PARAMETRIC STUDY AND NUMERICAL MODELING OF CFRP CRUCIFORM SPECIMENS UNDER BIAXIAL LOADINGS

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ABSTRACT

Composite materials are increasingly believed to be the materials of the future with potential for application in high performance structures. One of the reasons for that is the indication that composite materials have a rather good rating with regard to life time in fatigue. Fatigue of composite materials is a quite complex phenomenon, and the fatigue behavior of these heterogeneous materials is fundamentally different from the behavior of metals. In literature, many researches related to the biaxial fatigue experiments using tubular, bar and planar specimens can be found, the biaxial loading was achieved by using cruciform specimen with innovative mechanism. The influence of material behavior, numbers of layers, geometry of the cruciform specimen and loading ratio were investigated using a specialized fatigue software nCode LifeDesign 14.5 ®.

INTRODUCTION

The fatigue behavior of composite materials is considered one of the difficult problems with this type of materials, as it is more complex than metals. That problem seems to be an important topic for several researchers, as illustrated later in this section.

In literature, multiple papers related to biaxial fatigue experiments using tubular, bar and planar specimens can be found. There are (i) tension/torsion set-ups of composite tubes [1], (ii) internal pressure/tension of composite tubes [2], (iii) bending/torsion set-ups of composite bars [3] and (iv) axial loading or bending moment on the edges of cruciform specimens or rectangular plates, respectively [4].
The lack of reliable multiaxial or even biaxial experimental data to validate the failure theories is the critical step in the evolution and a most efficient usage of composite materials [5]. Due to the complex anisotropic behavior of composite materials, more advanced experimental testing is needed. The current practice of using uniaxial test results to predict the failure for multiaxial stress states seems inadequate. To study the mechanical behavior of fiber reinforced polymeric matrix composite laminates under static and cyclic in-plane complex stress states; a horizontal biaxial loading frame and a special cruciform type specimen have been developed.

The numerical work includes the simulation of the cruciform specimen under biaxial fatigue loading using ANSYS 14.5 ® and the specialized software in fatigue nCode DesignLife ® which enables to perform biaxial fatigue analysis with the actual loading data results in the fatigue life and damage.

EXPERIMENTAL SETUP AND SPECIMEN’S REQUIREMENTS

Many designs were made to achieve the planar biaxial loading of the composite plates; biaxial mechanism (Biaxial3) was the third and last mechanism designed which can achieve the required stretching ratios. Figure (1) shows the finished and the designed mechanism together.

![Figure (1) The Biaxial3 mechanism, (a) designed, (b) finished](image)

The current configuration of the linkages will perform either tension – tension or compression – compression loading in both the vertical and horizontal directions according to the direction of movement to the piston of the universal testing machine, another configuration can be arranged in order to obtain tension – compression loading. This configuration requires no additional parts; it only needs to replace the center of the angle that exists between the inclined shaft and the base square rod. It can perform (4) different stretching ratios, which are 1:1, 1:2, 1:3, and 1:4. The selected angles used to determine the stretching ratio can be summarized as follows:
In general, specimens that are suitable for biaxial characterization must satisfy a number of requirements, namely:

1. The shape of the test specimen shall be cruciform with a central gauge section, an example is shown in Figure (2).
2. The shape and dimensions of the test specimen shall be such that when loaded in tension in the primary and secondary loading directions simultaneously, a uniform biaxial strain field is produced within a minimum centrally located gauge-section of 20 mm diameter [6].
3. Failure has to occur in the biaxially loaded test zone and not in the uniaxially loaded arms.
4. The results should be repeatable [7], [8].

There is no standard shape or design for the biaxial specimens until now [9], so the specimen design was based on the generic form shown in Figure (2), with specimen arms all of the same length and a circular central gauge section. The exact dimensions used for the specimen were obtained from Optimat Blades [10], which they are first integrated European research project focusing on wind turbine rotor blade fatigue. The specimen’s dimensions are shown in figure (3-21).

<table>
<thead>
<tr>
<th>No.</th>
<th>Stretch Ratio</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1:1</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>1:2</td>
<td>26.58</td>
</tr>
<tr>
<td>3</td>
<td>1:3</td>
<td>18.39</td>
</tr>
<tr>
<td>4</td>
<td>1:4</td>
<td>14.15</td>
</tr>
</tbody>
</table>

Figure (2) The general shape for planar biaxial specimen (cruciform)
NUMERICAL SIMULATION OF THE CRUCIFORM SPECIMEN UNDER BIAXIAL FATIGUE

The formulation of the finite element model was accomplished by the aid of ANSYS APDL ® 14.5. It was used to construct the geometry of the flat and reduced central section cruciform specimen as shown in figure (4) followed by providing the engineering constants, specifying a finite element and mesh size specify constraints and boundary conditions apply loads and obtain solutions, and review the results.
The model material behaviors was considered as isotropic first and as orthotropic in the next step and the numerical values are given in the results and discussion chapter. It was required to simulate the behavior of layered composite material and to achieve that a certain element was chosen, the SHELL181 (4-Node). This element type is suitable for analyzing thin to moderately thick shell structures [11].

The specimen of reduced section had three regions of different number of layers as can be shown from figure (4) each color represent a section. The outer full section was named as section A; the middle which is a ring area was named Drop section and the inner section with the required number of layers was named as section B. Figure (5) shows the number of layers for each section in the meshed geometry of the cruciform specimen for CFRP6.

![Figure (5) The number of layers for each section of CFRP6 cruciform specimen](image-url)
The analysis of fatigue of biaxial loading was a very precise and neat process that constructed by the use of the above details. Figure (6) shows the complete process of fatigue analysis performed by nCode DesignLife ®. The process included two input Glyphs. The finite element model input Glyph, which contains the geometry, material properties, element type, mesh, constraints, loadings (from experimental tests), and primary results.

**RESULTS AND DISCUSSIONS**

i. Influence of Material Behavior and Numbers of Layers

The first model was assumed to have an isotropic material behavior and a flat specimen (no reduction in the central section). Figures (7) and (8) show the behavior of the first model with CFRP6 and CFRP10 respectively. The second model was to replace the isotropic behavior with orthotropic behavior with the properties obtained from the table (1). All the other parameters were kept the same. Figures (9) and (10) show the behavior of the second model with CFRP6 and CFRP10 respectively. The behavior of the second model was very similar to the first model but exception. That was that the second model gave less life than the previous one that was expected since the material behavior was changed. A further investigation of figures (7) and (9) give that the fatigue life reduction ratio for the CFRP6 isotropic material between 1000s and 4000s was 57.7% and for orthotropic material was 50%. While the fatigue life reduction ratio for the isotropic material between 4000s and 8000s was 64.9% and for orthotropic material was 68.65%. The orthotropic material was much sensitive to the load duration than the isotropic material.
Table (1) The mechanical properties of the CFRP6 laminates in the global coordinates

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (GPa)</td>
<td>80</td>
</tr>
<tr>
<td>$E_y$ (GPa)</td>
<td>80</td>
</tr>
<tr>
<td>$E_z$ (GPa)</td>
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</tr>
<tr>
<td>$\nu_{xy}$</td>
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<tr>
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<tr>
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<td>0.416</td>
</tr>
<tr>
<td>$G_{xy}$ (GPa)</td>
<td>5.858</td>
</tr>
<tr>
<td>$G_{yz}$ (GPa)</td>
<td>5.938</td>
</tr>
<tr>
<td>$G_{xz}$ (GPa)</td>
<td>5.938</td>
</tr>
</tbody>
</table>

**Figure (7)** The fatigue life of isotropic CFRP6 with flat specimen

**Figure (8)** The fatigue life of isotropic CFRP10 with flat specimen

**Figure (9)** The fatigue life of orthotropic CFRP6 with flat specimen

**Figure (10)** The fatigue life of orthotropic CFRP10 with flat specimen
ii. Influence of the Specimen Geometry

After investigating the cruciform flat specimen and it had been shown that the failure won’t occur in the central section. It was clear that the geometry needed to be changed. The change included either weakening of the central section or strengthening the arms and since the arms were difficult to strengthen, the first option was chosen. The third numerical model was built to achieve this new requirement of the geometry. Figures (10) and (11) show the behavior of the third model with CFRP6 and CFRP10 respectively. The behavior of the third model was very similar to the first and second models regarding the fatigue life with load duration; however the position of failure was changed from the previous positions to the central section this can be shown from figure (4-51). The figure also shows the damage element increase with increasing the load duration.

The final model (fourth) was built to achieve the most realistic properties and conditions. The material was considered orthotropic and the specimen contained a reduced central section. Figures (12) and (13) show the behavior of the fourth model with CFRP6 and CFRP10 respectively. As can be shown from the figures, the fatigue life behavior is more similar to the second model with orthotropic behavior. The life was reduced considerably for all the fiber types and number of layers. The percentage reduction in fatigue life for CFRP with reduced central section was 90.411% between the isotropic and orthotropic material behavior.
After presenting the models, a comparison was made between the various parameters. Figures (14) and (15) show the fatigue life behavior of CFRP6 for isotropic and orthotropic material behavior respectively. As can be seen from the first figure, the specimen with reduced central section had lower fatigue life for isotropic material, but it was not considered as lower fatigue resistance, that is because the flat specimen didn’t provide a valid biaxial loading in the central section. In figure (15) an interesting behavior was observed, that the reduced section specimen provided greater life and gave more fatigue resistance.

iii. Influence of the Loading Ratio

The final parameter to be investigated was the loading ratio; so far all the previous results were obtained using single loading ratio which was equiaxial (1:1). It was decided to increase the loading ratio to be (1:2) and (1:3) but by applying these new loading ratio into the finite element models the specimens were failed instantaneously by static failure, so the loading ratio were decreased instead of increase. The new loading ratio became (1:1/2) and (1:1/3). Figure (16) shows the different loading ratios for the CFRP6.

![Figure (14)](image1)

**Figure (14)** The fatigue life of isotropic CFRP6 with flat and reduced specimens

![Figure (15)](image2)

**Figure (15)** The fatigue life of orthotropic CFRP6 with flat and reduced specimens

![Figure (16)](image3)

**Figure (16)** The fatigue life of orthotropic CFRP6 reduced specimens for three different loading ratios
CONCLUSIONS

1. The numerical results are in agreement with the experimental tests results of enhancing the fatigue failure of the cruciform specimen under biaxial loading in the central reduction gauge section.

2. The isotropic behavior gives more fatigue life than the orthotropic behavior. The percentage reduction in fatigue life for CFRP with reduced central section was (90.411%) between the isotropic and orthotropic material behavior. It is concluded that the numerical simulation must be carried out with orthotropic behavior in order to ensure that the component will perform as required to in the design.

3. The cruciform specimens shape is a major parameter in obtaining a valid biaxial test result. It is concluded, from the experimental results and numerical simulation, that a reduction of the thickness in the central gauge section is enhancing the start of the failure at the center of the specimens and preventing the premature failure (the arms breaking).

REFERENCES


