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Effect of Ply Orientation on Strength and Failure Mode of Pin Jointed Unidirectional Glass-epoxy Nanoclay Laminates

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ABSTRACT

In the present work the effect of the different ply orientations and nano filler on the bearing strength and failure mode of the pin joints is investigated both experimentally and numerically. Glass-epoxy composite laminates were prepared with [0°/45°/90°], [0°/45°/0°] and [0°/90°/0°] ply orientations. Nanoclay filler with 1, 2, 3, 4 and 5 wt% were added in the epoxy for the said orientations to prepare the pin joints. Results show that the strength of the pin joints is drastically dependent on both ply orientations and nanofiller wt%. The joint geometry *i.e.*, the distance from the free edge of specimen to the diameter of the hole (E/D) ratio and width of the specimen to the diameter of the holes (W/D) ratio were also investigated which effected the failure mode of the joints. Tsai-Wu failure theory along with the characteristics curve method was used for the prediction of failure modes numerically.

Keywords: Polymer nano composites, ply orientations, nanoclay, pin joint, finite element methods

1. INTRODUCTION

Fiber-reinforced composites offer the most efficient structures in automotive, aeronautical, marine and aircraft engineering[1] applications, due to their high strength to weight and stiffness to weight ratios along with high durability, low coefficient of friction and high mechanical performance. For the design and assembly of the different structures holes are to be drilled. The stress concentration around the hole causes the unpredictable failure and results in poor performance of the joint[2]. Joint design and their efficiency are the major concern in the fiber reinforced laminate composites used for a structure.

Studies show that the failure strength of joints are affected by many parameters, such as the geometric dimensions, material properties, laminate lay-up, ply orientation etc[3,4,5]. A brief review of work carried on the effect of these different parameters on the failure analysis of pinned joints in polymer composites are given hereby.

Okutan[6], *et al.* examined the effects of woven fiber, specimen width-to-hole diameter ratio, and the ratio of edge distance to hole diameter on the bearing strength of woven laminated composites. Okutan[7] carried out tests on laminates of $[0/90/0]_s$ and $[90/0/90]_s$ ply orientation to determine the effect of ply orientation in fiber-reinforced laminated composite joints. Okutan and Karakuzu[8] investigated the response of pin-loaded laminated composites for two different ply orientations such as $[0/45]_s$ and $[90/45]_s$. Karakuzu[9], *et al.* observed the behaviors of pin loaded woven glass-vinylester composite plate with various dimensions both experimentally and numerically. Baba[2] investigated the effects of varying ratios of width-to hole diameter and edge distance-to-hole diameter and fiber orientation on the failure strength and failure mode in a pinned joint laminated composite plate. Karakuzu[10], *et al.* determined the failure mode, failure load and bearing strength in woven glass vinylester composite plates with two parallel circular holes. Numerical analysis was carried using two-dimensional finite element model to compare with the experimental results. Hashin failure criteria was used in the failure analysis. Karakuzu[11], *et al.* investigated the effects of geometrical parameters such as the edge distance-to-hole diameter ratio, plate width-to-hole diameter ratio and the distance between two holes-to-hole diameter ratio on the failure loads and failure modes in woven-glass–vinylester composite plates with two serial pin-loaded holes, experimentally and numerically. Sen[12], *et al*. determined the failure mode and bearing strength of mechanically fastened bolted-joints in glass fiber reinforced epoxy laminated composite plates, experimentally. Uddin and Sun[13] studied the strength of unidirectional glass/epoxy composite with silica nanoparticle enhanced matrix. Aktas[14], *et al.* investigated failure load and failure mode of glass-epoxy composite plates with single and double parallel pinned-joints experimentally and numerically. Kishore[15], *et al.* investigated various failure modes and failure loads for multi-pin joints in unidirectional glass fiber/epoxy composite laminates by finite element analysis and validating the results with the experimental work. Asi[16] studied the bearing strength behaviour of pinned joints of glass fiber reinforced composite filled with different proportions of Al_2O_3 particles, as a function of filler loading and joint geometry. Wei[17], *et al.* studied the effect of SiO_2 nanoparticles modified epoxy on the mechanical properties of basalt fiber rovings. Aktas[18]

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studied the failure modes and failure loads of woven glass epoxy composite plates with one and two serial pinned joints numerically and experimentally. Ondurucu[19], *et al.* investigated damage development process of glass–epoxy laminated composite pinned-joints due to varying stacking sequence. Pisano[20], *et al.* studied the prediction of the failure mechanism of pinned joints in composite laminates via limit analysis numerical procedure. Khashaba[21], *et al.* studied the influence of specimen stacking sequences on the mean bearing strength, mean ultimate failure stress, failure displacement and bearing stiffness. Qin[22], *et al.* revealed the effect mechanisms of different fasteners on mechanical behaviors of composite bolted joints. Attar[23] investigated the effects of geometrical parameters such as the edge distance-to-hole diameter ratio, plate width-to-hole diameter ratio and the distance between two holes-to-hole diameter ratio on stress distribution in a unidirectional composite laminate with two serial pin-loaded holes, analytically and numerically. Arun[24], *et al.* studied the strength of bolted fasteners and hybrid fasteners under tensile loading for unfilled, TiO_2 and ZnS filled Glass Fabric Reinforced Polymer Matrix Composites (GFRP). Olmedo[25], *et al.* proposed an analytical model to predict bearing failure of pinned-joint composite laminates. The model combined a mass-spring model to reproduce the joint stiffness and a characteristic curve model to predict bearing damage. The accuracy of the analytical model was validated through comparison with experimental results. Li[26], *et al.* used Subset Simulation technique to perform a probabilistic analysis on the bearing strength of a composite pin joint. A 2D finite element analysis was utilised for the deterministic progressive damage analysis.

From the literature review it was seen that various parameters were studied to find their effect on the strength of pin joints; ply orientation being one of them. The present work deals with the development of glass epoxy nanoclay (Cloisite 30B) laminates with different ply orientations. Thereafter the developed laminates were used to prepare the specimen for the pin joints. The pin joints were then analysed both experimentally and numerically.

2. EXPERIMENTAL

The following section gives the details of different materials used and methodology followed for the experimentation in the present work.

2.1 Materials

2.1.1 Resin

Materials used for the preparation of the laminates were epoxy, hardener, accelerator and glass fabric. The epoxy used ‘L-12’ also known as Lapox is DGEBA (Di Glycidyl Ether of Bisphenol-A). K-12 hardener and K-13 accelerator were used. Resin *i.e.* (epoxy, hardener and accelerator) were supplied by Atul Ltd., Gujarat, India. Tensile strength, elastic modulus in tension, flexural strength, compressive strength and impact strength for the resin were 70-90 N/mm^2, 15000-16000 N/mm^2, 100-120 N/mm^2, 190-210 N/mm^2 and 4-7 KJ/m^2 respectively.

2.1.2 Glass Fabric

Unidirectional *Advantex* glass fabric with 1200 gsm was used as reinforcing agent. It was supplied by the Owens Corning India Pvt. Ltd, Mumbai, India. The tensile strength, elastic modulus and elongation at breaking load for Advantex single filament are 3100-3800 MPa, 80-81 GPa and 4.6%, respectively.

2.1.3 Nanoclay

Nanoclay (Cloisite 30B) used in the present work was supplied by the Connell Bros. Company Pvt. Ltd., Mumbai, India. Cloisite 30B is a natural montmorillonite modified with a quaternary ammonium salt. Cloisite 30B is an additive for plastics to improve various physical properties.

2.1.4 Acetone

Acetone is an important solvent with molecular formula $(C_3H)_2CO$ and has been used to properly mix epoxy and nanoclay. It was supplied by the Loba Chemie Pvt. Ltd, Mumbai, India.

2.2 Material Processing and Sample Preparation

Laminates were prepared using epoxy resin as matrix and glass fiber as reinforcement. There are several methods for the preparation of laminates. The following procedure was used for the preparation of the laminates.

Epoxy resin and nanoclay (with different wt%), were mixed using homogenisation at 14000 rpm for 15 minutes. It was followed by sonication for ensuring the proper dispersion of the nanoclay in the epoxy resin. After sonication process, keeping hardener to resin ratio 1:1, hardener and accelerator were added to the epoxy-nanoclay mixture. Mechanical stirrer was used to mix all the components in the mixture.

Placing the first layer of the glass fiber on the Teflon sheet, resin was applied on it with a brush and then second layer was placed on it, following this procedure the laminate was formed with three layers of glass fiber. A hand roller was used to remove any entrapped air particles between the layers so that laminates can properly stick to each other. Laminates were prepared with three ply orientations *i.e.* [0°/45°/90°], [0°/45°/0°] and [0°/90°/0°]. These ply orientations were prepared with different wt% of nanoclay *i.e.*, 0,1,2,3,4 and 5.

After curing the laminates at room temperature for 24 h, they were pressed in the compression moulding machine by keeping at constant load of 120 kN and curing temperature of 150 °C for 2 h. Keeping the pressure constant, the laminates were finally cooled to room temperature.

3. RESULTS AND DISCUSSION

Tensile and shear test were conducted for the different ply orientations and with different wt% of nanoclay. Based upon their results, the pin joints were prepared and tested.

3.1 Tensile and Shear Test

The tensile and shear tests were performed at 25 ± 2 °C on a Universal Testing Machine – Model Z010, Zwick-Roell, Germany, according to ASTM D3039 and D5379 standards respectively.

Tensile strength and tensile modulus were determined for the different ply orientations and with different wt% of nanoclay. The grip to grip separation of the samples having 138 mm gauge length was 238 mm at the start position. A crosshead speed of 2 mm/min was maintained. At least 3 specimens of each blend were tested and the average values were reported. The results obtained for different ply orientations for various compositions of nanoclay are shown in Fig. 1.

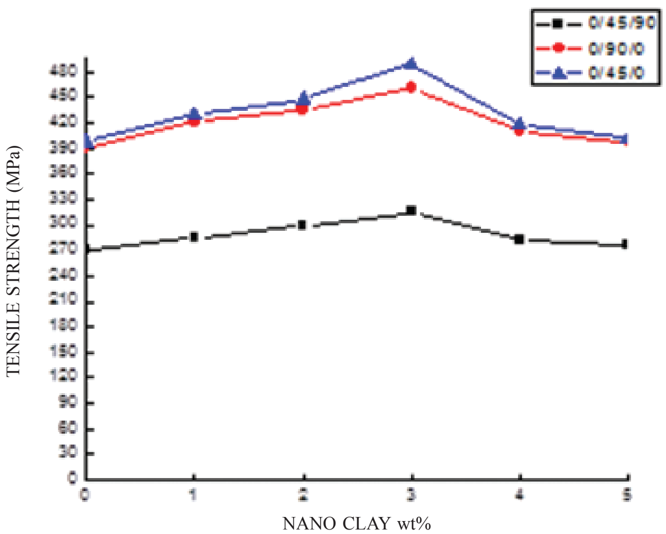
It can be seen from Fig. 1 that the tensile modulus and tensile strength of the glass fiber reinforced epoxy composite for all the ply orientations increased up to 3 wt% of nanoclay. Dispersed filler particles act as mechanical interlocking between fiber and epoxy matrix which creates a high friction coefficient. The decrease in tensile modulus and tensile strength beyond 3 wt% is due to the presence of a large agglomerate phase in the matrix which deteriorates their mechanical properties. Agglomeration may easily happen for smaller particles at higher filler contents due to the reduced inter particle distance[27].

For the shear test of different laminates, a crosshead speed of 2 mm/min was maintained. At least 3 specimens of each blend were tested and the average values were reported. Table 1 shows the mechanical properties of glass/epoxy nanocomposite laminates.

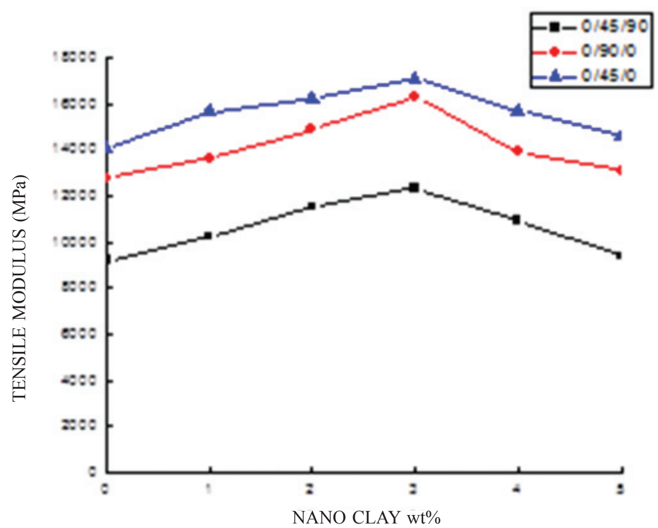
Mechanical properties given in Table 1 clearly show that the tensile and shear strength of the [0°/45°/90°] ply orientations with addition of 3 wt% of nanoclay are very less as compared to the [0°/45°/0°] and [0°/90°/0°] ply orientations. It can be seen that [0°/45°/0°] ply orientation has higher longitudinal properties than the [0°/90°/0°] orientations whereas [0°/90°/0°] ply orientations have higher transverse properties than the [0°/45°/0°] ply orientation. So both [0°/45°/0°] and [0°/90°/0°] ply orientations with the addition of 3 wt% of nanoclay were selected for making the pin joints to compare their bearing strength and failure modes.

3.2 Pin Joint Configurations

In the present work, a plate with a single pin hole of diameter D was used. The diameter of the hole was fixed to 4 mm for inserting a rigid pin. The hole was located along the centerline of the plate at a distance E from one end of the plate, shown in Fig. 6(a). A tensile load, P was applied on the plate. The rigid pin resisted this load. Load was parallel to the plate and was symmetric with respect to the centerline. Hence the load could not create bending moments about the x, y, or z-axis.



(a)



(b)

Figure 1. (a) Tensile strength vs. weight percentage of nanoclay and (b) Tensile Modulus vs. weight percentage of nanoclay.

Table 1. Mechanical properties of glass fiber/epoxy composite laminate

Mechanical Property	Symbol (Units)	Without nanoclay			3 wt% of nanoclay		
		[0°/45°/0°]	[0°/90°/0°]	[0°/45°/90°]	[0°/45°/0°]	[0°/90°/0°]	[0°/45°/90°]
Longitudinal modulus	E_1 (MPa)	14112.45	12809.23	9213.23	17113.6	16297.3	12345.7
Transverse modulus	E_2 (MPa)	6214.67	7802.23	5589.98	7145.67	8824.45	7324.56
Laminate shear strength	s (MPa)	123.45	155.68	132.14	139.44	178.45	151.12
Longitudinal strength in tension	X_t (MPa)	397.18	390.76	270.12	489.57	461.67	321.23
Transverse strength in tension	Y_t (MPa)	190.34	255.98	211.54	212.65	293.4	248.12
Poisson ratio	ν_{12}	0.33	0.32	0.32	0.325	0.31	0.3378
Longitudinal strength in compression	X_c (MPa)	330.89	324.11	240.72	422.24	407.11	296.51
Transverse strength in compression	Y_c (MPa)	182.33	224.45	165.12	197.18	272.14	207.12

Edge distance-to-hole diameter (E/D) and width-to-diameter (W/D) ratios in the specimen were designed from 2 to 5. The samples were prepared with different E/D and W/D ratios, given in Table 2, for the two different ply orientations *i.e.*,[0°/45°/0°] and [0°/90°/0°] for 3 wt% of nanoclay.

Table 2. Geometries of pin-joints samples tested for different ply orientations

E/D ratio	W/D ratio	D (mm)	E (mm)	W (mm)	Thickness (mm)	Length from hole to edge (mm)
2	2	4	8	8	2	100
	3	4	8	12	2	100
	4	4	8	16	2	100
	5	4	8	20	2	100
3	2	4	12	8	2	100
	3	4	12	12	2	100
	4	4	12	16	2	100
	5	4	12	20	2	100
4	2	4	16	8	2	100
	3	4	16	12	2	100
	4	4	16	16	2	100
	5	4	16	20	2	100
5	2	4	20	8	2	100
	3	4	20	12	2	100
	4	4	20	16	2	100
	5	4	20	20	2	100

3.2.1 *Results of pin joint with 3wt% of nanoclay*

It was seen that the mechanical properties of the laminates were maximum at 3 wt% of nanoclay. Hence the pin jointswith same W/D and E/D ratios were prepared by adding 3wt% of nanoclay to glass/epoxy laminates for the two ply orientations *i.e.*,[0°/45°/0°] and [0°/90°/0°]. The laminates were tested on Universal Testing Machine for their tensile strength. The plots of these results are shown in Fig. 2 and Fig. 3.

Joint failure with the net-tension and shearing modes is immediate without any warning. These failures result from excessive tensile and shear stresses. However, bearing failure is progressive and occurs in the material immediately adjacent to the contact area between the pin and the laminate. It is primarily caused by compressive stresses acting on the hole surface. Bearing failure is often considered as the desirable mode because it usually gives a higher strength. Other modes of failure should be avoided through proper design of the joint geometry and composite material itself. So, the optimal W/D and E/D ratios should be chosen to avoid such immediate failure in the joints.

Figures 2 and 3 shows that for low W/D ratio *i.e.*, 2 and 3, there is a sudden decrease after a peak point, which means it has failed either with net tension or shearing. The net tension failure mode is directly related to the width of the specimen. For W/D ratio to be 4 and 5, it can be seen that after the peak point, the values decreases to some extend and thereafter moves forward with zig-zag formation. This is due to the bearing failure mode. The matrix fracture, delamination between laminates, fiber breakages, fiber matrix interface deformation etc., may be the reasons for the zig-zag formation of the curve. The failure modes after the tensile test for all the different W/D and E/D ratios are given in Table 3. Specimens showing type of failure modes in different W/D and E/D are given in Table 4. From Table 3, it can be seen that for W/D≥4, the failure mode is shearing for E/D=2. The damage in specimens with W/D≥4 and E/D=3 is due to a mixed mode consisting of bearing and shearing failure mode. It seems that the failure begins with bearing mode followed by shearing. For W/D≥4 and E/D≥4 the bearing mode is the main cause of failure. It can be seen from Figs. 2 and 3 that the modes of failure for the two ply orientations are nearly same but the ply orientation [0°/90°/0°] bears more tensile stress than [0°/45°/0°] orientation.

Figure 4 shows the comparison of bearing strength for the two different ply orientations with addition of 3 wt% of nanoclay.

Table 3. Comparison of failure modes for the specimens experimentally and numerically

Specimen	Experimentally		Numerically by calculating the failure index and failure angle	
	[0°/45°/0°]	[0°/90°/0°]	[0°/45°/0°]	[0°/90°/0°]
W/D=2, E/D=2	N	N	N+S	N+S
W/D=2, E/D=3	N	N	N	N
W/D=2, E/D=4	N	N	B+N	B+N
W/D=2, E/D=5	N	B+N	B+N	B+N
W/D=3, E/D=2	N	N	N+S	N+S
W/D=3, E/D=3	B+N	N	S	N+S
W/D=3, E/D=4	B+N	B+N	B+S	B+S
W/D=3, E/D=5	B+N	B+N	B	B
W/D=4, E/D=2	S	S	S	S
W/D=4, E/D=3	B+S	B+S	B+S	B+S
W/D=4, E/D=4	B+S	B	B	B
W/D=4, E/D=5	B	B	B	B
W/D=5, E/D=2	S	S	S	S
W/D=5, E/D=3	B+S	S+B	S	S+B
W/D=5, E/D=4	B+S	B	B	B
W/D=5, E/D=5	B	B	B	B

The figure shows that [0°/90°/0°] ply orientation has approximate 10-12% higher bearing strength as compared to [0°/45°/0°] orientation with 3wt% of nanoclay. It is due to the fact that [0°/90°/0°] have higher transverse mechanical properties than [0°/45°/0°] ply orientation.

3.3 Numerical Analysis

Finite element method is a very versatile tool which can be used for analysis of nanocomposite laminates. Several strength prediction methods for composite joints have been proposed which are based upon stress concentration, fracture energy, failure index, etc. However, one of the most efficient methods of predicting the strength is the characteristic curve method[28,29]

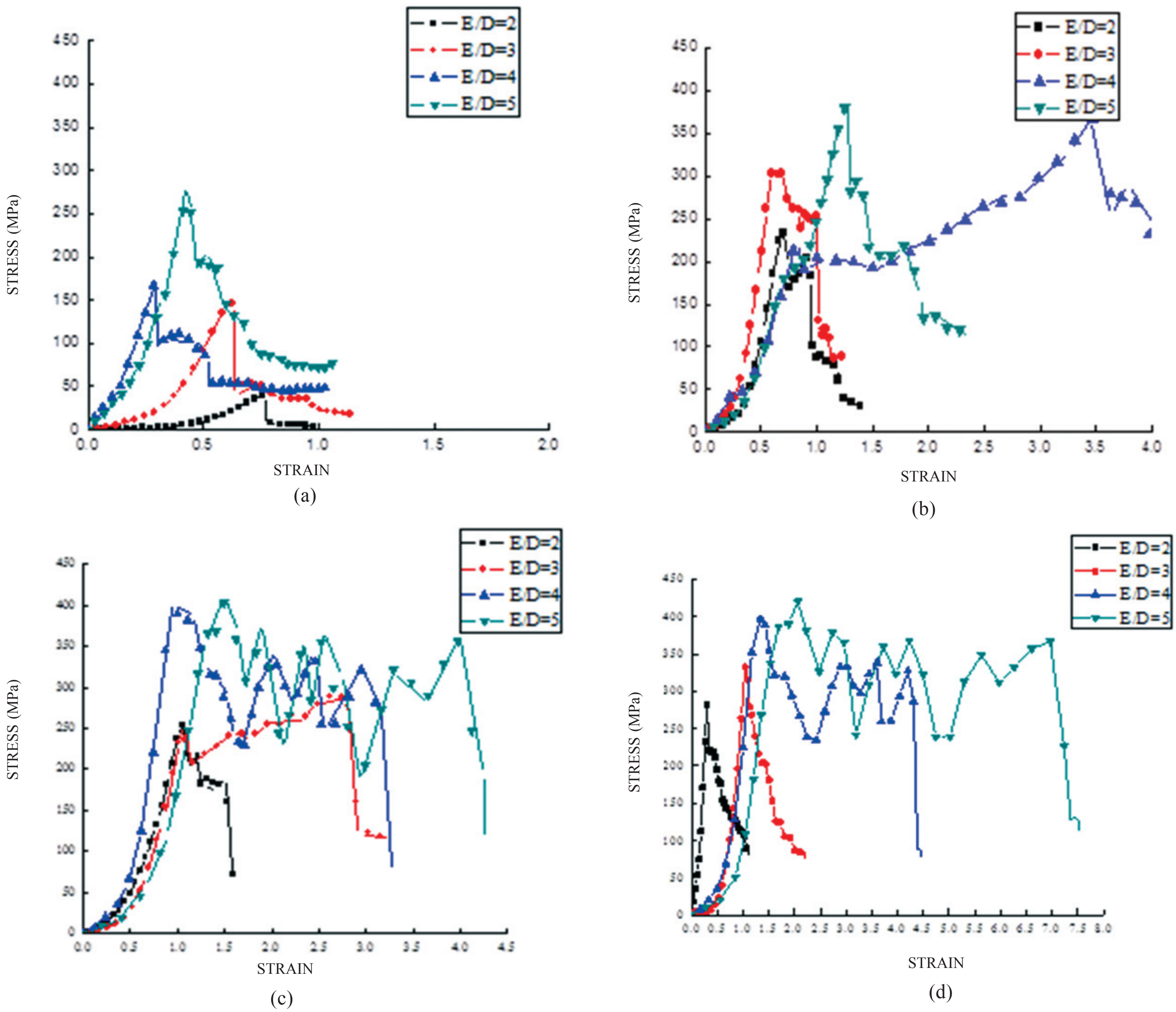


Figure 2. Stress vs. Strain curves of pin joints for ply orientation [0°/90°/0°] with 3 wt% of nanoclay: (a) W/D=2 (b) W/D=3 (c) W/D=4, and (d) W/D=5.

Table 4. Net-Tension (N), Shearing (S) and bearing (B) types of failure modes

Ratios	**W/D=2 E/D=3**	**W/D=2 E/D=3**	**W/D=4 E/D=2**	**W/D=5 E/D=2**	**W/D=5 E/D=5**	**W/D=5 E/D=4**
Specimens						
Failure Modes	N	N	S	S	B	B
Ply Orientations	[0°/45°/0°]	[0°/90°/0°]	[0°/45°/0°]	[0°/90°/0°]	[0°/45°/0°]	[0°/90°/0°]

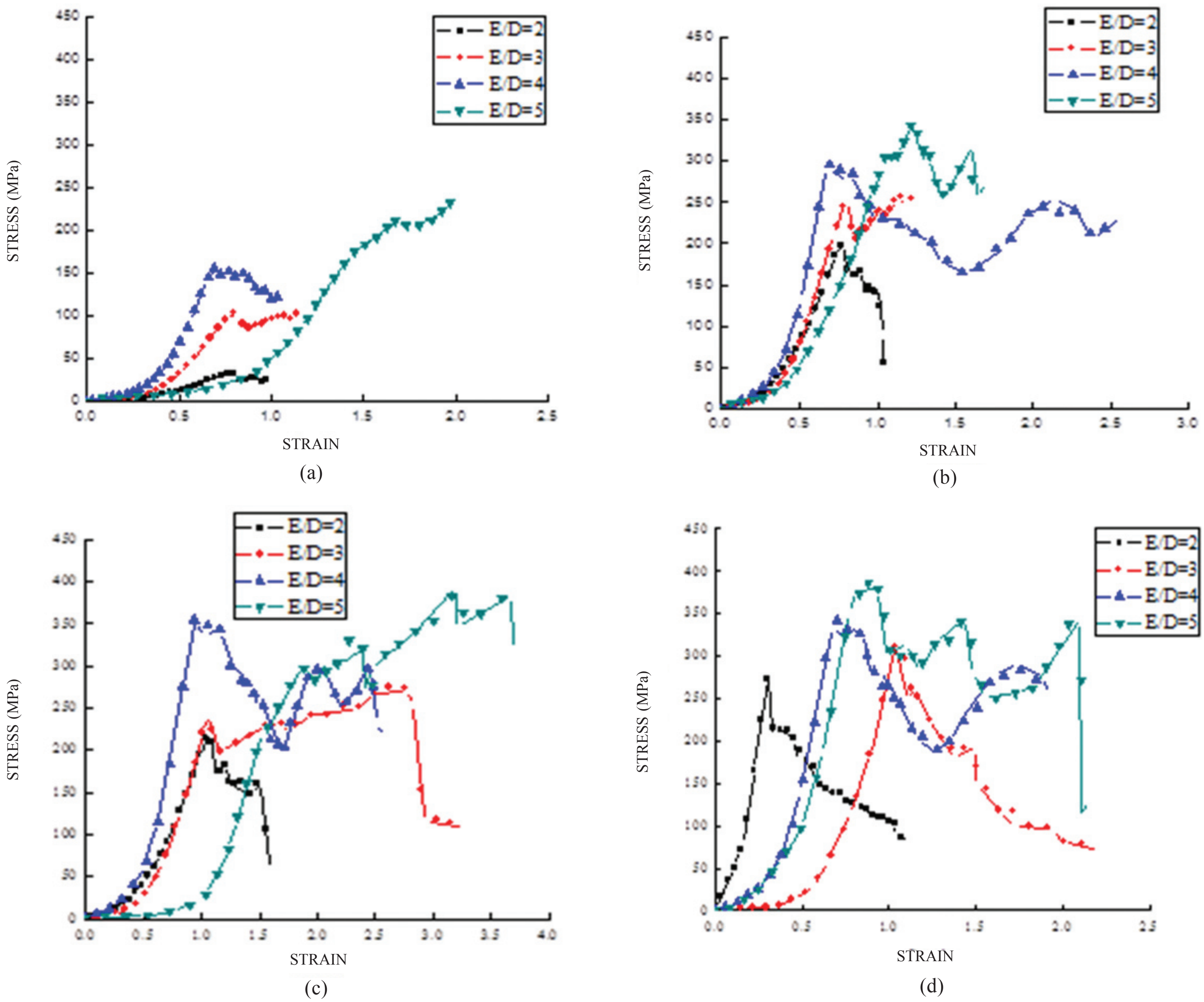


Figure 3. Stress vs. Strain curves of pin joints for ply orientation [0°/45°/0°] with 3 wt% of nanoclay: (a) W/D=2 (b) W/D=3 (c) W/D=4, and (d) W/D=5.

which was based upon Eqn (1)

$$R_c = D + R_{ot} + (R_{ot} - R_{oc})\cos\theta \quad (1)$$

where, D is the diameter of hole, θ is the failure angle, R_{ot} and R_{oc} are the characteristic lengths in tension and compression, respectively. These characteristic lengths, shown in Fig. 5, were determined using bearing and tensile tests on notched and unnotched plates before applying an appropriate failure theory.

Thereafter an appropriate failure criteria was used to calculate the Failure Index (FI) on the characteristic curve. In the present work, Tsai-Wu failure criteria[30] is being used for calculating the FI value.

According to this criterion, the FI value is calculated using Eqn (2).

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 = FI \quad (2)$$

where, six parameters F_1, F_2, F_{11}, F_{22}, F_{66} and F_{12} depend upon longitudinal tensile strength (X_t), transverse tensile strength (Y_t), longitudinal compressive strength (x_e), transverse compressive strength (Y_c) and shear failure strength (s), and are calculated using Eqns (3) to (8).

$$F_{11} = \frac{1}{X_t X_c} \quad (3)$$

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c} \quad (4)$$

$$F_{22} = \frac{1}{Y_t Y_c} \quad (5)$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c} \quad (6)$$

$$F_{66} = \frac{1}{s^2} \quad (7)$$

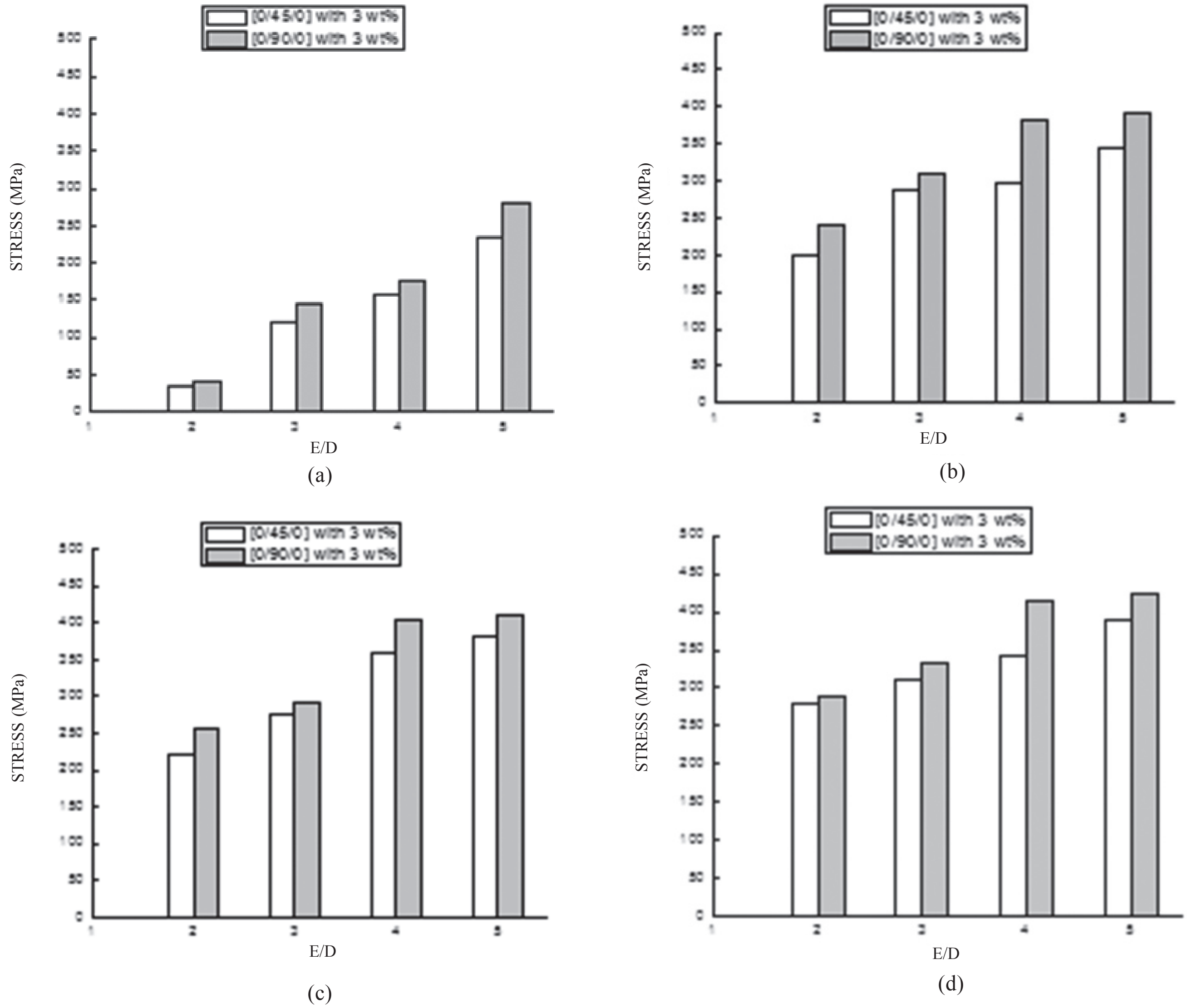


Figure 4. Comparison of bearing strength of pin joints for 3 wt% of nano clay samples: (a) W/D=2 (b) W/D=3 (c) W/D=4 (d) W/D=5.

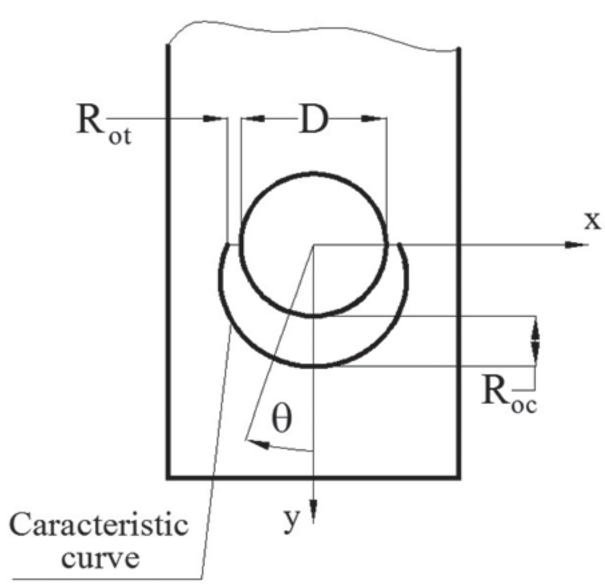


Figure 5. Characteristic curve schematic diagram.

$$F_{12} = -0.5\sqrt{F_{11}F_{22}} \tag{8}$$

If $FI < 1$; there is no failure in the composite laminate

If $FI \geq 1$; there is failure in the composite laminate

The mode of failure (for $FI \geq 1$) can be judged using the failure angle (θ) on the characteristic curve *i.e.*,

$$\begin{aligned} &0^{\circ} \leq \theta \leq 15^{\circ} \text{ Bearing mode (B)} \\ &30^{\circ} \leq \theta \leq 60^{\circ} \text{ Shear-out mode (S)} \\ &75^{\circ} \leq \theta \leq 90^{\circ} \text{ Net-tension mode (N)} \end{aligned} \tag{9}$$

The failure angle is measured on the characteristic curve for the point at which $FI \geq 1$.

3.3.1 Finite Element Modeling

Geometric model of pin joint was made in Hypermesh software for 3wt% of nanoclay by varying W/D and E/D ratios. The lamintes were modeled using the different ply orientations. The different ply orientations were specified as shown in Fig. 6(b). The ply orientation was symmetric with respect to the z = 0 plane. A rigid pin was inserted into the hole. Perfect bonding between each ply was assumed. The composite plate was loaded with an in-plane load, P for the pinned joint. Model was meshed using quadrilateral elements. One end of the composite laminates was fixed and the force was exerted through the pin of the hole, as shown in Fig. 6(c).

The characteristics curve, as shown in Fig. 6(c) was made using the R_{ot} and R_{oc} values.Failure angle was measured using the *FI* value on the characteristic curve. Figure 7 shows the *FI* values around the hole for one combination of geometric parameters.

Figure 8 shows the three basic failures by calculating the *FI* and failure angle on the characteristic curve.

The *FI* values and failure angles were calculated for all

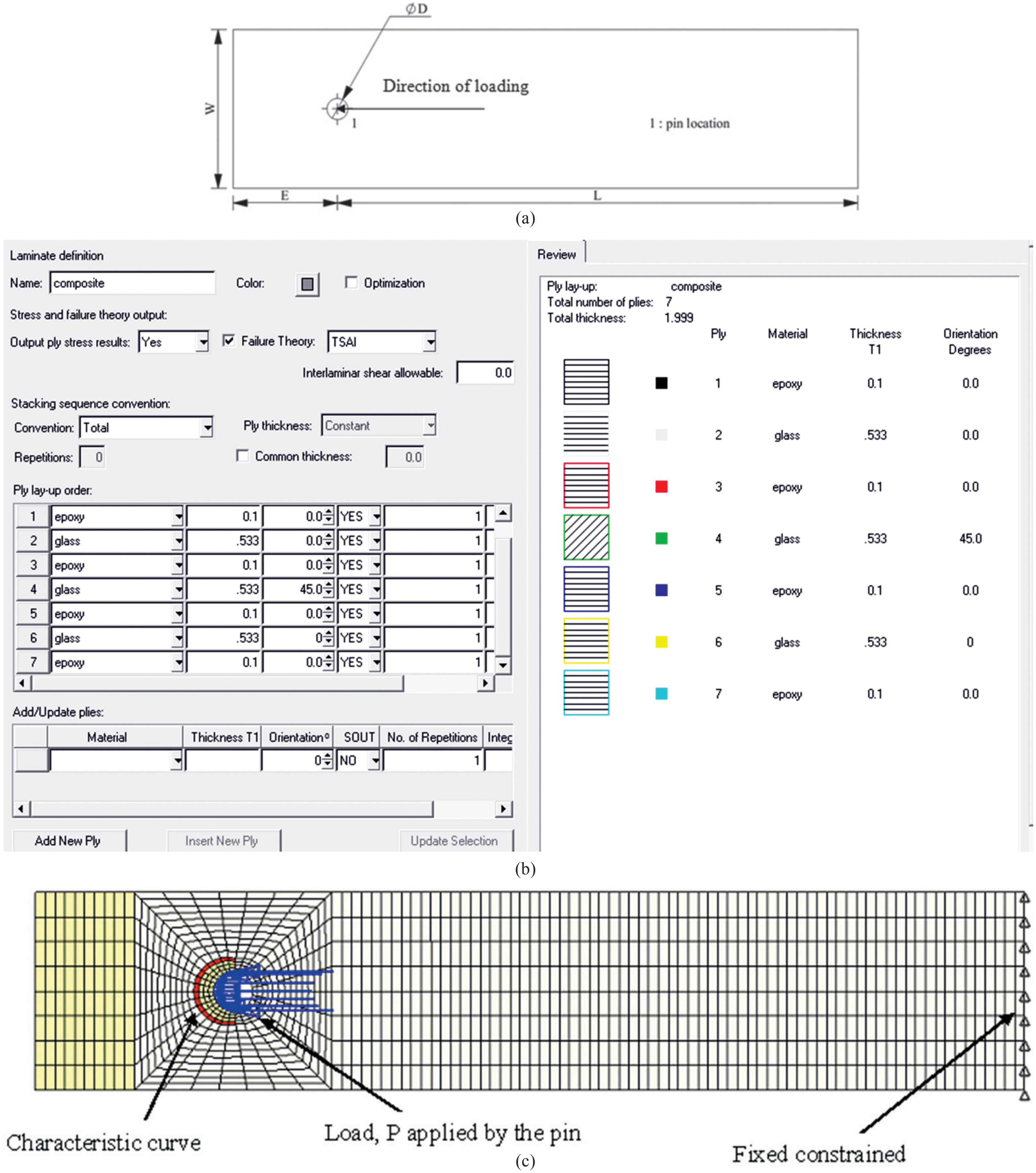


Figure 6. Analysis of the joint (a) Geometry of composite plate with hole (b) Ply Orientation as specified for analysis (c) Boundary conditions and characteristic curve.

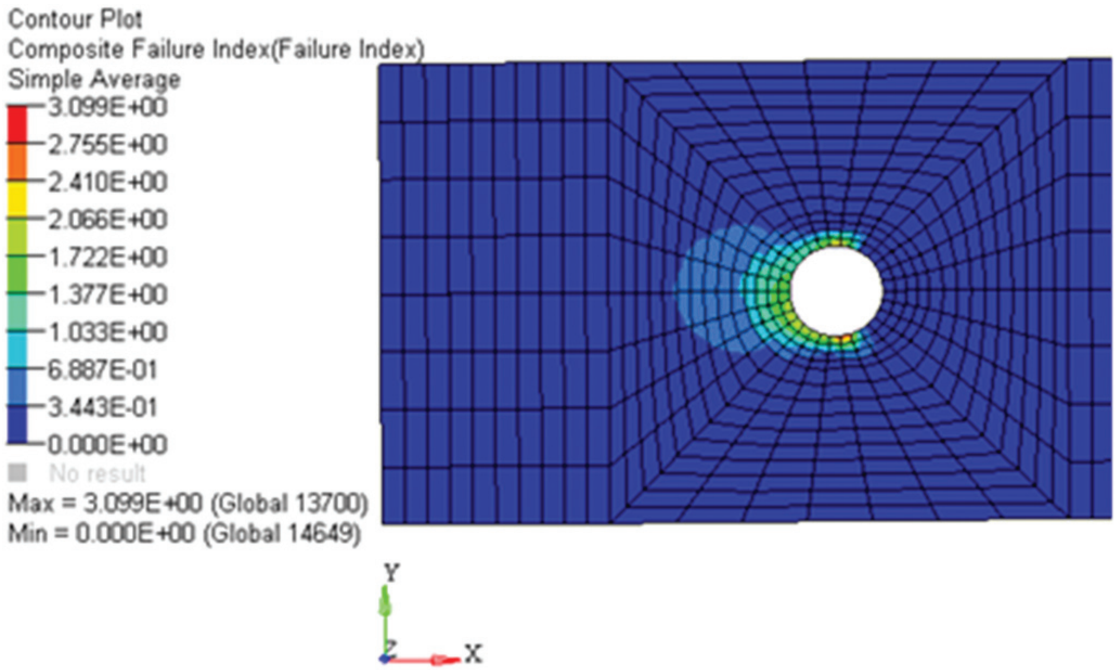


Figure 7. ***FI* value for W/D=4 and E/D=4 around the hole.**

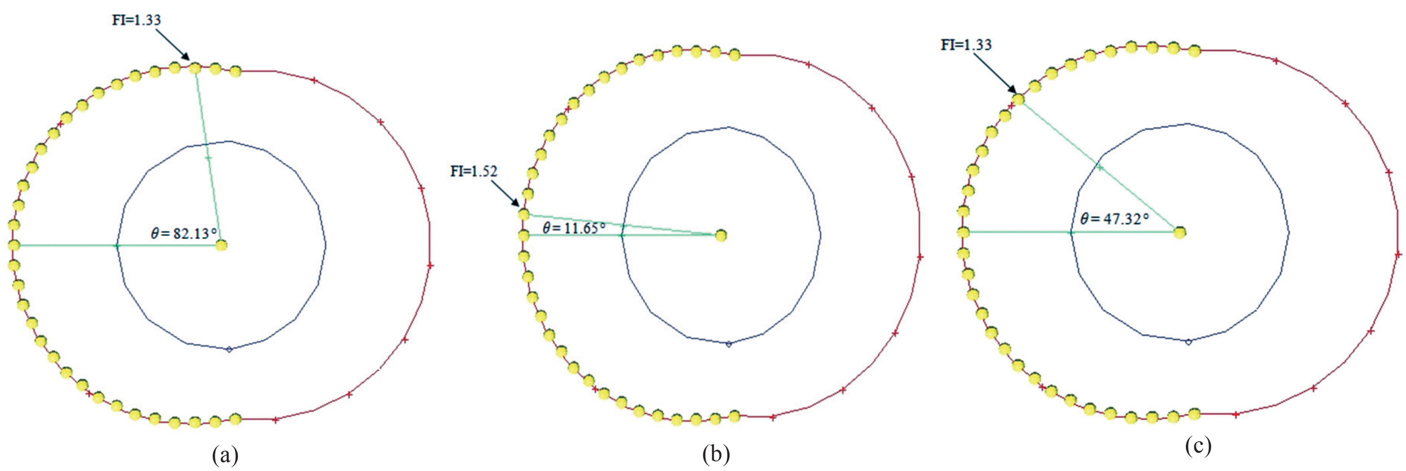


Figure 8. ***FI* and failure angle on characteristic curve for (a) Net-Tension, (b) Bearing, and (c) Shear-out.**

the different W/D and E/D ratios. The failure modes based upon failure angle for all the different W/D and E/D ratios are given in Table 3.

Table 3 also shows the comparison of the FEM and experimental results for the different W/D and E/D ratios for the 3wt% of nanoclay composite laminate specimens.

The results show that there is fairly good correlation between experimental and numerical results. The minor differences between experimental and numerical results are due to the manual preparation of large number of specimen.

4. CONCLUSIONS

The major focus of the study was to analyze the effect of ply orientations and nanofiller on the bearing strength and failure modes of pin joints.

Based on the experimental and numerical results the following observations are made:

(i). There is a definite dependence of joint strength on ply-orientations and the nanoclay composition. The tensile strength and tensile modulus of glass/epoxy nanoclay laminate specimens increased with the increasing amount of nanoclay up to 3 wt% of nanoclay. Thereafter it decreased with further increase in the wt% of nanoclay. This same pattern followed for the different selected ply orientations. The strength was around 15-20 per cent higher than neat glass/epoxy composite for the respective ply orientations.

(ii). The ply orientation of [0°/45°/0°] has higher mechanical properties in longitudinal direction where as ply orientations [0°/90°/0°] have high mechanical properties in transverse direction. Bearing strength of the pin joints depend on both longitudinal and transverse mechanical properties. Results show that the bearing strength of [0°/90°/0°] ply orientation is about 10-12% higher than [0°/45°/0°] ply orientation.

(iii). Type of failure is totally dependent on the geometric parameter i.e. W/D and E/D ratios. Net-tension and shear-out failure modes occur with small W/D and E/D values, respectively. These failures are immediate and without warning. So bearing failure is desirable as it is progressive. The bearing mode of failure occurs for W/D and E/D ratios to be greater than 4.

(iv). Finite element method is used to analyze the mode of failure using Tsai-Wu failure criterion along with characteristic curve method. The results were in a good correlation with the experimental ones.

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