the filler/backing medium was clearly apparent with the water filled tube reducing surface stains by ±60% in the sample.

2.2. Underwater blast loading of sandwich composite panels

These sets of blast data have shown the capabilities of simple constructions to resist blast loads. Various aspects of blast response have been highlighted by these studies such as the nature of underwater blasts, the damage these blasts can indict on sandwich structures as well as how boundary conditions can affect the outcome in terms of damage sustained. During the underwater trials the sandwich panels were subject to pressures of the order of 10 MPa in a short period of time (< 0.2 ms). During the underwater blasts, the cores experienced considerable crushing (up to 50%) and the skins experienced very large strains, causing fibre breakage on both front and back faces (with strains exceeding3% in some cases) when the targets were backed by air. The effect of having water asa backing medium reduced the surface strains experienced and hence damage incurredby the skins but increased the relative crushing observed in the core. Similar to thetube structures tested previously, the effect of the filler/backing medium was equally apparent in this set of experiments. Similar reductions in surface strains were observed in the case of the sandwich panels. This set of tests on sandwich panels reinforced the significance of support media on structural response to blasts generally and specifically during underwater blasts.

The influence of increasing the core thickness was also investigated. This caused highershear stresses, which lead to core/skin separation. This lowered the strain-to-failure given the blast energy was dissipated perhaps more locally within the skins rather than distributed further. The maximum strain magnitudes were higher in the thinner cored sandwich panels compared to the thicker ones, due to the lower section modulus providing less resistance to out-of-plane motion, allowing for bigger detections and larger strains for a given blast. Different skin configurations were tested during these experiments withthe more traditional GFRP skins proving most capable compared to the GFRP/KFRPcomposition. The idea of introducing stronger fibres into the skin design, seems a sensible one, however in practice there are more complex failure mechanisms occurring under blast conditions (than static conditions for instance). The GFRP skins performed relatively better due to the simple lay-up and perhaps the lack of mismatch between plies, thus forming a more structurally sound skin. Whereas the mismatch in the GFRP/KFRP lead to more significant damage development as the skin did not deform as one entity, leading to interlaminar and fibre breakage failures.

2.3 Air-blast loading of sandwich composite panels

These sets of blast data have shown the capabilities of simple constructions to resist blastloads in greater detail than the previous experiments. Various aspects of blast responsehave been highlighted by these studies such as the damage these blasts can inflict onsandwich structures as well as how boundary conditions can affect the outcome in termsof damage sustained. During these air blasts the sandwich materials were subject toblasts of lower peak shock pressures but higher duration compared to the underwaterblast experiments. Differences were highlighted between the two types of blast as wellas interesting features within this set of experiments, with regards to a number of testparameters.

Large-scale blast testing has proved that full-field displacement and in-plane straindata can be reliably obtained for composite sandwich panels secured around their edgeduring explosive events. Detailed deformation maps were obtained using digital imagecorrelation (DIC) under extreme shock loading conditions and have been validated bypoint measurements using a laser gauge system. The DIC technique is now being adoptedby other research groups for similar blast experiments. Important in this research was thesupport arrangement for the composite sandwich panels and how it influenced, as a designconsideration, the mode and location of failure. Several studies were conducted whichshowed a number of real scenarios for naval structures, such as multiple blast impacts aswell as a number of different blast impacts on a number of different constructions. Each ofthese studies have shown that the modes of failure are front-face dominated compared tothe underwater blasts, which involved both front and back-face failures being observed.

The modes of core failure were seen to change from compressive to shear failure, leadingto skin-to-skin core failures in blasts with I above approximately 500 kPams due to theexcessive shear stresses causing crack initiation early on in the target response.The results have shown that the CFRP-skinned sandwich material performs best, interms of exhibiting the lowest peak detection and surface strains, in response to thesame given blast conditions. The CFRP skins showed little skin damage compared tothe GFRP skins. Failure initiates in the transition region in the corners away from theclamped edges and propagates towards the centre of the targets and down the edges asindicated by the strain fields. Core damage was comparable. Furthermore, a conventionalnaval structural material, mild steel, was subject to the same blast as these sandwichcomposite panels (GFRP and CFRP) and performed significantly worse in terms of peakdetection and permanent damage. The steel sheet had a slightly higher areal weightcompared to the two composite targets discussed but this did not produce any savings inperformance. This reinforces the argument that fibre reinforced polymer materials canimprove performance against blast for the similar size and weight (or even less weight)of target. This full-field deformation and strain data provides for detailed validation of finite element models of large-scale explosive loading of composite sandwich panels. This dataadds to that already presented on the underwater-blast loading of composite tubularlaminates and sandwich composite panels.

2.4 Finite element modelling

Effective blast mitigation properties have been demonstrated experimentally for lightweightcomposite sandwich materials. Finite element modelling was used to verify the influencesbehind the experimental observations such as transient boundary conditions. It wasapparent during experimentation that the structural supports are not necessarily fixedduring such high rate and impulsive loading events. This relates well to many installationsof marine and other structures. Detailed deformation maps obtained experimentallyusing DIC provided for detailed validation of finite element models of large-scale explosiveloading of composite sandwich panels.The main outcome of these models is that simple material models, predominantly influenced by mass, initial elastic stiffness and support conditions, are sufficient to capture globally how the fibre-reinforced polymer sandwich composite target would respond toa given blast load. More advanced aspects of modelling can be implemented, howeverunless critical safety factors of the numerical analysis versus experimental (practical) areneeded i.e. high tolerance in the design process, these detract from the computational efficiency of the simulations without adding significantly to the result. This is due to thelocalized nature of the failures that were observed during these blasts. However when thefailure modes were more global i.e. for the steel plate, the material model became morecritical at producing a representative simulation of the blast event.Underwater blast was also modeled using ABAQUS 6.10/Explicit. These modelswere in the development phase particularly given access to the correct similitude parameterswas limited. The model developed, eventually, used the experimental pressure-timehistory as well as estimates of these similitude parameters to generate a blast pressurewave correlating to the underwater-blast experiments. These models of both the tube and sandwich panels confirmed the observations from the experimental. The two mainmodes of deformation highlighted. However, here, and more significantly when the sandwich panels were modelled, a need for a more detailed materialmodel for each target is required as well as improvements to the manner in which thetargets are restrained. Fluid structure interaction is strong and would have a great influence on the support as well as just the target. This, in addition to the elastic materialmodels, resulted in higher frequencies of response of the targets. The crushable foammodel in ABAQUS was implemented for the sandwich panels and showed a significantimprovement with regard to the simulation relating to the experimental observations.Comparable core crushing was observed ±50%.All models discussed showed great insight into the blast process, highlighting variousother important design considerations in addition to modelling considerations. Themodels produced were partly for predictive tools as well as for reflective tools, conformingvarious aspects of blast performance of the targets tested. Key modes of deformation andbehavior were highlighted, whilst validating experimental data and methods of producingand acquiring such data.

3. Conclusion:

Digital image correlation (DIC) will be employed to highlight any existing flaws spottedduring the visual inspection previously as well as highlighting the cause or initiation ofdamage during the tests. The tests that would be involved would include: compressionthrough the thickness of the core; edgewise compression of the sandwich panel samples;and flexural tests of beam sections. These are all to be conducted relative to referencematerial (un-blasted) to identify trends in impulse or skin configuration, for instance, onresidual strength of the target after blast loading.Micro-scale damage effects on the sandwich core The differences on a globalscale have been highlighted between air and underwater blast loaded sandwich panels.However depending on whether the core damage sustained by the target was due to themagnitude of the blast pressure or the duration of the pulse. This can affect the natureof the stress waves propagating through the panel. The homogeneity, distribution andnature of cell wall collapse would be interesting to compare between the two types ofblast. A set of samples have been prepared of damaged/undamaged foam cores for acollaborator for ct-scanning. The scan will produce a set of x-ray tomographic slices,which can then be used to reconstruct a three-dimensional volume of the respective coresusing commercial software. This will allow the microstructure of the cores to be analysedqualitatively and quantitatively to compare the different cores failures, relative to unblastedmaterial. Micro-scale imaging of the skin damage can also help to identify anynon-visible subsurface damage.

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