Structural Analysis of Composite Laminates using Analytical and Numerical Techniques

Divya Sanghi[1,*], *Divyansh* Singh [1], and *Vijay* Gautam[1]

[1]Delhi Technological University, Delhi-110034, India

Abstract. A laminated composite material consists of different layers of matrix and fibres. Its properties can vary a lot with each layer's or ply's orientation, material property and the number of layers itself. The present paper focuses on a novel approach of incorporating an analytical method to arrive at a preliminary ply layup order of a composite laminate, which acts as a feeder data for the further detailed analysis done on FEA tools. The equations used in our MATLAB are based on analytical study code and supply results that are remarkably close to the final optimized layup found through extensive FEA analysis with a high probabilistic degree. This reduces significant computing time and saves considerable FEA processing to obtain efficient results quickly. The result output by our method also provides the user with the conditions that predicts the successive failure sequence of the composite plies, a result option which is not even available in popular FEM tools. The predicted results are further verified by testing the laminates in the laboratory and the results are found in good agreement.

1 Introduction

Composites have been utilized to solve challenging technological problems since a very long time, but the true potential of composite structures and technology began to be exploited with the breakthroughs in automobile and aircraft industry where every ounce counts and for each pound of weight cut, the world goes faster and greener by a mile.

The term "composite" refers to any material constituting two or more substances with significantly different properties - physical and chemical, which remain integrated yet distinct in the final load bearing structure. Normally they are used in the form of layers of woven fibres or flat tapes wetted in a resin system. These materials have advantages [1] in comparison to metal that they can be easily moulded into complex shapes and curves providing smooth aerodynamic finishes. In terms of strength; careful design, appropriate material selection and cautious fabrication of composites can yield much stronger, stiffer and lighter structures than similarly loaded metallic parts.

However the design of a fibre-reinforced composite structure is considerably more difficult than that of a metal structure, principally due to the difference in its properties in different directions. Every composite structure consists of different layers called plies which can have different material properties and thickness. Therefore a composite structure can have several stacking sequences which can differ with the number of layers, material

---

[*] Corresponding author: divyasanghi.93@gmail.com

properties and orientation of each layer. The design consists of various stages; the pre-design stage is the most crucial stage as it involves material selection and preliminary composite laminate analysis to determine possible stacking sequence of a laminate taking in account different variables. This data can be then further modelled into complex geometries for final detailed analysis.

Since most of the existing design tools are less developed for composites than for conventional materials, experimental testing is still widely used to validate design and analysis models. Some FEM [2] solutions do offer composite analysis capability, but the analysis is not simple as with isotropic materials and usually involve high computational time and cost. It is also required that the models for analysis are perfectly tuned and validated against the experimental data.

2 Methodology

The main objective is to develop a MATLAB program on the basis of classical laminate theory which can be utilized to determine a preliminary ply layup order for the initial design stage. The results will act as a feeder data for the further detailed analysis. The MATLAB program will provide a user friendly interface to evaluate different stacking sequences in a shorter time and predict the results with reasonable accuracy without experimental cost of fabricating and testing the samples. Further, we have compared the MATALB results with experimental and FEM values to determine percentage of error and analyse the accuracy of the code as well.

2.1 Analytical Analysis

A laminate is constructed by stacking a number of such laminas in the direction of the lamina thickness. The design and analysis of such laminated structures require the knowledge of stresses and strains in the laminate. Macro-mechanics is the approach used to predict the strength and stiffness of such composite structures, based on the properties of each lamina.

The MATLAB code [3] for macro-mechanical analysis of a composite laminate is constructed using a plane stress assumption for a lamina. The code uses equations based on the classical lamination theory to compute stress and strain variations across the laminate thickness. It uses engineering elastic constants of the material used in each lamina and its orientation to form individual stiffness matrices. Each of these matrices is then utilized to form the extensional, bending and coupling stiffness matrices of the entire laminate. For a given laminate which is subjected to in-plane loads [4], namely axial and shear forces, and bending and twisting moments, the code can predict the values of local and global stresses, and local and global strains, at every co-ordinate within the laminate [5]. The deflection values for this code are then compared with the experimental and FEA results from ABAQUS.

2.2 Numerical Analysis

The analysis of the Composite Laminate was carried out in ABAQUS 6.14.1 using the following procedure:-

- The model was made using AUTOCAD in .dxf format and a planar shell of the sub-size dimension was created

- A pin of diameter 10 mm was then modelled using the 3D extrude option.
- The parts were appropriately partitioned for Mesh refinement and application of boundary conditions.
- The material properties were then added in the properties module, the material was given the properties of a Lamina and the fail stresses for each were given to separately calculate the failure of the different layers in the lamina.
- Further for a uniform mesh global and local seeds were created and then the assembly was made
- Now the boundary conditions are applied to various points, edges and partitions of the assembly
- The maximum loads as per the experimental values were applied.

2.3 Experimental Analysis

Along with FEA [6] analysis, testing of the laminates has been conducted so that the accuracy of the MATLAB program can be further verified.

2.3.1 Fabrication of Test Samples

One of the complexities involved in dealing with composite materials is the initial capital required to set up the advanced manufacturing techniques. Hence vacuum bagging using hand layup technique was used to fabricate [7] the samples for testing. Firstly E-glass fabric of 400 GSM and BD fibres was obtained locally along with the epoxy resin that would form the matrix of the composite. The epoxy selected was Araldite laminating epoxy due to its exceptional shear strength properties as well as being of medium viscosity allowing easy fibre penetration in vacuum moulding.

- The fabric was cut to shape and was laid out on an aluminium flat panel, whose top surface on which the moulding was to be done had been waxed to prevent the composite from sticking to the mould itself.
- Epoxy was then applied liberally to the layers and finally, after the last layer the peel ply (fibreglass coated teflon) was placed before the bleeder cloth. The edges of the aluminium panel was sealed using vacuum sealant tape and after connected a plastic bag with a vacuum pump the whole panel was sealed.
- The curing time of the epoxy is around 2 to 3 hours at 25 degree Celsius. After approximately 6 hours the plastic bag was opened and the laminate was removed off the panel, its GSM measured and labelled.
- The laminates were then cut according to **ASTM standard** for tensile tests using water abrasive jet cutting, utilising a cutting speed of 400mm/min.

Fig. 1. Prepared samples for testing.

Table 1. Details of the tested samples.

| S.No. | Sample ID | Ply Layup | | Thickness(mm) |
		No. of Layers	Orientation	
1	2-90-0	2	0/90	0.85
2	2-90-1	2	0/90	0.85
3	2-45-0	2	45/-45	0.85
4	2-45-1	2	45/-45	0.85
5	4-90-5	4	0/90	1.36
6	4-90-6	4	0/90	1.36
7	4-90-7	4	0/90	1.36
8	4-45-5	4	45/-45	1.36
9	4-45-6	4	45/-45	1.36
10	4-45-7	4	45/-45	1.36
11	6-90-2	6	0/90	1.81
12	6-90-3	6	0/90	1.81
13	6-90-4	6	0/90	1.81
14	6-45-2	6	45/-45	1.81
15	6-45-3	6	45/-45	1.81
16	6-45-4	6	45/-45	1.81

2.3.2 Testing of the samples

The samples fabricated were of three different thicknesses and fibre orientation of 90 degrees and 45 degrees. This would allow the MATLAB code to be verified for different fibre layups and also to help us in studying the effect of the number of layers and orientation on the laminate's strength. These samples were then tested under tensile loading using the machine which provided us with load versus displacement curves for each of the test samples. The maximum load capacity of the machine was 50KN which limited the thickness of the samples that could be tested and hence the maximum thickness was limited to 2.0 mm. The loading speed employed was 5 N/sec.

Fig. 2. Tensile test on the UTM machine.

3 Results

All 16 samples were tested on the UTM under tensile tests. The next step was to apply force with successive increments on the samples and the corresponding deflection data was then recorded. The force versus Deflection graph is plotted for each sample and a comparison was drawn between the values of the experimental analysis, analytical analysis and FEA analysis.
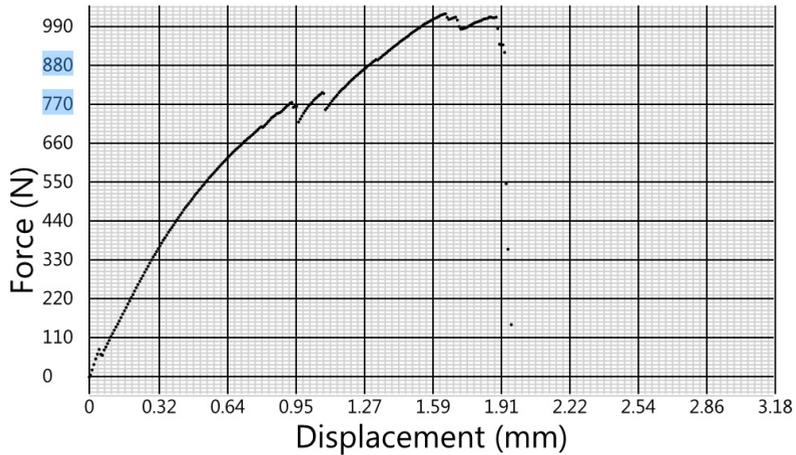

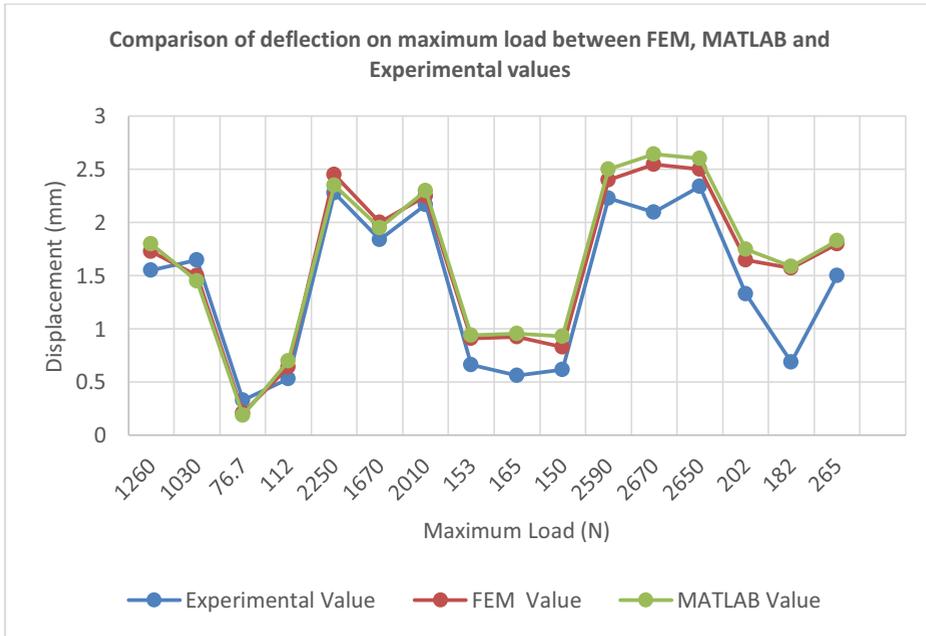**Fig. 3.** Force versus Deflection Graph of a 2 layer sample.

Fig. 4. Comparison of the FEA, MATLAB and Experimental Deflection Values.

The results showed that the FEA and MATLAB code values were consistent which proves the credibility of the MATLAB code. Also, it was found that the experimental results of the samples of same thickness were consistent. MATLAB and Experimental values showed a variance which was because of the defects caused during fabrication. It was also observed that the experimental and FEA results showed similar results for the region of failure at the maximum load.
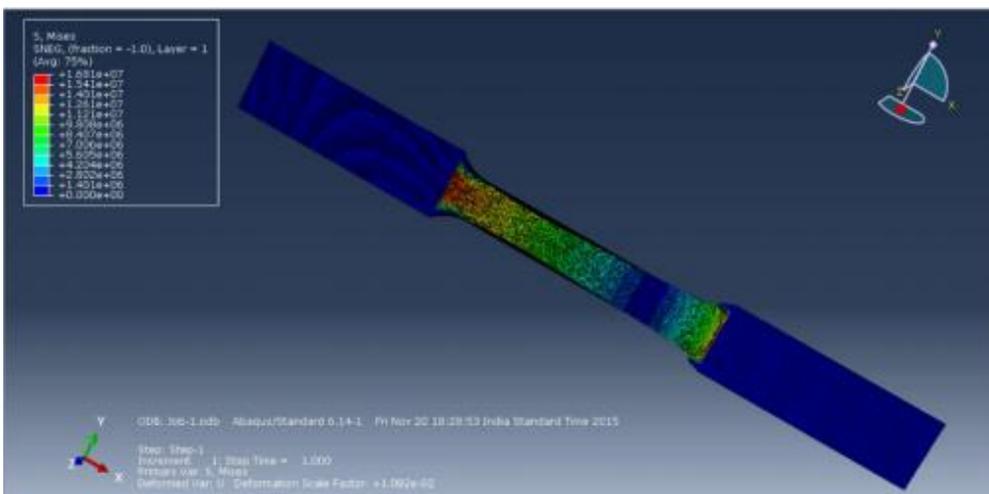

Fig. 5. Simulation results of the FEA analysis.

Fig. 6. Tested Samples under UTM machine.

4 Conclusion & future work

The study shows that the analytical calculation using the MATLAB code provides results with reasonable accuracy as compared to FEA and Experimental results. Further, it can be modified in a way that it can account for better accuracy of the experimental results. Work in underway so that the code can be implemented for 3-D figures and not just for 2-D laminates, such that more complex analysis of circular composite rods can also be done. Further Experimental tests need to be conducted on more samples varying in thickness and materials to analyse the scope of the MATLAB code.

References

1. http://www.autospeed.com
2. P. Roberts, *ABAQUS Lecture IV*, 2005
3. Y. Liu, *Introduction to Finite Element Methods*, *CAE Research Laboratory*, University of Cicinnati, 128, 2003
4. A.T. Nettles, NASA, 1994
5. G.H. Staab, *Laminar Composites,* Butterworth-Heinemann*,* Technology & Engineering*,* (1999)
6. H. Kim, *ABAQUS/CAE Tutorial*, 3 (2004)
7. http://alexpb.com