AXIAL AND FLEXURAL FATIGUE BEHAVIOR OF WOVEN COMPOSITES

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SUMMARY: Textile composites are materials reinforced by a network of tows and are formed by processes such as weaving, braiding or knitting. Woven fabric composites are a two-dimensional class of textile composites where the warp and fill fiber tows are woven into each other to form a layer. The composite laminate thus formed has good properties in mutually orthogonal directions as well as better out of plane impact resistance than the multidirectional laminate. These woven composites are being considered for several primary structural applications in place of conventional metals. They are being manufactured by using new processes such as Vacuum Assisted Resin Transfer Molding (VARTM). This new process is low cost, affordable and suitable for high volume manufacturing environment. This paper focuses on low cost affordable manufacturing of the popular woven composites using S2-Glass and vinylester C-50 resin system and VARTM process. This paper also presents performance evaluation of these VARTM manufactured thick composite woven laminates under the axial and flexural fatigue loading. Number of tests were performed to evaluate the basic properties such as modulus, ultimate tensile strength, and Poisson's ratio of these woven composites. Axial and flexural fatigue experiments with R ratio of 0.1 were conducted to generate two important curves to characterize the fatigue behavior of this material system: S-N diagram and stiffness degradation over the entire fatigue life of the specimens.

KEYWORDS: woven composites, textiles, fatigue, properties, characterization

INTRODUCTION

Textile composites are materials reinforced by a network of tows and are formed by processes such as weaving, braiding or knitting. Woven fabric composites are a two-dimensional class of textile composites where the warp and fill fiber tows are woven into each other to form a layer. The composite laminate thus formed has good properties in mutually orthogonal directions as well as better out of plane impact resistance than the multidirectional laminate. These woven composites are being considered for several primary structural applications in place of conventional metals. They are being manufactured by using new process such as Vacuum Assisted Resin Transfer Molding (VARTM). This new process is low cost, affordable and suitable for high volume manufacturing environment. Since these woven composites are being evaluated for primary load carrying structural applications, these components are expected to be under fatigue loading. To assess the feasibility of this material manufactured through VARTM process it is very important to understand the fatigue behavior of these composite materials.

The structural composites in the real world applications undergo various forms of static and cyclic loading during its life cycle. Cyclic loading of machine structures occurs often in mechanical systems. It is well known that fatigue strength is smaller than static strength due to the degradation of structure due to fatigue cycle. However, fatigue behaviors of composite
materials are quite different from isotropic materials, such as metals and polymers. This is because detectable damage in composites can be found very early in the fatigue life and the damage in individual ply causes substantial lowering of stiffness of the composites unlike that in the case of metals (Agarwal and Broutman)\(^1\). Thus, loss of stiffness by a fixed percent of the original stiffness is often a failure criterion, rather than complete rupture, as in the case of metals. If the stiffness is plotted versus fatigue life, typically this curve has three stages: stiffness decreases rapidly during first stage, the second stage is a long period of small reduction in stiffness and again the stiffness decreases rapidly until the specimen fails during the third stage. Each stage is associated with certain microscopic damage mechanism. (Reifsnider and Masters\(^2\); Talreja\(^3,4\); Agarwal and Broutman\(^1\); Allen\(^5,6\)). Hence it is important to have this stiffness degradation curve over the entire fatigue life of the composites.

Fatigue behavior of woven composites is similar to laminate composites as far as macroscopic stiffness degradation is concerned (Xiao and Bathias\(^7,8\)). That curve also has three similar stages, however, the microscopic damage mechanism is different (Fujii and Amijima\(^9\)). This is because each ply in woven composites is itself bi-directionally reinforced by fiber bundles in the different directions. The stress-fatigue life (S-N) diagram is widely used method to characterize and to quantify the fatigue behavior or resistance of materials. If the stress is normalized with respect to its ultimate static strength, this normalized \(S/S_u-N\) diagram is useful for comparing different materials for their relative capabilities under fatigue. The slope of \(S-N\) or \(S/S_u-N\) diagram gives a good measure of the resistance of a material to fatigue. Hence the specific objectives of the present study were:

**OBJECTIVES**

- To obtain basic properties of S2 glass/C-50 plain woven composites under axial and flexural loading.
- To generate two important curves to characterize the axial and flexural fatigue behavior of this material system with R ratio equal to 0.1:
  1. The stress-fatigue life (\(S/S_u-N\)) diagram
  2. Stiffness degradation over the entire fatigue life of the specimens.
- To compare the axial and fatigue behavior of these VARTM manufactured plain woven composites.

**MATERIAL SYSTEM**

Material system used was S2-Glass plain woven fabric and vinylester C-50 resin system.

**PROCESSING OF LAMINATES USING VARTM**

In the current work, a single sided tooling process is adopted to manufacture the composite laminates. In the VARTM process the desired number of layers of the glass fiber preform are placed on a flat aluminum plate. A thin layer of porous teflon and a highly permeable membrane is then placed over the preform (Fig. 1 and Fig. 2). The injection and vacuum lines are placed at desired locations of the preform. Subsequently, a vacuum bag is applied over the preform and the part is debulked for three hours. The low viscosity vinylester C-50 resin with R9550 hardener is then infused with the aid of vacuum from one end of the preform to the other end, until full wetting occurs. The preform gets wetted-out both in the in-plane and transverse directions. The cure characteristics of the resin are monitored using an embedded IDEX dielectric sensor placed in the mid-plane of the fibrous preform. In this work, S2-Glass woven fabric was utilized to obtain the resin infused woven composite laminate. The laminate was cured for 10 hours and subsequently post-cured for three hours at 80 degree C. Fiber volume fractions of 50%-55% were achieved with void contents measured to 2%-3% in most of the panels manufactured.
Fig. 1 Schematic for the fabrication of the composite panel.

Fig. 2 VARTM fabrication

**TESTING PROCEDURE**

All the tests were performed on MTS testing machine with Instron Controller 8500 and with Instron Hydraulic Grips (300 KN). Static tests were performed using the fabricated coupons to evaluate the basic properties such as tensile and flexural modulus and ultimate tensile and flexural strength. Initially the fatigue tests were performed at 5 Hz to 10 Hz. However, this material system is more flexible as compared to graphite fiber system. So the data acquisition system was unable to gather data with large deformation at these higher frequencies. This is because the controller system parameter could not be fine-tuned for higher frequencies and the machine could not reach the specified loads. It was observed that the recorded peak load
values were up to 80% of the specified peak values. It was possible to gather data at 3 Hz; hence, all the fatigue tests were performed at 3 Hz frequency, unlike conventional 5-10 Hz.

In the fatigue tests, the applied $\sigma_{\text{max}}$ was varied from 55% to 35% of the ultimate tensile strength for the axial fatigue testing, whereas for flexural fatigue testing $\sigma_{\text{max}}$ was varied from 80% to 55% of the ultimate flexural strength. For axial and flexural fatigue, the specimen thickness was 12.7 mm. Flexural fatigue tests were performed using three-point-bend fixture. These tests were carried out according to ASTM standard D790-86. Both axial and the flexural fatigue tests were performed using a stress ratio of $R = 0.1$, in load control mode using a sinusoidal waveform. Strains were measured by clip gage extensometer for axial fatigue and using strain gages for flexural fatigue. Peak values of loads and strains were recorded over the entire fatigue life. Stiffness degradation of all the specimens was monitored from those values during the testing.

**RESULTS AND DISCUSSION**

Static test results are presented in Table 1. For tension-tension axial fatigue testing, the applied $\sigma_{\text{max}}$ was varied from 55% to 35% of the ultimate tensile strength (540 MPa). For flexural fatigue testing, the applied $\sigma_{\text{max}}$ was varied from 80% to 55% of the ultimate flexural strength (410 MPa). Axial fatigue life cycles at various applied maximum stress values are given in Table 2 and flexural fatigue life cycles at various applied maximum stress values are presented in Table 3.

<table>
<thead>
<tr>
<th>% $\sigma_u$ (Tensile)</th>
<th>Axial Fatigue Life Cycles ($N_f$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>55</td>
<td>1,280</td>
</tr>
<tr>
<td>50</td>
<td>8,711</td>
</tr>
<tr>
<td>45</td>
<td>12,005</td>
</tr>
<tr>
<td>40</td>
<td>72,151</td>
</tr>
<tr>
<td>35</td>
<td>Run-out</td>
</tr>
</tbody>
</table>

Table 2 Axial Fatigue Life Cycles at Various Applied Stresses.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Modulus, $E_o$</td>
<td>21.0-22.5 GPa</td>
</tr>
<tr>
<td>Ultimate Flexural/Tensile Strength, $\sigma_u$</td>
<td>410/540 MPa</td>
</tr>
<tr>
<td>Ultimate Flexural/Tensile Strain, $\varepsilon_u$</td>
<td>2.79%/3.356 %</td>
</tr>
</tbody>
</table>

Table 1 Static Test Results

| Table 3 Flexural Fatigue Life Cycles at Various Applied Stresses. |
One of the two important curves to characterize the fatigue behavior of this material system is $S$-$N$ diagram. It is constructed using data presented in Tables 2 and 3 and is shown in Figure 3. Another important curve to characterize the fatigue behavior is stiffness degradation over the entire fatigue life of the specimen. All the fatigue specimens were monitored for stiffness during the axial fatigue testing. The stiffness degradation curves for applied maximum stress of 40% is presented in Figure 4.

![Fig. 3 Stress-fatigue life ($S/S_u$-$N$) diagram.](image)

![Fig. 4 Stiffness degradation during axial fatigue](image)
CONCLUSIONS

The study indicated that for VARTM manufactured S2-Glass plain weave/ vinyleser C-50 resin composites have endurance limit of approximately 35% of ultimate tensile strength and 55% of ultimate flexural strength. The study indicates that these composites perform well under flexural fatigue as compared to axial fatigue. The fatigue tests clearly show that these composites exhibit three stages of fatigue life as shown in Figure 4. The stiffness decreases rapidly in the first stage. This is because of debonds (between fibers and the matrix) in the weft direction and the matrix cracks. The stiffness remains steady during the second stage. This is because of the debonds in warp direction and metadelamination, which causes gradual decay. When these internal damages become critical, fibers start breaking and the stiffness again decreases rapidly in the third stage, which is a very short one.

ACKNOWLEDGEMENT

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REFERENCES