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PROGRESSIVE FAILURE ANALYSIS OF HYBRID COMPOSITE LAMINATES UNDER STATIC TENSILE LOADING

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Abstract

During the past decade use of both carbon and fiberglass composites have increased in aerospace, marine and automotive applications. One of the drawbacks of using carbon composites is that they are strong in axial direction but weak in transverse direction and hence are susceptible to impact damage. On the other hand fiberglass composites have excellent impact resistance, but typically less strength in axial direction. Recently aerospace manufacturers have started using hybrid laminates, comprising of both fiberglass and carbon materials. This paper presents the finite element modelling of the progressive failure analysis of hybrid composite laminates. The progressive deformation and damage mechanisms under static loading are investigated and compared with 3-D finite element progressive failure analysis of hybrid laminates under static loading. The model predictions showed good agreement with experimental data. The present modelling approach is computationally efficient and provides an effective method for the design of the hybrid composites.

Key words: *Finite element model, Hybrid composite, Progressive failure.*

1. INTRODUCTION

During the past decade use of both carbon and fiberglass composites have increased dramatically in aerospace, marine and automotive applications (Rice 2001, Fukushima 2009). One of the drawbacks of using carbon composites is that they are very strong in axial direction but weak in transverse direction and hence are susceptible to impact damage. On the other hand fiberglass composites have excellent impact resistance, but typically less strength in axial direction (Li 2009, Chandra 1999). Recently aerospace manufacturers have started using hybrid laminates, comprising of both fiberglass and carbon materials (Artemenko 2008). One of the other drawbacks of use of composites is high manufacturing cost. To overcome the high manufacturing cost, recently several manufacturers have started using low cost vacuum assisted resin transfer molding process (VARTM) to fabricate composite parts (Fu 2011). One of the difficulties involved with VARTM process is suitability of epoxy resins for ambient temperature VARTM (O'Brien 2001). In particular when higher glass transition temperatures are required (most of the aerospace components), the conventional VARTM fails. Although it is possible to pursue a conventional VARTM inside an oven, it has limitations on the size of the fabricated parts. An alternative H-VARTM© method, which uses a very low cost approach to achieve the VARTM fabrication at elevated temperatures without use of an oven was employed for the fabrication of these hybrid composites (Mall 2009). A combination of hybrid carbon and glass fibers woven laminates in conjunction with high glass transition temperature resins demonstrates the process. Mechanical properties of H-VARTM fabricated composite panels will be presented.

While the manufacturing can be achieved with the alternate process, the designs of stacking sequences present significant challenges (Vanaja 2002). Computational modelling facilitates the analysis of different stacking sequences towards developing an optimal design configuration (Pepyne 2000).

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Finite element methods is a strong tool which can be used in analysing elastic and dynamic properties, thermal distributions, transient, wave propagation and magnetic fields (Kyriazoglou 2007). This paper offers a finite element model which can be used for prediction of progressive failure analysis of hybrid composites.

2. EXPERIMENTAL

2.1 Hybrid composite fabrication

2.1.1 Materials

The Epoxy resin Epon 862 and hardener DETDA were purchased from Miller Stephenson Chemical Company Inc. and were used as per the manufacturer's recommendation.

2.1.2 Fabrication process

Composite specimens were manufactured using the low cost technique known as Heated Vacuum Assisted Resin Transfer Method (H-VARTM). H-VARTM uses vacuum to achieve a pressure differential to flow resin across a fabric gradient. All composite laminates were manufactured using this method. H-VARTM can be used in remote locations and does not require the use of an autoclave.

Three composite laminates were manufactured for this study. The glass laminate consisted of 4 plain weave lamina. The carbon laminate consisted of 4 plain weave lamina. The hybrid laminate consisted of 8 plain weave lamina. The stacking sequence of the hybrid is shown in Figure 1.a where four glass lamina outlined the inner four carbon lamina.

A glass mold was used to generate a vacuum bag. The glass and carbon fabric sheets were placed into the vacuum bg. Resin distribution media and release ply were installed. Vacuum was applied to the bag to aid in wetting the fabric. Figure 1.b shows a completed bag with fabric sheets installed during a vacuum loss test.



Fig 1. a) Stacking sequence of hybrid composite; b) Completed vacuumed bag of laid laminate.

Epon 862 and curing agent W were mixed with the ratio of 100:26.4 which recommened by manufacturer. The mixture was hand stirred for 4 minutes followed by degassing at 70 °C for 30 minutes under a vaccum of 30 in Hg. The degassed resin was flown into the prepared vacuumed bag and the composites were cured at 250 °F for 2 hours followed by another 2 hours postcuring at 300 °F. Final composites were cut with water jet machine to the size of tension specimens. In order to obtain

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strain values during the tensile test, strain gages were applied to the specimens according to ASTM E1237. In case of hybrid, specimens were notched before applying the strain gages (Fig. 2).

2.1.3 Fundamental properties evaluation

Speciments of glass, carbon and hybrid composites were tested for obtaining their tensile strength using ASTM D3039/D3039M. An Instron test frame 3384 was utilized to apply the load to the specimens and record the stress-strain curves.

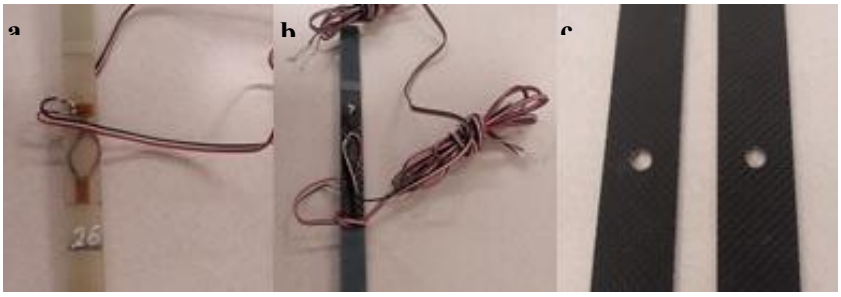


Fig.2 Tension samples a) glass fiber, b) carbon fiber and c) hybrid composites.

2.2 Finite element model

The finite element model was built using Brick element and was analyzed using ANSYS 14.0. The model shown in Figure 2 which contains 71,672 nodes and 64,384 elements. Table 1 shows the geometrical parametyers of the model and comparison with samples made using H-VARTM technique. The model consists of 8 layers including 2 layers of glass fibers followed by 4 layers of carbon fiber and another 2 layers of glass fibers, where each of these are divided into 2 sublayers; one reperesenting the fibers longtitual properties and another one for transversal properies of fibers. Therefore there are a total of 16 sublayers in the numerical model. This model is built based on the actual configuration of woven fabric (Fig. 4) where half of the tows going from left to right (weft) and the other half going from bottom to top (warp); therefore at each point in one layer, two yarns are presented (one weft and one warp). In order to create the same structure, each layer in the numerical model is divided into two sublayers repesenting weft and warp. Weft and warp of glass and carbon are shown in different colors where each layer is made from stacking sublayer 1 and sublayer 2 (Fig. 5).

Table 1. Geometry description of model and experiment samples (Unit: inch).

	GLASS		CARBON		HYBRID	
	MODEL	EXPERIMENT	MODEL	EXPERIMENT	MODEL	EXPERIMENT
LENGTH	6.9972	7	6.9972	7	6.9972	7
THICKNESS	0.0487	0.0487	0.038	0.038	0.0835	0.0835
WIDTH	0.4998	0.4995	0.4998	0.4982	0.9996	0.9972
HOLE DIAMETER	N/A		N/A		0.25	0.25

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The input values of Young's modulus and poisson ratio and shear modulus were obtained by performing experiments on two different composite systems, one made out of 4 layers of glass fiber and 862 epoxy resin and the other with 4 layers of carbon fiber in the same matrix. The experimentally obtained properties were then used in conjuction with simplified micromechanics equations to predict all the three dimensional propertoies including tensile modulii, poisson's ratios and shear modulii and are given in Table 2. In addition experimental results for the failure strengths were used to determine the onset of failure in hybrid laminates. The failure stress of glass and carbon in 90 degrees was considered to be equal to failure stress of matrix itself (Epoxy 862) since the fibers do not have compatable strength in 90 degree. In order to verify the mechanical criteria used in the hybrid model, a model of glass and carbon composite were built and the progressive failure behavior of models and experiment were compared (data not shown). Figure 3. shows a schematic of the finite element model. Warp and weft elements were stacked on each other to build the necessary thickness of the hybrid laminate. A single lamina consists of 2 layers in the numerical model. Warp and weft elements were alternated longitudinally as well as laterally. This system was followed throughout in order to build the complete finited element model.

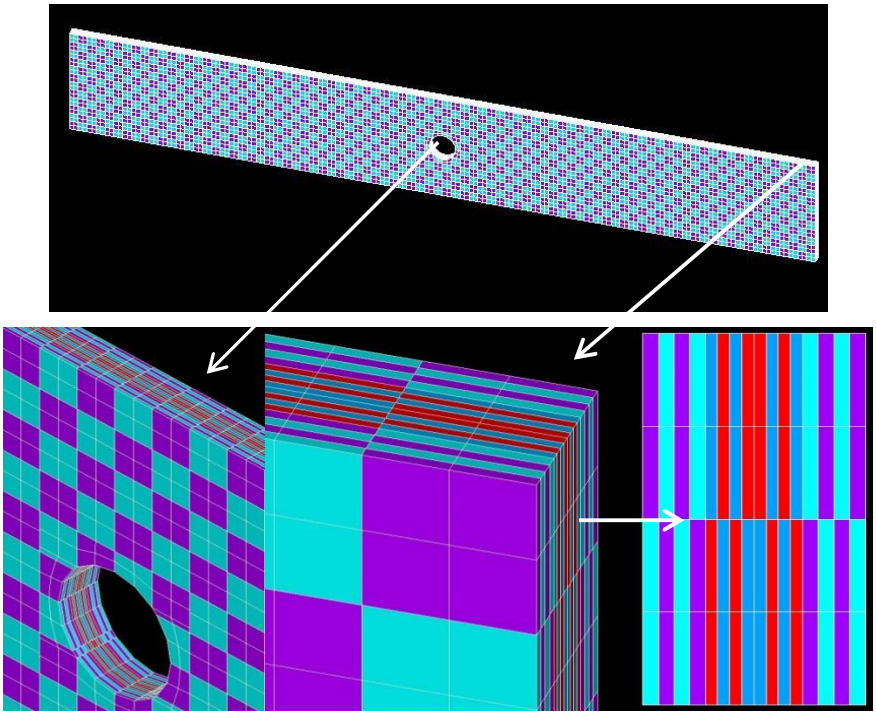


Fig.3 Finite element model of notched hybrid composite.

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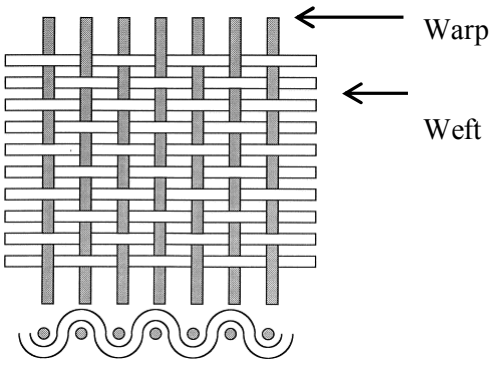


Fig.4 Schematic of component in woven fabric (Peled et. al., 1998).

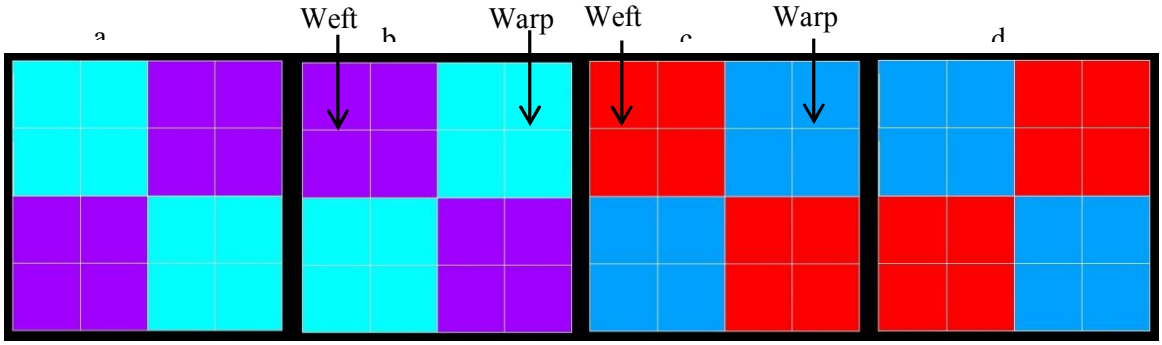


Fig.5 Finite Element Model of sublayers: a) glass sublayer 1, b) glass sublayer 2, c) carbon sublayer 1, d) carbon sublayer 2.

The model was built on the assumptions that the effects of undulations are negligible and the laminate can be fully represented using 3-D mosaic elements. Once the finite element model was complete, model was subjected to appropriate boundary conditions.

Table 2. Mechnaical criteria used in Finite Element Model (Unit: Msi).

	GLASS		CARBON	
	0 DEGREE	90 DEGREE	0 DEGREE	90 DEGREE
FAILURE STRESS	0.06	0.009	0.18	0.009
E_1	4.73	1.03	12.4	0.873
E_2	1.03	4.73	0.873	12.4
E_3	1.03	1.03	0.873	0.873
G_{12}	0.448	0.448	0.351	0.351
G_{23}	0.574	0.448	0.437	0.351
G_{13}	0.448	0.574	0.351	0.437
PR_{12}	0.28	0.06	0.34	0.02
PR_{23}	0.43	0.28	0.46	0.34
PR_{13}	0.28	0.43	0.34	0.46

2.2.1 Progressive failure analysis

In order to study the hybrid laminate behaviour under tensile loading, one end of the model was fixed in all three dimensions while a displacemnet of 0.01 in X direction (increment of 0.01) was applied to the other end. After each load step, the maximum stress in all four types of laminas and reaction forces at nodes where displacements were applied were calculated. Those elements for which assigned failure criteria have satisfied, were not used for load transmission. This was achieved by lowering the modulus of the failed elements to essentially zero. This method prevents load transmission through the failed elements simulated as if the element is no longer capable of carrying further load.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties of glass, carbon and notched hybrid composites

Three types of composites were made and were tested to obtain their mechnaical proeprties: glass composite (4 layers of E-glass fabric in Epoxy 862 matrix), carbon composite (4 layers of AS4 carbon fabric in Epoxy 862 matrix) and hybrid composite (2 L of G + 4 L of C + 2 L of G in Epoxy 862). Figure 6 presents the experimental data which shows that the strength of 91.6 Ksi for carbon laminates, 25.7 Ksi for glass glass laminates and 34.16 Ksi for hybrid laminates. This result indicate an increase of 33% in mechanical strength of glass composite by adding carbon layers.

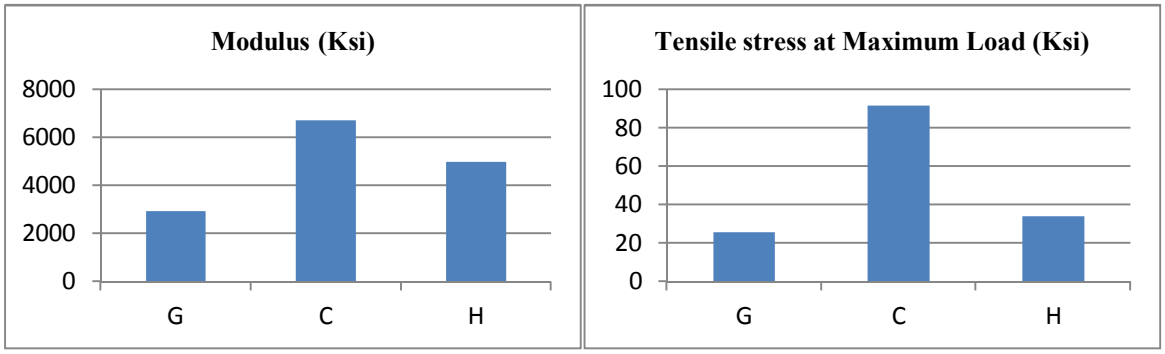


Fig.6 Young's modulus and tensile strength of glass (G), carbon (C) and hybrid (H) composites.

3.2 Finite Element Model data

Three dimensional finite element model was used for the prediction of notched hybrid composite. The load was applied in the form of displacements (increment of 0.01 inches to one end while the other end was fixed) and at each step, elements which have exceeded their failure strength were removed from load carrying capability. Figures 7 and 8 show the failed elements after applying different displacements (pink elemts are the one which have failed).

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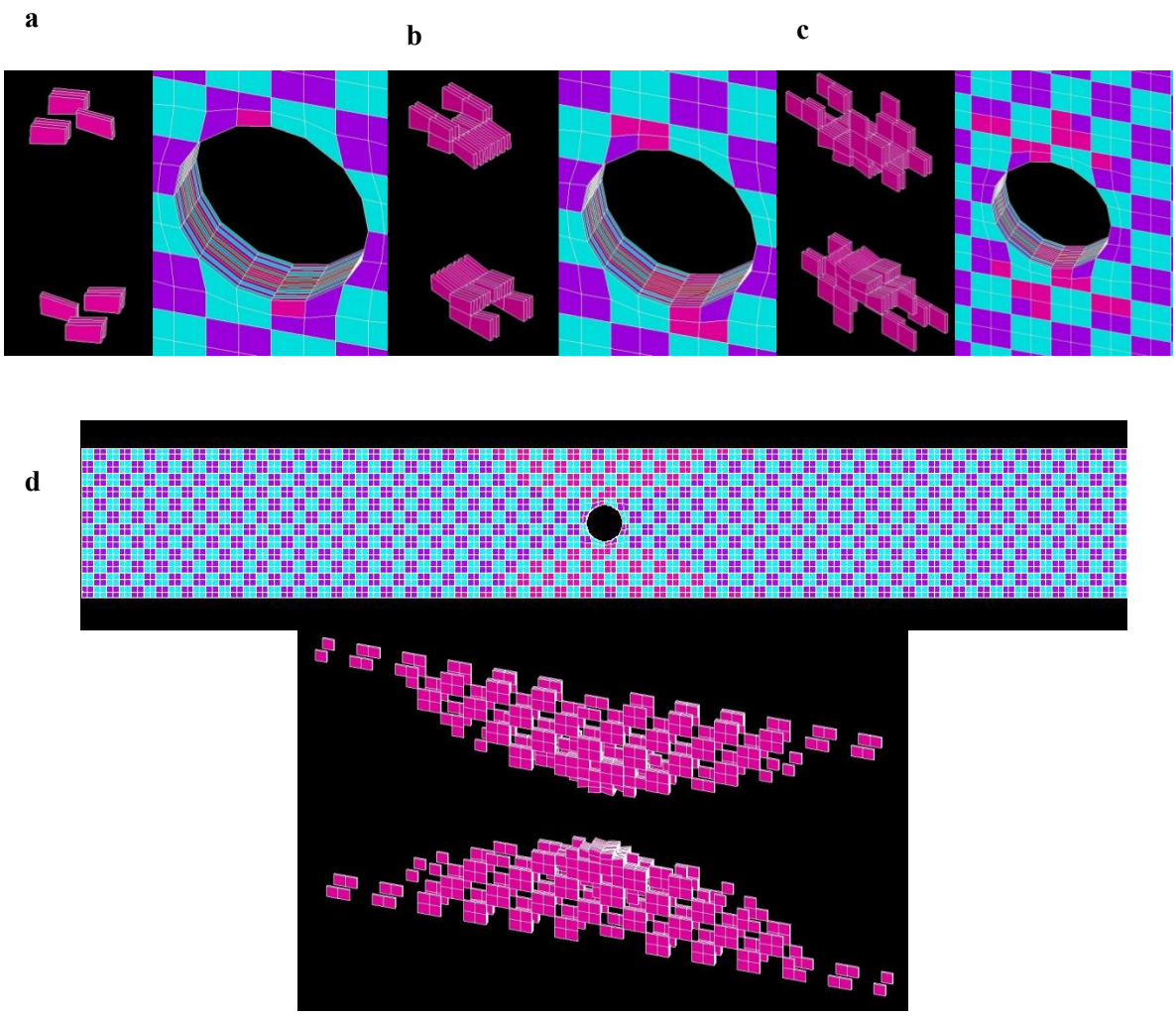


Fig.7 Failed elements at different tensile displacements: a) 0.02", b) 0.03", c) 0.04" and d) 0.05"

Table 3 shows the number and attribute of failed elemets at each load step. The total number of failed elemets are 6,876 from which 74% are glass weft (glass in 90 degree), 20% are carbon weft (carbon in 90 degree) and the rest are warp of glass and carbon. The failure starts around the hole and among the glass wefts and expands in 45 degree plane (shear plane). This behaviour was expected since a unidirectioal load is applied to the model where yarn align with the load holds huge portion of the stress while yarn in 90 degree is weak and cannot hold large stress which results in its failure.

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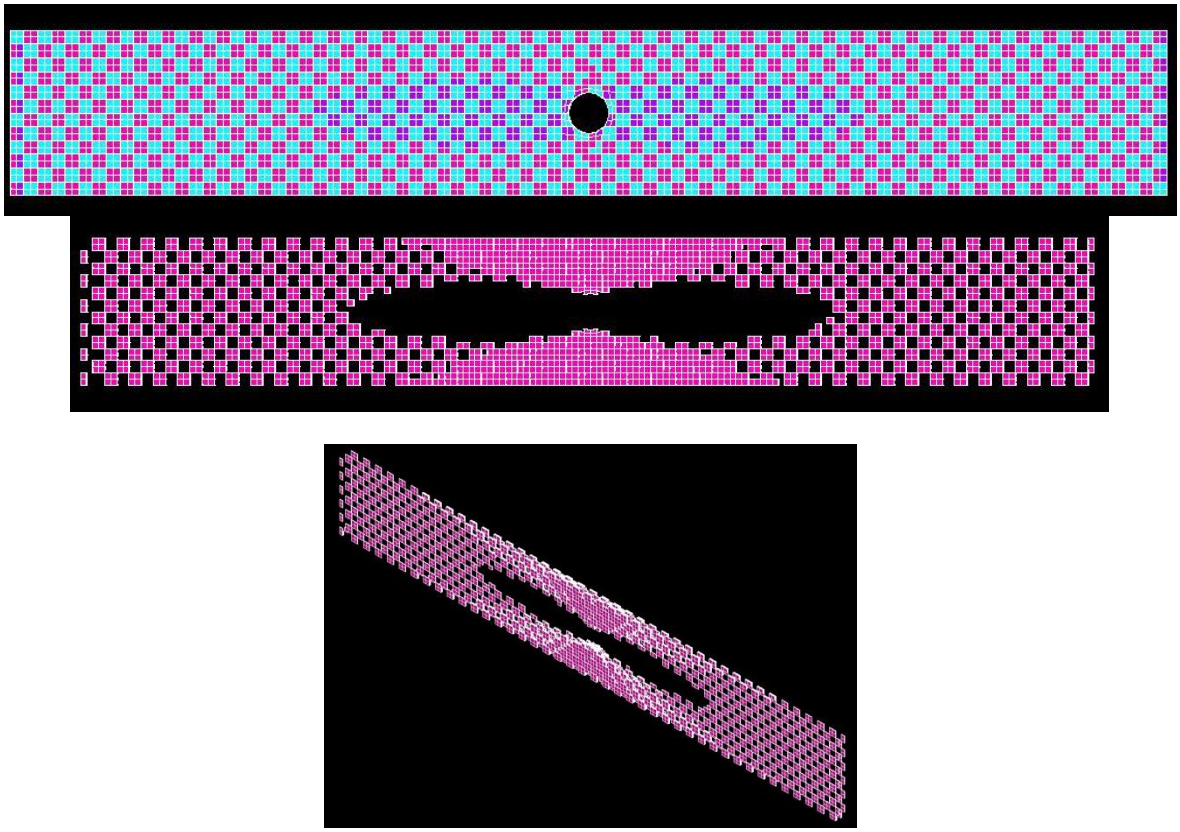


Fig.8 Failed elements at 0.06 in displacement (complete failure of the hybrid laminate).

Table 3. Failed elemets number and attribute.

	Glass		Carbon	
Extension (in)	0 degree	90 degree	0 degree	90 degree
0.01	-	-	-	-
0.02	-	8	-	4
0.03	8	24	-	12
0.04	8	52	8	40
0.05	40	696	24	132
0.06	252	4304	100	1164
Total	308	5084	132	1352
%	4.48	73.94	1.92	19.66

3.3 Comparison of model prediction and experiments

Table 4 shows the obtained mechanical data from the model and experiments. The model predicts a maximum load of 3170 lb which was 12% higher than the experimental load of 2824 lb. This difference was also observed in maximum stress values. The values of extension and maximum strain are closer with only 7% difference. These data indicates that the finite element model behaves slightly stiffer than the actual fabricated composites. This was expected since the finite element model is asuumes no presence of defects while the fabricated composites typically have defects like voids, tow distortion and micro-delaminations.

Table 4. Comparison of mechanical proeprties predicted by model and obtained from experiment.

	MODEL	EXPERIMENT	DEVIATION %
MAXIMUM LOAD (LB)	3170	2824	12.25
MAXIMUM EXTENSION (IN.)	0.06	0.056	7.14
MAXIMUM STRESS (PSI)	37979.26	33913.62	11.98
MAXIMUM STRAIN	0.008575	0.008	7.18

Figure 9 shows a load verses extension of hybrid composite and its model. It is obvious that except a slight error in obtaining maximum load (12%) and maximum extension (7%), the model is able to predict the progressive failure behaviour of the hybrid composite. Most notable is how well the numerical model followes the experimental load-extension trace. In this regard, the numerical model fits very well.

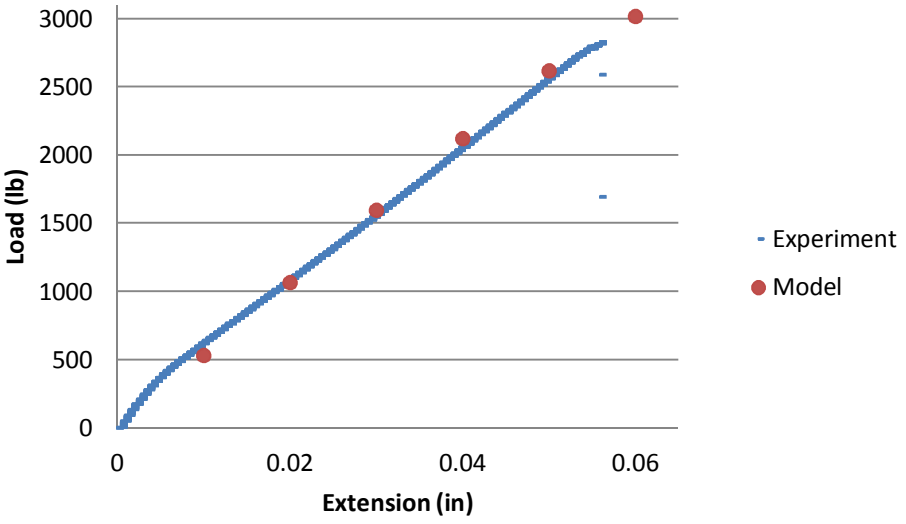


Fig.9 Experimental and Analytical Comparison of Load vs. Displacement

4. CONCLUSIONS

A three dimensional finite element was developed to predict progressive failures in hybrid composite

laminates. The finite element model accurately predicts the mechanical behaviour under static tensile loading and also provides a good estimation of failure strength (12% deviation) and strain (7% deviation). The potential of this model has far reaching implications due to the hybrid configuration, which is likely to have many structural applications including aerospace, automotive and alternate energy such as wind turbine blades. Given the high costs of today's composite material and the ultra high costs of test equipment and testing, the present finite element model offers a reasonable alternative in designing and fabricating innovative hybrid composite materials.

REFERENCES

Artemenko SE & Kadykova YA 2008, 'Hybrid compopsite materials', *Fibre Chemistry*, vol. 40, no. 6, pp. 490-492.

Chandra, R Singh, SP Gupta, K 1999, 'Damping studies in fiber-reinforced composites: a review', *Composite Structures*, vol. 46, pp. 41-51.

Fu, X Zhang, C Liang, R Wang, B Fielding, JC 2011, 'High Temperature Vacuum Assisted Resin Transfer Molding of Phenylethynyl Terminated Imide Composites', *Polymer Composites*, vol. 32, Issue 1, pp. 52-58.

Fukushima, H Jurek, H Drzal, R 2009, 'Carbon Fiber/Graphite Nano Platelet Hybrid Composites', ICCM-17, Edinburgh, Scotland, July 27-31.

Li, Y Hori, N Arai, M Hua, N Liua, Y Fukunaga, H 2009, 'Improvement of interlaminar mechanical properties of CFRP laminates using VGCF', *Composites: Part A*, vol. 40, pp. 2004–2012.

Mall, S Katwyk, DW Bolick, RL Kelkar, AD Davis, DC 2009, 'Tension–compression fatigue behavior of a H-VARTM manufactured unnotched and notched carbon/epoxy composite', *Composite Structures*, vol. 90, pp. 201–207.

O'Brien, DJ Mather, PT White, SR 2001, 'Viscoelastic Properties of an Epoxy Resin during Cure', *Journal of COMPOSITE MATERIALS*, vol. 35, no. 10.

Peled, A Bentur, A Yankelevsky, D 1998, 'Effects of Woven Fabric Geometry on the Bonding Performance of Cementitious Composites Mechanical Performance', *Advanced Cement Based Materials*, vol. 7, Issue 1, pp. 20–27.

Pepyne, DL & Cassandras, CJ 2000, 'Optimal Control of Hybrid Systems in Manufacturing', PROCEEDINGS OF THE IEEE, vol. 88, no. 7, July, pp. 1108-1123.

Rice, BP Chen, C Cloos, L Curliss, D 2001, 'Carbon Fiber Composites Prepared From Organoclay-Aerospace Epoxy Nanocomposites', SAMPE, Long Beach, CA, May 6-10.

Vanaja, A & RAO RMVGK 2002, 'Fibre Fraction Effects on Thermal Degradation Behaviour of GFRP, CFRP and Hybrid Composites, *Journal of REINFORCED PLASTICS AND COMPOSITES*, vol. 21, no. 15, pp. 1389-1398.