NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF NONLINEAR DEFORMATION OF GLARE

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Abstract

GLARE (GLAss REinforced), is a fibre metal laminate that consists of aluminium layers and glass fibre/epoxy composites. The analysis of this composite structure is non-linear and very complex. Its analysis can be carried out though simulation exercises employing numerical tools/techniques such as finite element modeling. The present paper describes finite element modeling of the GLARE laminates. The deformation characteristics of such hybrid materials are non-linear. In this paper, the numerical analysis based on finite element modeling is used to predict the deformation behavior of various GLARE configurations. The results of numerical analysis obtained are then compared with experimental results for verification and validation.

Keywords: Laminate, Glass fiber, Composite, Hybrid, Glass reinforced

Introduction

In the search for optimal performance, metals and fibre reinforced epoxy are combined to obtain ‘the best of both worlds’. An example is GLAss REinforced (GLARE), a fibre metal laminate that consists of aluminium layers and glass fibre/epoxy composites. The number and the thickness of the aluminium layers may vary, as well as the number of prepreg layers and their orientation. The GLARE, which is a combination of metals and composites in one laminate, combines the advantages of its constituents (metal alloy and composite), not the disadvantages. GLARE laminates are commercially expressed based on their lay-up configurations, such as 2/1, 3/2 and 4/3 and so on. The first-digit indicates the number of aluminum alloy layers and the second digit indicates the number of blocks (grouped plies) of composite layers. In the present investigations, six different grades of GLARE material, viz., GLARE-3/2, GLARE-4/3, GLARE-5/4, GLARE-6/5, GLARE-7/6 and GLARE-8/7 are analyzed. The material constituents of GLARE are Aluminium alloy - 2024T3 and S2 glass fibre as reinforcing material.

Literature Review

A review of literature indicates that number of researchers have carried out modeling and analysis in various aspects related to fiber metal laminates. Fiber metal laminates offer significant improvements over current available materials for aircraft structures according to Vogeleseang and Vlot [1]. Restellini et al [2] have developed an innovative computational method for modeling the material for nonlinear analysis. Nam et al [3] have explained the possibilities of employing genetic algorithms to study the optimal design of fiber metal laminates under various loading conditions through FEM approach. Tarun and Menon [4] have also given a brief account of various methods to analyze two dimensional analytical models including classical, first order, higher order discrete layer and zig-zag theories for stress analysis of laminates under mechanical loads. A review of literature indicates that the research activities related to GLARE laminates are largely focused on their modeling. However a lot of experimental evidence is required for certification and qualification purposes.

Methodology

Finite Element Model of Glare

GLARE laminates are symmetric in their geometry as well as their properties about the middle surface. The geometry of multi-layer laminate is shown in Fig.1 and the stacking sequence of GLARE-3/2 is shown in Fig.2. The necessary property parameters of all the constituents [5], or the purpose of calculation of stiffness matrix are given in Table-1.

The laminate considered for the analysis is composed of 0° and 90° plies of S2 glass/epoxy and 2024-T3 aluminum alloy sheets. The physical properties defined in Table-1 enable any laminate to be represented by an equivalent homogeneous shell element for structural analysis. With this definition of the local values of the variables, a laminate analysis can be performed to determine the state of stress in each lamina with the help of numerical analysis.

Numerical Analysis

The characteristics of a typical GLARE laminates are simulated by modeling the same through a commercially available Finite Element Analysis software MSC/NASTRAN. While defining elemental material property, material ID (Identification), thickness and orientation angle for each layer parameters were defined. Leaving the material ID blank or zero eliminates that layer. The layers are specified in order starting from the bottom [6]. The fiber angles are specified relative to the material axes which were defined for the element. MSC/NASTRAN also supports the failure theories. To make use of the failure theory calculations the allowable band shear and allowable strength were also specified. These failure theories produce failure indexes. An index greater than 1 denotes failure. Meshing is a critical aspect to be considered in any finite element analysis. In the present work, shell type of element and a free meshing was adopted. The inter elemental and node-to-node connectivity has been maintained. Then the loads and boundary conditions are specified. The finite element model is then ready for the analysis.

For the purpose of nonlinear analysis a thin square laminated plate of size 1m x 1m is considered. The plate is modeled by treating them as shell elements. In the nonlinear numerical stress analysis, the local stresses and strains of the shell element in each lamina within the laminate can be automatically transformed to global coordinates. Also stresses and strains are calculated at each incremental step and evaluated by the failure criteria to determine the occurrence of failure. In the present laminate material, each Al 2024 T3 alloy lamina can be considered as an isotropic layer and the fiber lamina can be considered as orthotropic layer in a plane stress condition. Taking into account the elastic-plastic behavior in the longitudinal direction and the nonlinear behavior on the transverse direction, there is a significant presence of nonlinearity in the laminate. By defining the characteristic material direction individually the stress-strain relation is obtained layer wise. The material parameters are given in Table-1 and adopted with respect to the direction chosen in the layer. The laminate plate is clamped at one end. The thickness is added later as a property of the element in which the surface is divided [7]. The thickness of the Al 2024 T3 alloy is varied from 0.2 mm to 0.7 mm. The S2-glass fibre thickness is kept constant at 0.127 mm. A tensile force of 500N is applied to the free end as shown in Fig.3. In the test specimen of GLARE 3/2 it has been found that the stresses in different layers are nonlinear. There are abrupt changes of slope for the variation of stresses over the depth. The stress varies from lamina to lamina in a discontinuous manner. The deformation (T1 in meters) and the layer by layer variation in the stress (in Pascal) values for the test specimen GLARE 3/2 are given in Table-2.

<table>
<thead>
<tr>
<th>Constituents</th>
<th>$\text{S2 Glass}/\text{Epoxy}$</th>
<th>Aluminum Alloy 2024-T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$ (GPa)</td>
<td>49.9</td>
<td>72.4</td>
</tr>
<tr>
<td>$E_{22}$ (GPa)</td>
<td>10.8</td>
<td>72.4</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$v_{21}$</td>
<td>0.067</td>
<td>0.33</td>
</tr>
<tr>
<td>$G$ (GPa)</td>
<td>3.7</td>
<td>27.2</td>
</tr>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>2.46</td>
<td>2.77</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.127</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Failure Analysis of GLARE

The two failure criteria that have been applied are the maximum strain theory and the Tsai-Wu theory. In an effort to predict experimental results more accurately, Tsai and Wu proposed lamina failure criterion [7]. A Tsai-Wu failure criterion is adopted for the present analysis to predict the failure of a laminate based on first-ply failure
analysis. This criterion was chosen because it considers interaction of the stress components as a possible cause of failure, in contrast to the maximum stress criterion, which assumes failure is due to only one stress component [8]. Also the Tsai-Wu failure criteria has been extensively used in literature. The quadratic failure criterion in tensor form can be expressed as

$$f(\sigma) = F_i \sigma_i + F_{ij} \sigma_i \sigma_j \quad (i, j = 1, 2, \ldots, 6) \quad (1)$$

Where $F_i$ and $F_{ij}$ are functions of material strengths and $\sigma_i$ are stresses in material directions. All shear and normal-shear coupling terms of $F_i$ and $F_{ij}$ are neglected by the fact that the shear strength is independent of sign in the material coordinates. The expressions for strength parameters in terms of ultimate strengths for Tsai-Wu are as follows [9]:

$$F_1 = \frac{1}{X_T} - \frac{1}{X_C}; \quad F_2 = \frac{1}{Y_T} - \frac{1}{Y_C}; \quad F_3 = \frac{1}{Z_T} - \frac{1}{Z_C};$$

$$F_{11} = \frac{1}{X_T X_C}; \quad F_{22} = \frac{1}{Y_T Y_C}; \quad F_{33} = \frac{1}{Z_T Z_C};$$

$$F_{44} = \frac{1}{R^2}; \quad F_{55} = \frac{1}{S^2}; \quad F_{66} = \frac{1}{T^2};$$

$$F_{12} = -\frac{1}{2 \sqrt{X_T X_C Y_T Y_C}}; \quad F_{13} = -\frac{1}{2 \sqrt{X_T X_C Z_T Z_C}};$$

$$F_{23} = -\frac{1}{2 \sqrt{Y_T Y_C Z_T Z_C}} \quad (2)$$

Here $X_T$, $Y_T$, and $Z_T$ indicate the ultimate tensile strengths in the fiber direction and two transverse directions, $X_C$, $Y_C$, and $Z_C$ the ultimate strengths in compression; and $R$, $S$ and $T$ the ultimate shear strengths. In the present failure study of fiber metal laminate, the laminates under investigation are composed of two types of materials. Their ultimate strengths used for the calculation are given in the Table-3.

**Experimental Validation**

Tensile specimens as per IS 10192-1982 standards are machined from compression molded sheets of GLARE-3/2 and GLARE-4/3. For each specimen configuration, three replicates were tested. Dog-bone type specimen geometry as shown in Fig.4 is used. The tests were carried out at slow rate of 5% per minute. All laminates exhibited load-deformation curves with some degree of non-linearity before maximum load as a result of development of incipient damage such as matrix cracking, fiber failure or fiber pull-out.

**Results and Conclusion**

Finite element models are becoming more and more versatile and used in a wide range of applications. Finite element models can be validated and improved so that they can be used with more confidence in further analysis. In the present work the test specimens of GLARE-3/2, 4/3, 5/4, 6/5, 7/6 and GLARE-8/7 are subjected to analytical and numerical analysis. The experimental tests were conducted for test cases for only one thickness of 0.5 mm of aluminium 2024 alloy. With this thickness of 0.5 mm,
GLARE-3/2 and GLARE-4/3 specimens are fabricated for experimental validation. Only two types of specimens are made because of laborious processes involved in manufacturing and machining. The deformations obtained from Numerical analysis (six types of GLARE) and Experimental analysis (two specimens only) are shown in Table-4. Numerical predictions showed good agreement with experimental results. The percentage of variation of numerical results compared to experimental results and they are within the limits. The comparison of displacement as shown in Table-4 demonstrates the validity of the implemented constitutive model.

To bring out the nonlinear behavior of GLARE types, layer by layer comparison of stresses is made for GLARE 3/2 by varying the thickness of Al alloy 2024 T3 from 0.2 mm to 0.7 mm, incrementing by 0.1 mm in each step and the results are shown in Fig.5. The layer by layer numerical values are also shown in Table-2.

Similar trend of nonlinear stress variation is found in GLARE 4/3, 5/4, 6/5, 7/6 and 8/7. These tests conducted on test specimens indicate that the magnitude of stresses in the layers is material dependent. There is no variation in stresses due to the change in the stacking sequence of GLARE 3/2 and GLARE 4/3. Further, when thickness of Al alloy 2024 T3 is changed from 0.2 mm to 0.7 mm there is a marked reduction in magnitude of the stresses, demonstrating the improvement in the adoptability of the design. The magnitude of the stresses estimated from the test specimens for all the types of GLARE laminates considered in this investigation are shown in Fig.6. The magnitude of the stresses decreases with the increase in the thickness of 2024-T3 alloy.

### Table-3 : Ultimate Strengths of GLARE Constituents

<table>
<thead>
<tr>
<th></th>
<th>Al-2024T3 Alloy</th>
<th>S2-Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dir 1</td>
<td>Dir 2</td>
</tr>
<tr>
<td>Tension</td>
<td>345 MPa</td>
<td>345 MPa</td>
</tr>
<tr>
<td>Compression</td>
<td>345 MPa</td>
<td>345 MPa</td>
</tr>
<tr>
<td>Shear</td>
<td>170 MPa</td>
<td></td>
</tr>
</tbody>
</table>

### Table-4 : Comparative Results of Deformation Predictions

<table>
<thead>
<tr>
<th>GLARE Type</th>
<th>Numerical</th>
<th>Experimental</th>
<th>% Variation of Numerical Results with Experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE-3/2</td>
<td>3.968E-3 mm</td>
<td>3.8E-3 mm</td>
<td>4.23</td>
</tr>
<tr>
<td>GLARE-4/3</td>
<td>2.949E-3 mm</td>
<td>2.7E-3 mm</td>
<td>8.44</td>
</tr>
<tr>
<td>GLARE-5/4</td>
<td>2.322E-3 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLARE-6/5</td>
<td>1.923E-3 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLARE-7/6</td>
<td>1.645E-3 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLARE-8/7</td>
<td>1.431E-3 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### References


Fig. 5 Layerwise Stress Variation: GLARE 3/2 Specimen

Fig. 6 Stress Variation: All Types of GLARE Specimens