Procedures for monitoring the structural response of such materials during blast events

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Abstract

The effect of the supporting/backing medium (air or water) of the target facing the shock has been identified during these studies. Mechanisms of failure have been established such as core crushing, skin/core cracking, delaminating and fibre breakage. Strain gauge data supported the mechanisms for such damage.A transition in behavior was observed in the sandwich panels when subjectto an underwater blast as opposed to an air-blast load. Damage mechanisms notably shifted from distributed core shear failure originating from regions ofhigh shear in air blast to global core crushing in underwater blast.These studies were part of a research programme sponsored by the Office ofNaval Research (ONR) investigating blast loading of composite naval structures.The full-scale experimental results presented in this thesis will aid andassist in the development of analytical and computational models. Furthermore,this work highlights the importance of support and boundary conditionswith regards to blast resistant design. These outcomes were analyzed further in finite element simulations of both air and underwater blast conditions, where boundary stiffness and support conditions were, as expected, shown tostrongly influence structural response and deformation of the target.

1. Introduction

To explore the mechanical performance of traditional FRPC sandwich and laminate materials against blast loads and evaluate them with respect to their suitability for future marine applications. Laminate materials consist purely of the FRPC material, whereas sandwich constructions comprise of FRPC layers (skins) with a polymer foam spacer material in between them (core). Specifically, this investigation aims to evaluate the strength and damage tolerance of composite materials as agreed by the Office of Naval Research (ONR) and Imperial College London. This evaluation includes conducting full scale air-blast and underwater-blastexperiments.

2. Composite materials

A composite is, in its simplest definition, a material having two or more distinct constituents or phases [6]. Composites can be either synthetic (e.g. cement or bricks) or naturally occurring (e.g. bones or wood). Over the last fifty years there has been a boom in the production of composites, with the fabrication of those containing fine fibres in various polymer matrices dominating. Fibre reinforced polymer composites (FRPCs) have a combination of low weight and excellent mechanical performance, which has lead to their wide use in highly demanding structural applications (such as boat and ship building as well as construction, aerospace and automotive industry). FRPCs work by combining the strength and stiffness of (otherwise brittle) reinforcing fibres with load transferring and protective properties from a polymer matrix, generally, although other matrix materials exist such as metallic or ceramic, to form a heterogeneous and anisotropic material with exceptional specific properties.

There are numerous ways to class a FRPC, in terms of: matrix immaterial; fibre material; fibre content; fibre lay-up; fibre weave amongst others. This review will distinguish between the various fibre weaves available. There are four main types of weave or fabric: pre-impregnated tapes (also known as prepregs); conventional two-dimensional woven; two-dimensional stitched or non-crimp fabric (NCF) and three-dimensional woven.

3. Use of composites in naval structures

Naval superstructures and hulls are generally assembled from unidirectional plies that are laminated to form panels which are transversely isotropic [10]. Leading on from the thin laminate structure, sandwich structures are prevalent within the engineering industry as they have a higher bending stiffness but increase the overall mass of the structure minimally. The core is commonly made of isotropic foam with a uniform relative density (although graded cores also exist) such as PVC or a metal honey comb structure, which gives additional structural stability [6] but still maintains its low weight. The adoption of sandwich structure applications for marine structures was mainly due to their ability to meet defection limits against out-of-plane stresses, which were previously exceeded when using single skin laminates [11]. Various loading conditions are tested for the design of a ship, commonly constructed from panels which are then assembled.

4. Mechanical testing of fibre reinforced polymer composites

Composites technology is based on taking advantage of the stiffness and strength of high performance fibres by dispersing them in a matrix, which acts as a binder and transfers forces to the fibres across the fibre-matrix interface. The performance and mechanical properties of a composite are determined by a number of factors including: elastic/shear module and strengths of the fibre and matrix; aspect ratio, length distribution, volume fraction, uniformity and orientation of the fibres; the integrity of the fibre-matrix interface, which is influenced by the presence of foreign objects such as voids and inherent defects; and the interfacial bond strength [18]. These factors are all controlled during the design and manufacture stages. It is the final product that is subject to various types of mechanical testing to assess its performance under different conditions, prior to recommendations being made with regards to suitable applications for each product. These sets of mechanical tests take place in industry and research institutions over a broad range of scales, whether it is full scale as mentioned previously in Section 2.2 or on a micro-scale. The nature of these tests varies greatly. This review is restricted to those areas of research relevant to blast and impact loading of composite structures and are highlighted in this following section.

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 aims to highlight the mechanisms of failure observed within commercially available naval materials and improve the understanding behind the sequence of events responsible for such damage. This is with the aim of improving computational simulations and hence the design process for marine structures.

Although a significant amount of work is being conducted over a range of scales and types of experimentation, as highlighted in this chapter, suitable standards for scaling and test procedures have not been established. Therefore data that is most valuable to industry is full-scale explosive testing and will be of focus for this investigation. Methods of instrumentation and sample restraint will also be of focus, highlighting the precautions required to implement the traditional instrumentation methods and more modern techniques currently in use in a number of related research areas.

4.1. Underwater-blast loading of composite tubular laminates

A series of underwater blast trials were performed at RAF Spadeadam, Cumbria, UK. The facility for underwater testing had not been used for fully-instrumented testing of any nature for over 20 years. Therefore a test procedure and instrumentation method had to be established and proven. This was required to show that reliable, repeatable and interpretable data could be acquired during underwater blast testing. These tests could therefore show that useful results could be obtained and that this aspect of the experimentation was worth taking further. This was important given the expense of full scale testing, taking into account the consumables used during testing and time spent at the facility. This set of trials was conducted as a precursor to detailed studies, investigating the effects of underwater blast loading of composite tubular laminate structures and sandwich composite panels, to prove the test method.

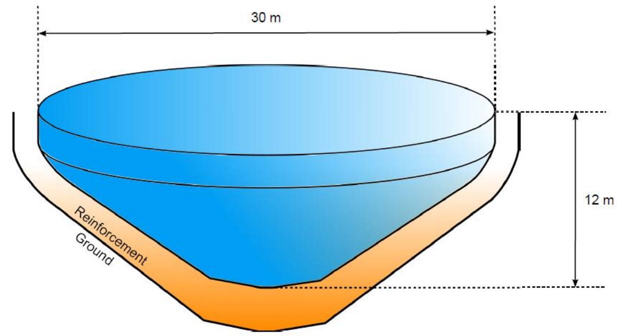

Figure 4.1: Schematic diagram showing the dimensions and shape of the test pond. GFRP composite laminate tubes were subject to two different underwater blast scenarios. The six tubes tested were restrained within an aluminum test frame prior to testing. Strain gauges were used to monitor their structural response during each test.

4.2. Underwater blast loading of sandwich composite panels

The test sampleswere prepared to identify the modes of failure observed and to determine the effect of thebacking medium (air or water) behind the panel on the observed response during a givenblast. A total of four explosive charges (each 1.0 kg C4 or 1.28 kg TNT equivalent) were tested over a range of stand-offs (1.0-1.4 m) against four targets. Each blast scenarioand panel design was chosen to allow for multiple comparisons to be made. Preliminaryunderwater blast test data has proven the suitability of applying traditional strain monitoringinstrumentation during underwater explosive testing, as described.Procedures for monitoring the structural response of sandwich composite materials duringunderwater blast events have been devised. The effect of the backing medium (airor water) of the target facing the shock has been identified during these studies. Straingauge data and post-test sample inspection supported the observed mechanisms of failurewithin commercially available naval materials. Failure modes have been established suchas core crushing, skin/core cracking, delimitation and fibre breakage.

The experiments represent the face sheets of a ship's hull present below the waterline,which could be subject to subsurface blasts. These experiments provide full-scale data toenable the validation of analytical models and assist the development of computational (finite element) models of such structures. Furthermore, it highlights the importance ofsupport and boundary conditions with respect to blast resistant design.

4.3. Air-blast loading of sandwich composite panels

The nature and quality of scaling from small-scaleto large-scale blast response is still in development. Therefore, large scale data and novelapproaches applied to data acquisition are an important contribution to this fieldof research.The experiments were carried out at the same specialized test facility, as usedfor the underwater blast experiments, located at RAF Spadeadam, Cumbria,UK. A totalof seven explosive charges either 30 kg C4 or 100 kg nitro methane (each 38.4 or 100 kgTNT equivalent) were tested over a range of stand-off distances (8-16 m) against 13 target(some repeat blasting of 11 samples). The aim of these air-blast experiments wasto capture displacement-time histories of the sandwich composite panels and understandhow damage develops during a given blast event. Two methods were employed to obtainthese 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. Pointdisplacement 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. Employing the DIC techniquewas an advancement on the underwater-blast tests as this allows for full-field strain mapsto be produced rather than point measurements alone. The experiments represent theface sheets of a ship's hull present above the waterline, which could be subject to surfaceor open-air blasts. These experiments provide full-scale data to validate analyticaland numerical models of such structures and allow for evaluation of the transitions inbehavior between underwater-blast and open-air blast response of sandwich materials.

5. Conclusion

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 in Chapter 3 were shown. 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.

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