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New 'Fish Tank' approach to evaluate durability and dynamic failure of marine composites

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ABSTRACT
The major objectives of this paper include: 1) developing a novel approach to accurately simulate the material/mechanics conditions of composite structures in seawater; 2) characterizing the impact damage, and the residual compression strength of marine composites as a function of time of seawater exposure; and 3) conducting a combined experimental and numerical investigation of the compression failure of marine composite with impact damage. In this study, a new composite "fish tank" approach was developed. Four E-glass/vinyl ester composite specimens were weakly bonded together and inserted into a polymethyl methacrylate (PMMA) base plate. Only one surface of the composite specimen was exposed to seawater. This surface will be subjected to the drop weight impact, which is very similar to the dynamic failure of ship structures subjected to underwater explosion. The specimens will then be subjected to compression until failure. For the simulation of the compressive failure after impact, finite element method with cohesive element was employed.

INTRODUCTION
Composites are frequently used in naval construction and in underwater structures. Constant exposure to seawater makes durability and dynamic failure properties critical for naval composite ships. However, previous approaches and measurements have significantly underestimated the actual durability of a composite structure inside seawater. For a composite ship as shown in Fig. 1, a rectangular composite specimen, which is a part of an "infinite" large panel, only has one external face exposed to seawater.

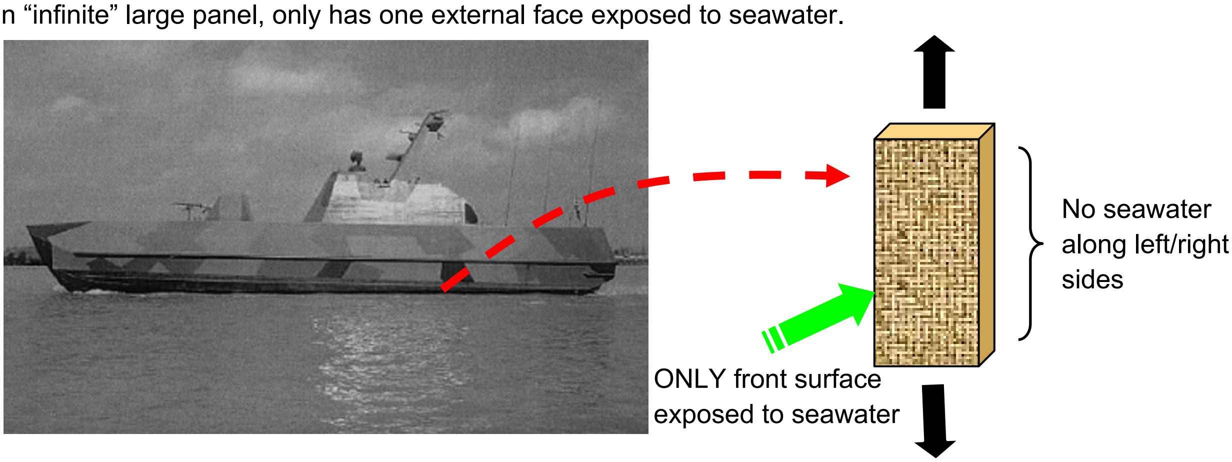

Fig. 1 A composite sample from a composite ship should represent the actual material and loading conditions--- its left/right sides and back surface are not exposed to seawater

During an underwater explosion, only this front surface is subjected to shock loading first. During the life time of the composite ship only the front surface of a composite panel will be directly exposed to seawater. Therefore, property degradation and damage from the front surface will be a major issue to determine the durability and life of the composite ship structure. However, almost all previous experiments have ignored this "single-surface environment effect". For example, Karasek et al. [1] have evaluated the influence of temperature and moisture on the impact resistance of epoxy/graphite fiber composites. They found that only at elevated temperatures did

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moisture have a significant effect on damage initiation energy and that the energy required to initiate damage was found to decrease with temperature. Impact damage resistance and tolerance of two high performance polymeric systems was studied after exposure to environmental aging. For cross-ply laminates, the post-impact tensile strength values fell significantly (by maximum 70–75% of original composite strength) depending on ageing time, environment and impact velocity. Sala [2] found that barely visible impact damage, due to the impact of 1 J/mm (for 2.2-mm laminate thickness) increased the moisture saturation level from 4.8% to 6% for aramid fiber-reinforced laminates and enhanced the absorption rate. Very recently, Imielinska and Guillaumat [3] investigated two different woven glass–aramid-fiber/epoxy laminates subjected to water immersion ageing followed by instrumented low velocity impact testing. The impacted plates were retested statically in compression to determine residual strength for assessment of damage tolerance. The delamination threshold load and impact energy absorption were not significantly affected by the absorbed water. Due to low fiber–matrix adhesion, the prevailing failure modes at low impact energy were fiber/matrix debonding and interfacial cracking. The compression strength suffered significant reductions with water absorbed (28%) and impact (maximum 42%). In addition to impact experiments, other mechanical experiments related to seawater durability also reported similar approaches using fully immersed composite specimens [4-7]. In these previous specimens, property degradation such as matrix cracks in two vertical edges occurred, while these cracks never had the chance to initiate in a closed-edge, "infinite large" composite ship hull. Therefore, the previous data significantly underestimated the actual durability of composite structures inside seawater. In this paper, our new "composite fish tank" will provide more accurate measurements for composite durability.

MATERIALS AND SAMPLE PREPARATION

Glass fiber reinforced vinyl ester (glass/VE) panels were produced using vacuum assisted resin transfer molding (VARTM) by Prof. U. Vaidya's group at the University of Alabama at Birmingham [8]. Eight layers of plain weave glass fabric (CWR 2400/50 plain weave, Composites One, LLC) were used to produce the panels with approximately 5mm thickness which is required by ASTM D 7137 "Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates". The fiber fraction of the panels was found to be 54% vol. after burn off testing was conducted. Compression after impact (CAI) testing samples with a dimension of 101.6 mm x 152.4 mm (4" x 6") were cut and machined to meet the strict dimension requirement specified in ASTM D 7137.

As shown in Fig. 2, silicone rubber as aquarium sealant (Perfecto Manufacturing, Noblesville, IN) were applied to four slots of a base PMMA plate before four composite specimens were inserted. PMMA has very little reaction with seawater. The reason to use silicone rubber is that it provides enough bonding strength under water pressure, at the same time, it is not too strong for us to break this tank for future impact experiments. After one week of the construction of this tank (full bonding strength), it was filled with synthetic seawater (Ricca Chemical Co., TX). This tank will be disassembled after certain periods of time such as three months, six months etc. to conduct impact and compression experiments (see Fig. 3). The impact experiments of dry specimens were conducted to provide baseline data for future durability experiments.

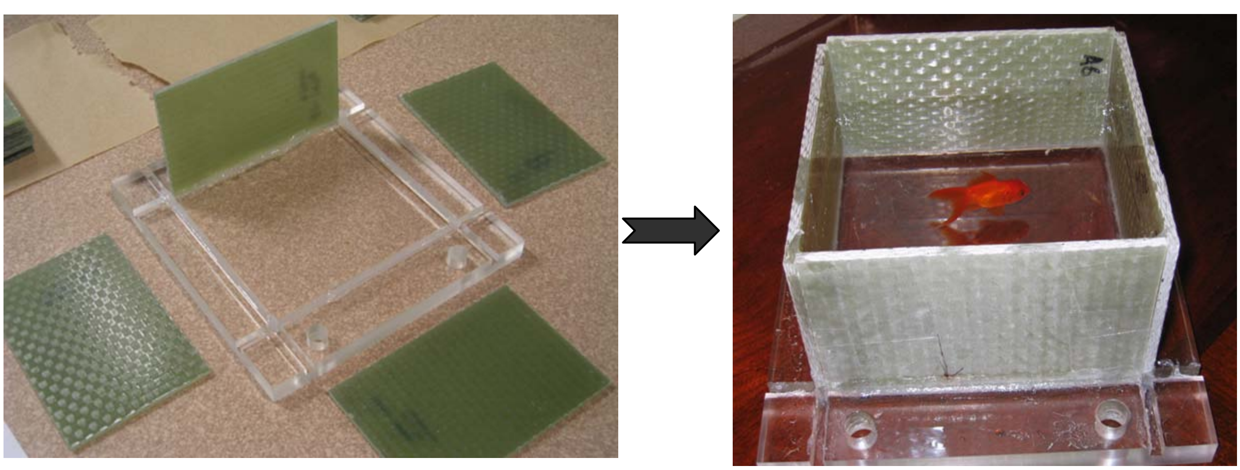

Fig. 2. A composite tank before construction (left) and after construction with seawater inside (right)

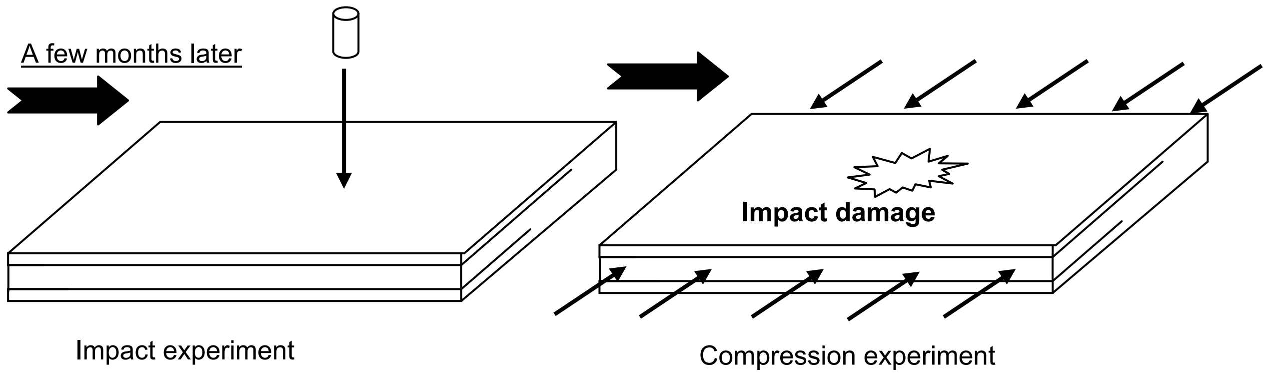

Fig. 3. Layered composite specimens subjected to out-of-plane impact and compression

EXPERIMENTAL METHODS INVOLVING IMPACT EXPERIMENTS

Impact damage was introduced using a drop tower setup [9]. All samples (fixed four edges) were subjected to an impact (60 joules impact energy) using a 16mm (5/8") diameter hemisphere impactor. Damage zones of the impacted samples are clearly seen in Fig. 4(a), (b). For the front surface directly subjected to impact, dark areas represent internal delamination, with possible several delaminations at the different interfaces. As discussed by Xu and Rosakis [10], these delaminations are mainly shear-dominated so the interlaminar shear strength is an important parameter for delamination resistance characterization.

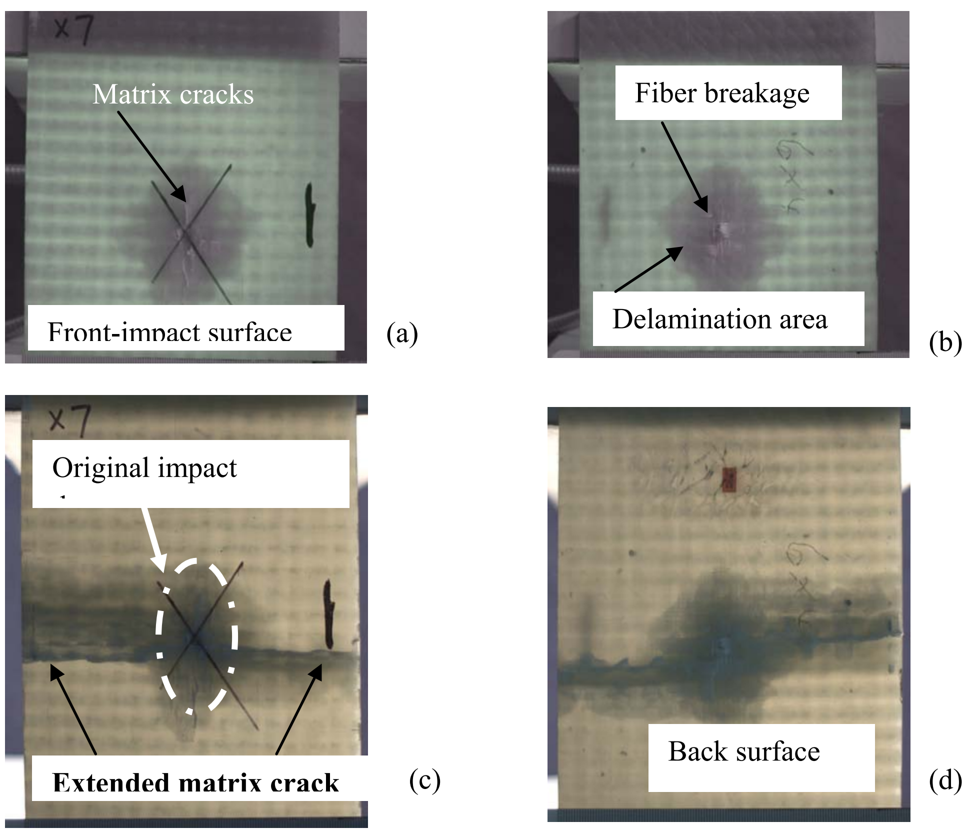

Fig. 4. Typical impact damage on the front and back surfaces, (a) and (b), and typical compression failure of the impacted specimen (c) and (d).

Also, two major matrix cracks were observed near the impact site (as shown by two dark mark lines). One matrix crack was along the horizontal direction and the other one was along the vertical direction. On the back surface of the impacted specimen, fiber breakage was observed at the impact site and this failure mode contributed to major impact energy absorption. Meanwhile, fiber/matrix debonding appeared as white thin lines on the back surface of the impacted specimens. These four major failure modes indeed make different contributions to the composite impact resistance [11], and we believe fiber breakage and delamination play the major role to absorb impact energy.

COMPRESSION TESTS FOR IMPACTED SPECIMENS

Impacted samples were mounted into a compression fixture. Strain gages were attached on the sample back and front surfaces to monitor the strain variations at both surfaces during compression. The reason to use strain monitoring is to avoid any global laminate buckling during compression because buckling failure leads to positive and negative strain readings from both surfaces, while a valid compression failure should lead to the same negative strains of both sides of the specimen. A loading rate of 1 mm/min was used. The progressive compression failure started from the impact damage as shown in Fig. 4. Initially, as the compression load increased, delamination from the previous impact propagated in a local buckling form (see more details by Kadomateas [12]). Unlike impact-induced delamination, its propagation is mainly opening-dominated. Notice that delamination also appeared along the horizontal matrix crack and this matrix crack extended to the two edges as the compressive loading increased, as seen in Figure 4. The final failure (maximum load) was controlled by a shear crack near the horizontal matrix crack as seen in Fig. 5. An inclined angle around 30-45 degrees (with respect to the compressive loading direction) was observed from the two vertical edges of the failed specimen. These results are similar to previous compressive failure results by Daniel [13], Tsai and Sun [14], Oguni and Ravichandran [15]. A load-displacement curve is illustrated in Figure 5 for a compressive experiment of an impacted specimen. The initial non-linear part is caused by the initial gap of the compressive fixture. Then a long linear load-displacement part was recorded. The failure mode starts from the opening delamination from the impacted-induced delamination (shear-dominated), followed by a sudden propagation of the longitudinal matrix crack and a final shear crack appeared along the specimen edge based on the recorded high-definition video.

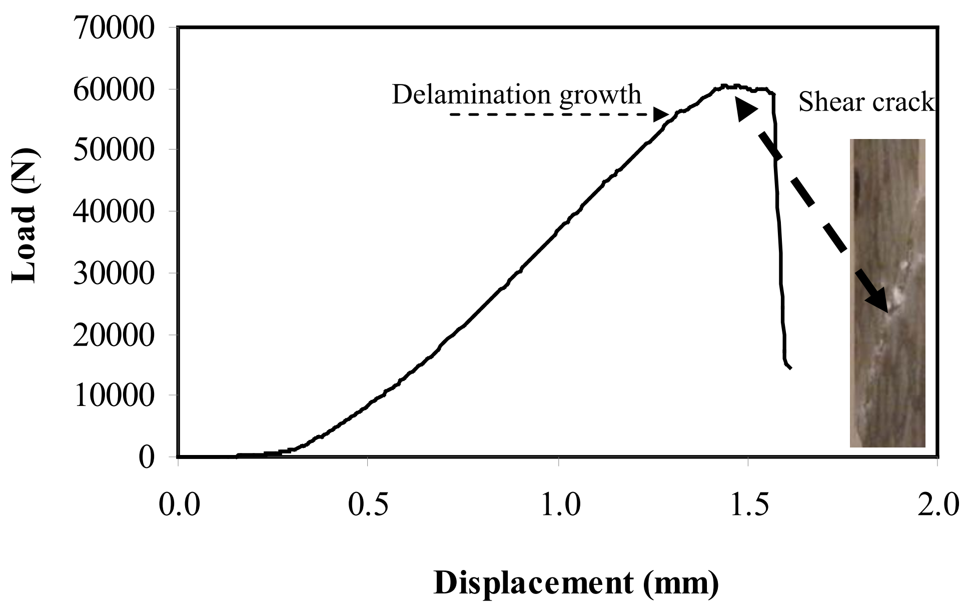

Fig. 5. A typical load-displacement curve of an impacted marine composite laminate in compression

RESULTS AND CONCLUSIONS

Table 1 depicts CAI data up to 13 months. The dry specimen was used as a baseline specimen or comparison. Since the CAI strength combines the effects of the seawater exposure and impact damage, it is very convenient to be used as a durability property plus the dynamic failure behavior. From the table, we notice that the CAI strength reduction is less than 10% after one-year seawater exposure. This is much lesser than 40% as reported by Imielinska and Guillaumat [3] on the same compression after impact experiments with different composite materials. This comparison confirms that our new approach produces more reasonable data as our experiments simulate the right material conditions. These CAI data are also plotted in Figure 6. A slight increase in CAI strength for the specimen after four-month seawater exposure is probably due to the specimen size effect. The average thickness of this set of specimens is at least 10% higher than other specimens. The CAI strength is not a material property as it is sensitive to the specimen size especially the specimen thickness.

Table 1. Variation of Compression-After-Impact (CAI) Strength with seawater exposure time

	Dry	**Seawater exposure**		
Time (months)	0	4	9.5	13
Mean CAI (MPa)	132.98 ±7.59	140.4 ± 4.38	121.38 ± 10.98	125.63 ±10.82
Reduction in CAI (%)	baseline	+5.580	-8.723	-5.527

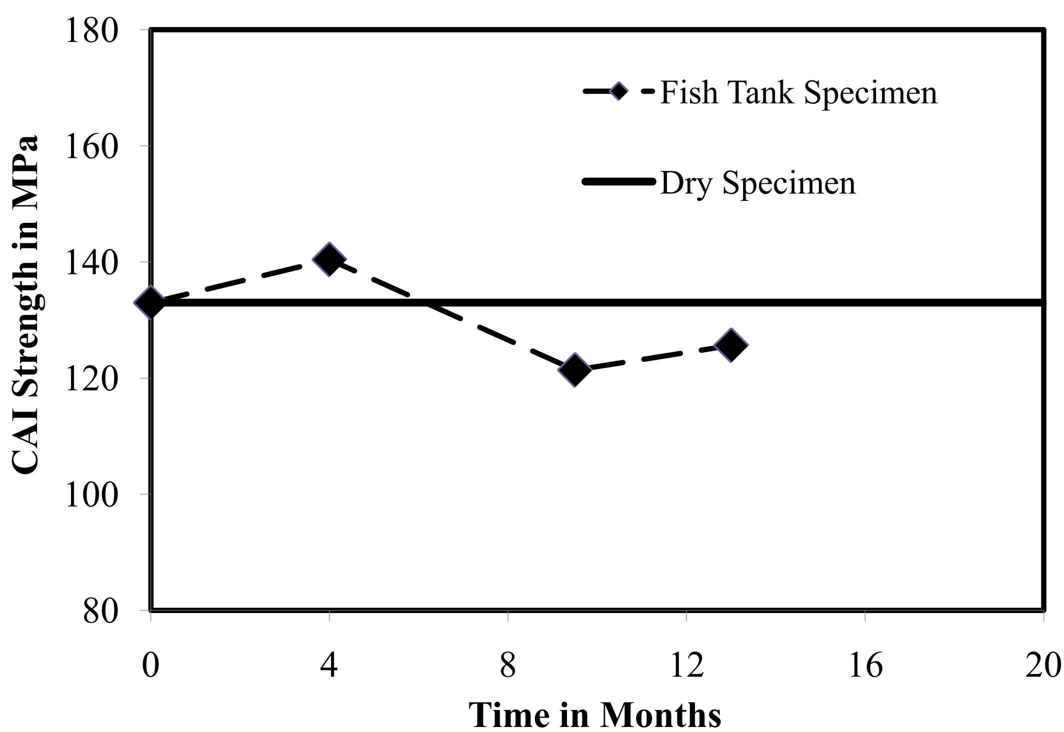

Fig. 6. Change in compressive strength (CAI) as a function of seawater exposure time

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