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Effect of seawater immersion on the explosive blast response of a carbon fibre-polymer laminate

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ABSTRACT

Explosions are an ever-present risk to laminates used in naval ships, submarines and offshore oil/gas platforms that are immersed in seawater. This study determines whether the absorption of water by a carbon fibre laminate changes its deformation response and damage resistance when impulsive loaded by an explosive blast. The stiffness and strength properties of the laminate were reduced with increasing immersion time in seawater up to and beyond the point of saturation. Explosive blast tests of increasing shock wave impulse were performed on the laminate before immersion and when in the saturated and beyond saturated conditions. Softening and weakening of the laminate caused by absorbed water reduced the resistance against deformation and damage when subjected to an explosive blast. The amount of blast-induced damage to the laminate increased with the immersion time in seawater due to plasticisation of the polymer matrix and weakening of the fibre–matrix interphase region.

1. Introduction

Fibre-reinforced polymer composites are used in a wide range of naval ship structures, such as superstructures, masts, helicopter hangers, rudders and propellers [1,2]. Composites are also used in submarines and submersibles, such as the sonar dome and fairings. Composites offer many advantages over metal alloys when used in ship and submarine structures, which include reduced weight (which improves range and fuel economy), superior corrosion resistance, lower radar cross-section for stealth, and weak magnetic properties which reduces the likelihood of detonation of magnetic sea-mines. In addition, electronic devices and other systems (e.g. antennas) can be integrated into composite structures, which is not possible with metals. Composites are also being used increasingly on offshore oil and gas platforms to reduce weight and corrosion problems, and uses include risers, pipes, decks and gratings [3].

Despite the benefits of using composite materials in ship, submarine and offshore platform structures, a concern is the loss of stiffness, strength and other mechanical properties caused by water absorption. Composites can be immersed or exposed to seawater for many years, during which time water molecules are absorbed into the polymer matrix and the fibre-matrix interphase region. Water can reside within composite materials as free and chemically-bound molecules; with the latter being dependent on the chemical nature of the polymer matrix and fibre-matrix interphase region. Free water molecules reside in the free volume between the polymer chains. Chemically-bound water molecules usually attach themselves to hydrophilic groups (e.g. polar hydrozyl (-OH) sites) of a polymer chain or sizing agent [4–6]. The amount and rate at which water is absorbed by polymer composite materials depends on many factors, including the volume fraction of fibres [7], fibre-matrix interphase properties [8–10], location, type and size of defects (e.g. cracks, voids) [7,9], chemical composition and degree of cure (cross-linking) of the polymer matrix [11–13], and environmental conditions (e.g. humidity, temperature, applied stress) [9,14–16].

A potential problem with the absorption of water by composite materials (particularly as chemically bound water) is softening and damage to the polymer matrix and/or fibre-matrix interphase [12,16,17]. Damage can be categorised as chemical or physical degradation. Chemical degradation is often the result of hydrolysis of the polymer matrix or fibre/matrix interphase [12,18]. Mechanical degradation is usually the result of damage such as matrix cracking or fibre-matrix interfacial debonding, often caused by strains induced by swelling [12,15,18]. For many composite materials the absorption of water reduces the stiffness, strength and other mechanical properties under tensile [7,19–22], bending [12,14,23], compressive [23,24] and

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interlaminar shear [8,25,26] loads. However, improvements can occur to some properties; for example, higher toughness and ductility leading to better impact damage resistance due to plasticisation of the polymer matrix [27,28].

It is possible that reductions to the mechanical properties caused by water absorption reduce the deformation and damage resistance of composites when impulse loaded by the shock wave generated by an explosive blast. This is a risk for naval ships, submarines and offshore oil/gas platforms. Ships and submarines may experience underwater blast loads from sea-mines and torpedoes in addition to air blasts from missiles and other munitions. Accidental explosion of liquid or gaseous fuels is an ever-present risk for offshore platforms.

The response of composite materials to explosive blasts has been extensively studied [29–42]. Under the shock wave generated by an explosion, composite materials deform at high strain rate (typically above $\sim 500\,s^{-1}$) and under excessive deformation will be damaged, which can involve matrix cracks, delaminations, broken fibres and, in severe cases, complete rupture. In addition to the shock wave, other dynamic loads generated by an explosion (e.g. fragmentation, cavitation and multiple shocks for underwater blasts) can cause further damage. The resistance of laminates to deformation and damage depends on many factors including the fibre type [29–32], fibre content [38], polymer matrix [32,40], fibre-matrix interfacial properties [34], and thickness. Despite the large body of research into the blast response of composites, most studies have been performed on 'dry' materials which have not been exposed to water or moist environmental conditions. Matos et al. [43] recently reported that the deformation and damage due to a near-field underwater explosive blast on a carbon fibre-epoxy laminate was increased by water absorption caused by hydrothermal (hot-wet) ageing. The hydrothermally aged laminate experienced greater centre-point deflection and more cracking damage from an explosive blast than the laminate in the dry condition. Matos and colleagues attributed this deterioration to the blast resistance to weakening of the material by the absorbed water. Apart from this single study, the effect of water absorption on the explosive blast resistance of composite materials is unknown. Understanding the possible adverse effect of water absorption on the explosive blast responses of composite materials used on naval vessels and offshore platforms is important.

The aim of the present study is to determine the effect of water absorption on the explosive air blast response of a composite laminate. The material is a woven carbon fibre-vinyl ester laminate, which is used in some naval ships, submarines, submersibles and offshore platforms. The laminate was submerged in artificial seawater for increasing periods of time up to and beyond saturation, and then its deformation response when impulsive loaded by the airborne shock wave generated by an explosive charge was determined. The effect of increasing the peak overpressure and impulse of the explosive blast on the amount and types of damage to the laminate before and after seawater immersion was investigated. The results presented in this paper provide new insights into the effect of absorbed water on the response of composite materials to explosive blast loading.

2. Materials and methodology

2.1. Composite material

The carbon used in the laminate was single ply plain woven fabric with an areal density of $600\,g/m^2$. The ratio of warp and weft tows in the carbon fabric was the same (i.e. 1-to-1). The carbon fabric was stacked into a flat preform with the warp tows aligned in the same direction, thereby producing a cross-ply fibre [0/90] pattern. The preform was infused with liquid vinyl ester resin (SPV 1265, Nuplex Composites) at room temperature using the vacuum bag resin infusion (VBRI) process. Before infusion, the vinyl ester was catalysed using 0.8 wt% MEKP solution (40 wt% MEKP in dimethyl phthalate) (Norox, Nuplex Composites). Following the VBRI process, the laminate was allowed to gel and partially cure at 20 °C for 24 h, and was then post-cured at 80 °C for one hour. The laminate was cut into square panels (4.2 ± 0.1 mm thick) which had a fibre volume content of 50 ± 4%.

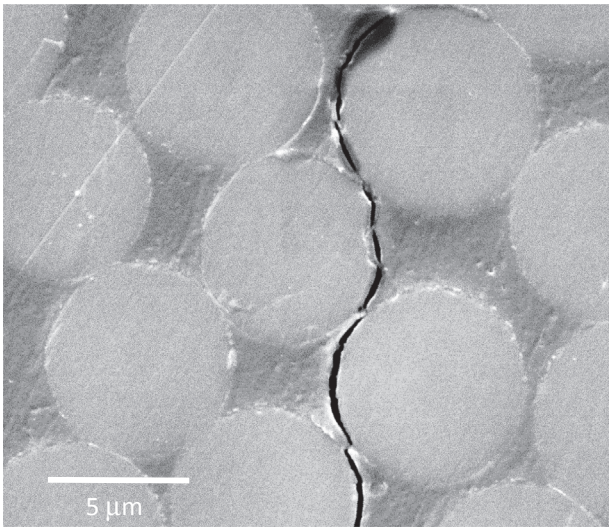

Fig. 1. Fibre-matrix interfacial cracking in the laminate before seawater immersion and blast loading.

Inspection of the laminates following manufacture revealed the absence of voids, however interfacial cracks were present between the carbon fibres and vinyl ester matrix in localised regions. An example of this fibre-matrix interfacial cracking is shown in Fig. 1, and is attributed to the relatively low interfacial bond strength (only 18.2 MPa). It is believed that these cracks develop from internal stresses generated in the laminate during cool-down from the post-cure temperature (80 °C) caused by the difference of the coefficients of thermal expansion between the carbon fibres and polymer matrix. It is important to note, however, that these cracks were often very short (under 200 µm long) and was present in low numbers (typically 0.5 cracks per mm^2).

2.2. Seawater durability testing

The laminate was fully immersed in a tank containing artificial seawater with a salinity content of 2.9% and temperature of 30 ± 1 °C for up to three months. These conditions were selected as they are representative of the sea surface conditions of northern Australia, and have been used in other seawater durability studies on composite materials [12,26]. The edges of the laminate specimens were not sealed to prevent water ingress. Instead, all the surfaces of the specimens were exposed to seawater, although due to the high surface area-to-edge area ratio (about 33-to-1) the water absorption occurred mostly from the surfaces and not the edges. The laminate panels were withdrawn from the seawater at regular intervals to measure the change in mass. The specimens were kept in the seawater within a water-tight bag during transportation between the seawater tank and measurement scales. This same method was also used during thermal, mechanical and explosive blast testing to ensure the laminate was tested in the wetted condition and did not loss any absorbed water. The panels were wiped dry using a lint-free towel to remove surface moisture, and then weighed within an accuracy of 0.1 mg to monitor the mass change. The percentage mass change of the laminate panel (M) was calculated using:

$$M = \frac{M_i - M_0}{M_0} \times 100 \quad (1)$$

where M_i is the mass after a given immersion time and M_o is the original mass.

The effect of immersion time on the percentage mass change for the carbon/vinyl ester laminate is shown in Fig. 2. The laminate rapidly