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SEAWATER EFFECTS ON THE COMPRESSION BEHAVIOR OF CARBON FIBER VINYLESTER BASED NAVAL COMPOSITES AND MULTISCALE MECHANICS

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1. INTRODUCTION

The effect of sea water on the compression behavior of Vacuum Assisted Resin Transfer Molding (VARTM) based Carbon Fiber Vinyl Ester (CFVE) composites of relevance to US Navy has not been studied in the past and the most important aspect that has been neglected in the past is the role of microstructure on compressive loading. Evaluation of compression response for fiber reinforced composites has led to lot of scatter in the reported measurements and often assumed be partially coming from loading fixture misalignment and/or test procedures, without much consideration to local microstructure effects largely due to an inability to noninvasively probe the related multi-scale features governing the deformation mechanics. Degradation from exposure to harsh marine environment (seawater effects and temperature) observed for this CFVE material system under tension during the recent studies sponsored by US Office of Naval Research is proving to be further exacerbated in compression. This study provides the compression response of laminate facings that correspond to sandwich structures with PVC foam core and seawater effects.

2. MATERIALS, SPECIMEN PREPARATION, AND TESTING SETUP

The composite laminates were reinforced with carbon stitch bonded fabric (LT650-C10-R2VE from Devold AMT AS, Sweden), an equi-biaxial fabric produced using Toray's T700 12 K carbon fiber tow with a vinyl ester compatible sizing. The resin matrix used is Dow Chemical's DERAKANE 520A-40, a brominated vinyl ester formulated for the vacuum assisted resin transfer molding process and included post-curing after infusion. The VARTM process, offers a cost-effective way of manufacturing large and complex parts with appreciable consistency as per the US Navy experiences to date. Stitching has been shown to improve the inter-laminar fracture toughness in mode I and mode II and impact damage tolerance with minimal effects on the in-plane properties. The fiber tows were stitched with 14 g/m^2 polyester knitting as shown in the photographs of this biaxial fabric in Figs. 1(a) and 1(b).

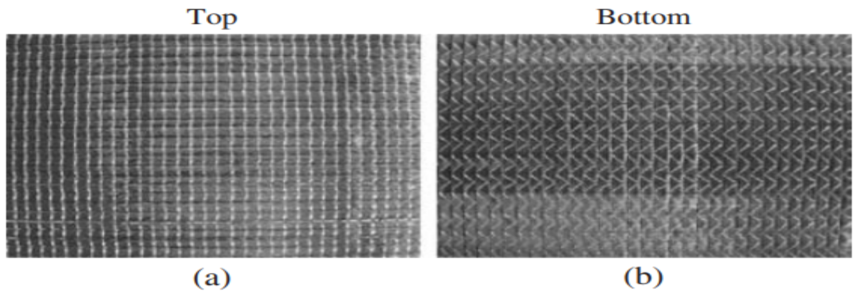

Fig. 1: T700 carbon fiber based equi-biaxial fabric: (a) fill (horizontal); (b) warp (vertical).

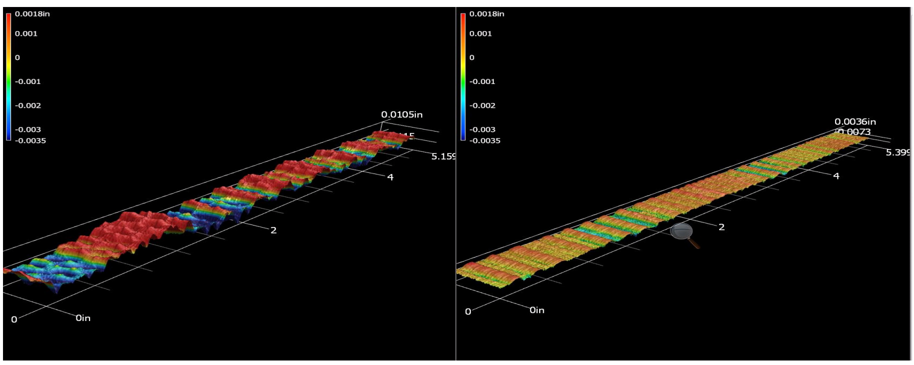

Fig. 2: Laser scan profiles of vacuum bag side versus mold side of the laminate showing substantially different microscale surface features on the top (B-side) and bottom (A-side) surfaces with impact on compression response.

VARTM process was used to fabricate composite panels by combining individual layers of the biaxial fabric using symmetrical lay-up. The total thickness of the panels obtained varied by 5% with an average thickness value of 2.7mm. Fig. 2 shows the difference of the surface roughness across the two faces (vacuum bag side and mold side) of the carbon fiber vinyl ester composite, measured using a Keyence 3D laser scanning instrument with violet laser for exceptional precision. The top face (towards vacuum bag) shows significantly more roughness compared to the bottom face (mold plate side). This difference in roughness can be primarily attributed to the infusion where the facing in contact with the mold is smoother because of the resin settling down due to gravity before curing and the top face is rougher with interface to the vacuum bag during the infusion process. Tensile testing of Carbon Fiber Vinyl Ester composite was done as per ASTM D3039 with an extensional displacement rate of 2mm/min. Rectangular coupons of 200 x 25.4 x 2.7 mm are cut from the panels and tabbed at the ends as per the standard. Fig. 3(a) shows an example of a tabbed tensile specimen with dimensions. Compressive properties of carbon fiber vinyl ester composite (CF/VE) facings consisting of fiber dominated samples of $[0/90]_{2s}$ and matrix dominated samples of $[\pm45]_{2S}$ orientation are evaluated using ASTM D6641. Fig. 3(b) shows the compressive specimen dimensions, used without tabs as per the standard procedures. A gauge length of 12.7mm (0.5") was used to eliminate the size effects and to ensure that the failure does not happen because of the stress concentration at the ends of the gauge length. To determine the effects of fill, warp and shear, the laminates are cut along fill, warp and off-axis at 45^0 to give a laminate layup of $[0/90]_{2s}$, $[90/0]_{2s}$ and $[\pm45]_{2S}$ respectively.

Fig. 3: (a) Specimen dimensions in tension; (b) specimen dimensions in compression.

3. EFFECT OF SEAWATER AND COMPRESSION BEHAVIOR

Compression behavior of fiber reinforced composites has proven to be a very important but poorly understood aspect fiber reinforced composites and over the years there has been a considerable lack of understanding on best ways to measure it experimentally. This led to the development of Combined Load Compression (CLC) approach as the test fixture is easier to use, repeatable to manufacture, and less massive than the Illinois Institute of Technology Research Institute (IITRI) developed compression fixture. Standards exist for both approaches (ASTM D 6641 and D 3410). CLC test fixture is more recently widely adopted by the composites industry as the fixture is small, relatively easy to fabricate, and the combined use of end loading and shear loading in the grip region leads to more uniform state of compressive stress in the gage section, thus was used for this initial phase of this research. Specimens from two different panels were evaluated as shown in Table 1. Part of the specimens were time aged (dry) while other specimens from a given panel and location and orientation were soaked in sea water at 40^0C for several weeks (wet) till the moisture uptake reached saturation equilibrium monitored by periodic weight gain data.

Table 1: Summary results of compression behavior and sea water effects.

Panel	Environment	Specimen Orientation	Compression Modulus (GPa)	Compression Strength (MPa)	Compression Strength Reduction due to Sea Water Exposure (%)
Panel 1	Dry	0	49.35	399	
Panel 2	Dry	0	49	461	
Panel 1	Wet	0	43.75	269	32
Panel 2	Wet	0	57.4	349	24.3
Panel 1	Dry	45	11.6	127	
Panel 2	Dry	45	14.96	124	
Panel 1	Wet	45	11.55	118.5	7
Panel 2	Wet	45	14.55	118.1	4.7
Panel 1	Dry	90	46.96	422	
Panel 2	Dry	90	55.5	489	
Panel 1	Wet	90	47.35	415	1.6
Panel 2	Wet	90	56.1	444	9.2

In the absence of global buckling, polymer laminates in which most fibers are aligned with the external load, fail in compression by one of the three mechanisms: delamination, kink band formation or fiber collapse. Stitching causes significant distortion of both in-plane fibers and fibers within the stitches [1]. Due to the presence of localized defects and mis-orientations, fiber collapse is rarely the controlling failure mode for stitched laminates. The buckling stress can be estimated accounting for shear deformation and compliance of end condition [2].

The failure mechanism in tension is governed by the cluster of fiber breaks. The initial loading causes localized damage or local fiber breakage which is further arrested by the adjacent fibers. Since the ratio of the length of an individual fiber to its critical length, typically an aspect ratio of 100 is sufficient to fully mobilize interfacial shear stress for this particular sizing for the T700 carbon fiber with considered sizing, the tensile stress transfer is optimal leading to multiple locations of fiber breaks, leading to a coalescence of tow breaks and eventual failure. This failure mechanism in tension suggest less dependence upon the microstructural defects in the composite such as resin pockets and fiber misorientation. The tensile strength will certainly be affected by the misalignment of fibers due to stitching, but for fill and warp directions, the local misorientation due to stitching is much more critical for compression strength as can be seen from Fig. 4 which shows a decrease in fiber dominated directions along fill and warp of 60% when compared to tensile strength. Noticeable knock down was also observed for the modulus values. The matrix dominated laminate orientation is much less prone for reduction in compression response compared to tensile behavior.

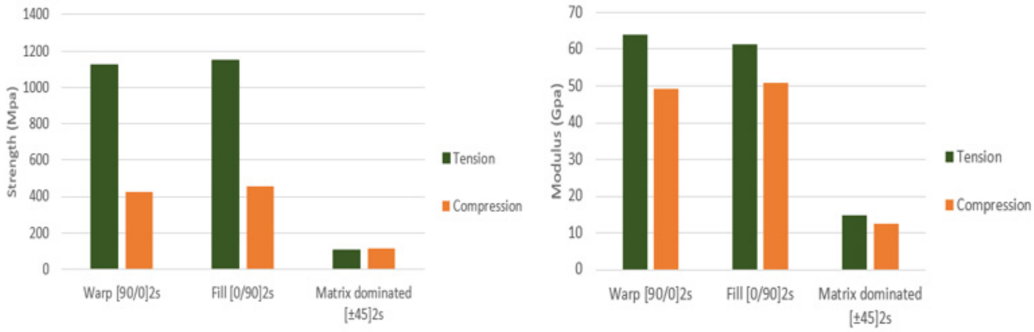

Fig. 4: Mechanical properties in tension and compression.

High resolution X-ray computed tomography show the importance of local microstructure on the observed differences in the compression response for warp and fill directions (Fig. 5).

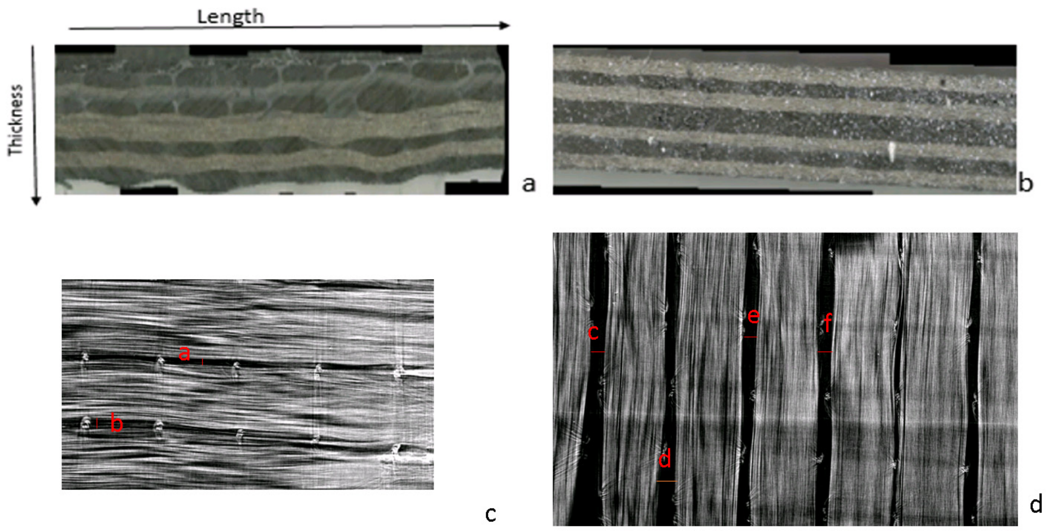

Fig. 5: Fiber waviness comparison: (a) Laminate cut parallel to warp; (b) laminate cut paralle to fill (X-ray CT Results); (c) front view of fabric showing straight stitched pattern; (d) back view of fabric showing zig-zag stitched pattern.

4. CONCLUSIONS

Compression behavior of carbon fiber based vinyl ester composites is largely dependent on the local fiber mis-orientations which were found to be significantly different along warp and weft directions for stitched fabric infused laminates. Largest degradation in the mechanical properties is observed along fiber direction with reductions as high as 32% due to long-term sea water exposure corresponding to post-‘Fickian’ moisture saturation state.

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