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Effect of Glass Fiber Stacking Sequence on The Notch Sensitivity of Glass Fiber Reinforced Epoxy Matrix Composites

G. A. Abdalla, Elsayed A. Elbadry*, M. Aboraia

Mining and Metallurgical Engineering Department, Faculty of Engineering, Assiut University, Assiut 71515, Egypt, Tel: + 20-88- 241-1231& Fax: + 20-88- 233-6672.

THIS research article investigated the effect of stacking sequence of glass fibers on the notched and unnotched tensile strength of glass fibers plies reinforced epoxy matrix composites fabricated by the hand lay-up technique. The orientation of glass fabrics was kept at $[(0/90)]_5$, $[(45/-45)]_5$ and $[(0/90), (45/-45), (0/0)]_s$ and all the laminates were prepared using five plies for different stacking sequences with fiber volume content of 38.6 vol.% with different ratios of the specimen hole diameter to the specimen width with three different values (0.1, 0.2, 0.5). The notch sensitivity of these composites was evaluated applying Whitney-Nuismer mathematical model. The results indicated that the composites with $[(0/90)]_5$ stacking sequence displays the highest tensile unnotched strength, whereas the composites with $[\pm 45°]_5$ stacking sequence displays the least strength. Moreover, the notch sensitivity of $[\pm 45°]_5$ composites is almost higher than those of other stacking sequences with different D/W ratios. On the other hand, the notch sensitivity of $[(0/90), (45/-45), (0/0)]_s$ composites is slightly lower than those of $[(0/90)]_5$ composite structures for different D/W ratios. Moreover, SEM micrographs indicates the most common failure modes for $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ are more significant delamination and matrix cracking than that of $[(0, 90)]_5$.

Keywords: Stacking sequence, Notch sensitivity of glass composites; Characteristic distance.

Introduction

The mechanical properties of polymer composites such as glass fiber reinforced polymer composites make fiber matrix attractive for structural applications due to low cost, low density, high stiffness and strength-to-weight [1-7]. The mechanical properties of the composites depend upon the properties of fibers, the matrix, types of fibers and matrix and stacking sequence of the fibers. Many researchers have evaluated the effect of different stacking sequence of the fiber on the different properties of the composites [8-12]. The effect of different stacking sequence of jute and glass fibers on the wear properties of jute-glass hybrid epoxy have been evaluated by [8,9]. They reported that the erosive wear of stacking sequence with two jute layers between two glass layers at extreme ends gives the lowest value. Different researchers [10-12] have reported that stacking sequence of the fibers has pronounced effect on the mechanical properties of glass and glass hybrid polymer composites.

Glass composites are possibly used as mechanical fastening joints to join different structural members applied in different industrial applications. However, a source of stress concentration around the hole may results and thereby the tensile strength of the composite structures decreases as reported in [13-15]. The failure and damage in composite laminates with a central hole subjected to uniaxial tension have been simulated as was investigated in [16-18]. Good agreement between experimental data and numerical analyses results were observed and numerical results showed that the damage model can be used to accurately predict the

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*Corresponding author e-mail: elsyed.ahmed@eng.au.edu.eg

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progressive failure behavior both qualitatively and quantitatively.

The stress distribution due to the presence of a circular hole in a composite plate has been simulated by mathematical modeling [19-22]. According to the point stress criterion in Whitney and Nuismer mathematical model [23] the characteristic distance is the distance which the failure occurs when the stress over some distance away from the discontinuity is equal to or greater than the strength of the unnotched material. Eriksson and Aronsson [24] have reported that the tensile strength of carbon fiber-epoxy laminates containing open and filled holes used the damage zone criterion (DZC), for notched composite laminates. In this approach, a damage zone is assumed to be found in the maximum stress region of the laminate when the tensile stress reaches the tensile strength of the unnotched composite laminate. The projected damage zone length was also close in value to the characteristic distance of the point stress criterion of Whitney and Nuismer model.

Green *et al.* [25] found that the failure stress and mechanism are dependent upon hole size and thickness of the carbon/epoxy composites. The notched failure response of wood composite and carbon fiber/epoxy composites has been investigated in [26.27], they concluded that wood and carbon fiber/epoxy composites are notch insensitive due to the internal stress concentration arising from the heterogeneous nature of the substructure. Moreover, Kortschot *et al*. [28] reported that the sub-critical damage around the hole affected on the notched strength of graphite/epoxy composites.

Shembekar and Naik [29] reported that the stacking sequence has a significant effect on the notched and unnotched tensile strength of E-glass woven fabric composite laminates. They reported that the fabric structure governs the failure modes of woven fabric composites. Moreover, a comprehensive evaluation of the effect of unidirectional fiber stacking sequence on notched strength and the fracture behavior of fiber reinforced polymer composites for different tests have been widely investigated as reported in [30-33].

From the literature review, only few studies have been investigated the effect of stacking sequence of plain woven glass fiber on the notch sensitivity of glass woven composites. Recently, the authors have studied the notch sensitivity of short and 2D plain-woven glass fibres reinforced with unsaturated polyester and epoxy matrix composites [34], Therefore, the objective of this work is to investigate the effect of stacking sequence of plain woven glass fiber on unnotched tensile strength and the notch sensitivity of glass fiber reinforced epoxy matrix composites. The notch sensitivity is based as on the residual tensile strength (ratio of notched to unnotches tensile strength) through open hole tension test with different ratios of the specimen hole diameter to the specimen width (D/W) with three different values (0.1, 0.2, 0.5). The calculated characteristic distance using Whitney and Nuismer mathematical model of the composites for different stacking sequence are compared to validate the notch sensitivity.

Experimental

Materials

Five layers of plain woven glass fibers with a density of 430 g/m^2 were used as reinforcements. The fibers were obtained from Al Ahram Company Export and Commercial Agencies, Egypt. Kemapoxy 150 is a thermosetting transparent epoxy matrix polymer and it was used with the hardener with ratio of 2:1 and they were obtained from Chemicals for Modern Building International Company (CMB International Company), Egypt.

Preparation of the composites

Glass fiber reinforced unsaturated matrix was fabricated using the traditional hand lay-up method. In this method, the polymer or epoxy resin after mixing with the hardener was poured on the mold plate and the first layer of woven glass fiber was impregnated with the resin and the details were reported by *Elbadry et al*. [34]. The volume fraction of fiber was determined according to the ignition loss method according to ASTM D2548-68. The studied stacking sequences are $[(0/90)]_5$, $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ and with fiber volume content of 38.6 vol.% and the fiber yarn orientation and the abbreviations of the composites are shown in (Fig. 1) and Table 1.

Mechanical characterization

Tensile test was carried out with the unnotched sample dimensions of 200×20×2 mm using aluminum taps of 1 mm thickness to prevent gripping damage. The measurements were carried out using a universal computerized tension-testing machine at room temperature.

For the notched specimens, the hole diameter was varied as D= 2, 4, 10 mm with 20 mm specimen width with different (D/W) with three different values (0.1, 0.2, 0.5) and the drilling was carried out on wooden plates to avoid any delamination during the drilling.

Surface Morphology Test

The morphology, the fracture surface and the adhesion between the fibers and matrix of composite was examined by a Scanning electron microscope (SEM) using a Joel- JSM-5400 LV -SEM at Electron microscopy unit- Assiut university. The SEM sample was prepared by putting a smooth part of polymer powder on a copper holder and then coating it with a gold-palladium alloy. SEM images were taken using a Pentax Z-50P Camera with Ilford film at an accelerating voltage of 15 kV using a low dose technique.

Results and Discussion

1.1 *Effect of stacking sequence on unnotched tensile strength of the composites*

The tensile strength of fiber-reinforced polymer composite materials is not only influenced by the type of reinforcements or the matrix used, but also by other factors, such as the stacking sequence, fiber type, fiber orientation, and the process curing system. Therefore, the tensile strength of glass fiber reinforced epoxy composites with different stacking sequences is compared in order to understand and analyze the behavior of composite materials.

The unnotched tensile strength of the composites, σ_o can be determined from Equation 1:

$$\sigma_o = \frac{F_{max}}{W * t} \qquad (1)$$

Where F_{max} is the maximum load (N), W is the specimen width (mm), and t is the specimen thickness (mm)

Fig. 2 displays the effect of stacking sequence of glass fabric on the unnotched tensile strength of glass fiber reinforced epoxy composites. It can be observed that the stacking sequence has a pronounced effect on the unnotched tensile strength. The results show that SS1 composites provide the highest tensile strength, whereas SS3

TABLE 1. Laminate stacking sequence of the composites

Material Notation	Laminate configuration	
	Contracted	Expanded
SS1	$[(0/90)]_5$	$[(0/90), (0/90), (0/90), (0/90), (0/90)]_T$
SS2	$[(0/90),(45/-45), (0/0)]_s$	$[(0/90), (45/-45), (0/90), (45/-45), (0/90)]_T$
SS3	$[(45/-45)]_5$	$[(45/-45), (45/-45), (45/-45), (45/-45), (45/-45)]_T$

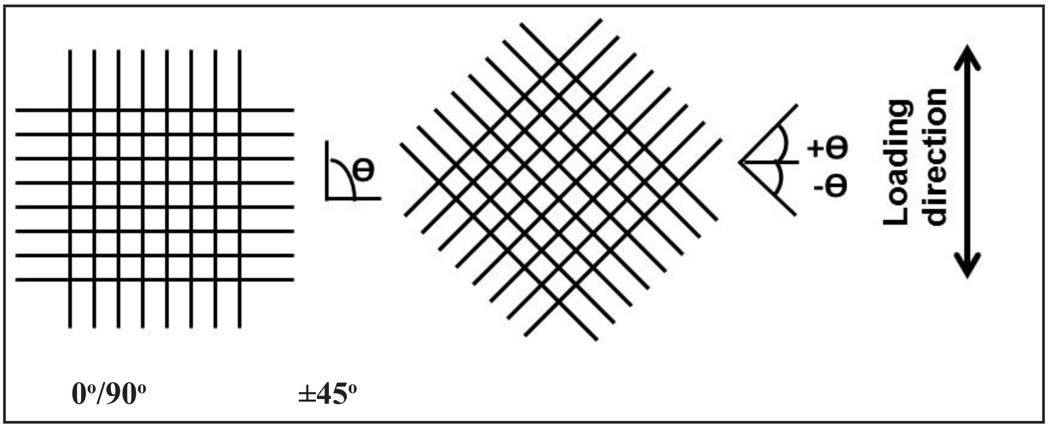


Fig. 1. Fiber yarn orientation of glass fiber.

composites give the least one. When the loading direction is parallel to the fiber direction, the tensile strength displays high value due to the high fiber content in the loading direction [36]. Therefore, the tensile strength of SS1 composites is nearly two folds and four folds higher than that of SS2 and SS3 composites, respectively. Similar results were reported by Shembekar and Naik [29] for the effect of stacking sequence on the unnotched tensile strength of an unbalanced plain weave fabric of E-glass fiber reinforced epoxy matrix composite.

Fig. 3 shows the top view of the failure damage for the unnotched samples with different stacking sequences through visual inspections. It can be observed that the fracture surface of composite laminates underwent five typical failure modes, namely, fiber breakage, fiber pull out, delamination, matrix cracking and debonding. The most common failure modes of S1 composites with $[(0, 90)]_5$ cross ply composite laminates are fiber breakage and fiber pull out, while most common failure modes for angled ply orientations in S_2 and S_3 with $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ stacking sequences are delamination and matrix cracking. This is due to the fact that the fibers with cross ply orientations in S_1 carry most of the tensile loads whereas, for angled ply orientation in S_2 and S_3 the matrix carries most of the tensile loads.

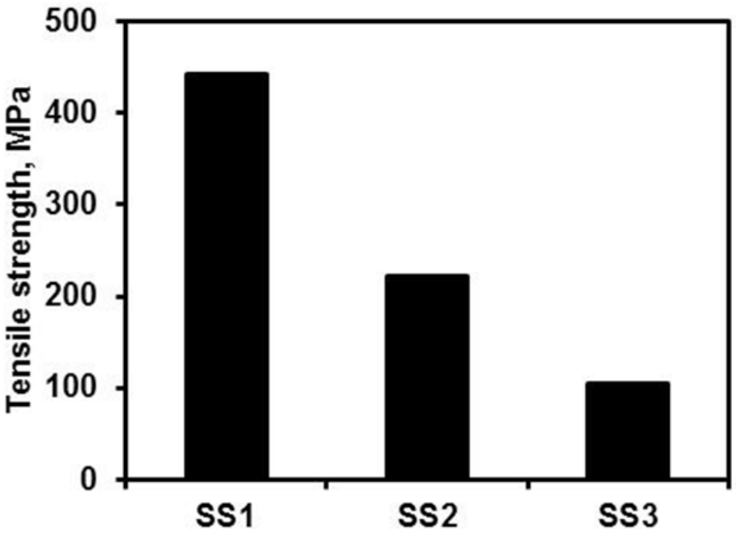


Fig. 2. Effect of stacking sequence on the unnotched tensile strength of the composites.

Fig. 3. Top view of failure of unnotched specimens with different stacking sequences.

Moreover, according to Shembekar and Naik [29] it was found that the single 45º ply was found to twist, while no twisting was observed in the case of single (0º) ply under uniaxial tension. As expected due to the presence of (±45º) layers in S_3 composite layers and in the inner mid plane layers of S_2 composites may cause twisting. As a result of that, delamination appear in the composites with S_2 and S_3 stacking sequences due to the twisting of the (±45º) plies as shown in (Fig. 3) and therefore, the laminate strength of S_2 and S_3 composites is lower compared with that of S_1 composites as shown in (Fig. 2). Moreover, when the (±45º) plies in S_3 composites are laminated together, the cumulative effect of twist is expected to be predominant, leading to severe delamination as shown in (Fig. 3) and therefore the tensile strength value of S3 composites displays the least one as indicated in (Fig. 2) and similar results were reported in [29].

Effect of stacking sequence on the notch sensitivity of the composites

The tensile strength of notched composites, σ_n can be determined from Equation 2:

$$\sigma_n = \frac{F_{\max}}{(W - D) * t} \qquad (2)$$

Where D is the notch diameter

The characteristic distance d_o is an indicator of the notch sensitivity of the composites, the higher value of d_o, the lower sensitivity and vise versa and is a material property representing the distance over which the material must be critically stressed to initiate the brittle failure. The characteristic distance d_o is the distance at which the failure occurs when the stress σ_y over some distance d_o away from the discontinuity is equal to or greater than the strength of the unnotched material σ_o According to the point stress criterion of Whitney-Nuismer Mathematical Model [23]. The details of Whitney-Nuismer Mathematical Model was reported by Elbadry *et al.*[35].

Table 1 indicates the experimental data obtained from tensile tests, which used for the Whitney-Nuismer Mathematical Model calculation to calculate the characteristic distance. Relatively recent studies have also proven the use of this model with a reasonable degree of confidence at similar conditions [19-21, 27, 35, 37].

The tensile strength of the notched specimens (σ_n) and the unnotched strength (σ_o) for different stacking sequences are calculated from the results of the tension test. It is indicated in (Fig. 4) that as D/W ratio increases, the residual tensile strength ($\boldsymbol{\sigma}_n$/ σ_o) decreases for different stacking sequences due to stress concentration and load distribution.

Fig. 4. The effect of D/W ratio on σ_n/ σ_o for different stacking sequence composites.

The residual tensile strength of SS_3 composites is lower compared to other SS1 and SS3 composites so the notch sensitivity of the composite in case of SS_3 stacking sequence is more sensitive compared with other stacking sequences SS1 and SS2. The specimen containing the larger hole has a lower residual strength than the plate containing the smaller holes because as the hole diameter increases, the probability of having a large flaw in the highly stressed region is greater, resulting in a lower average strength for this plate as reported by Nuismer *et al.* [23] (Fig. 5) illustrates the stress distribution around the

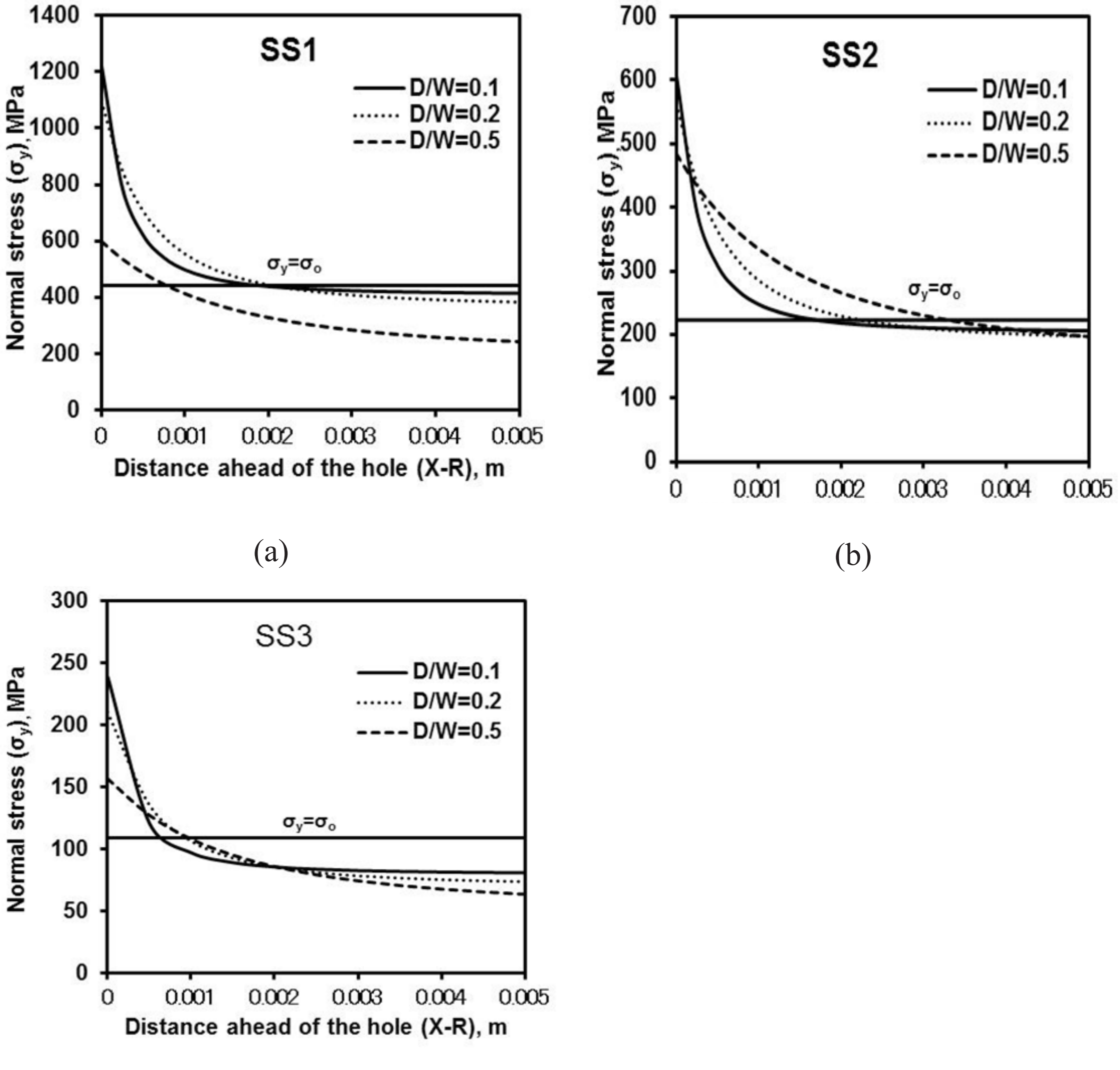
TABLE 2. Experimental data used for the characteristic distance calculation according to Whitney-Nuismer Mathematical Model.

Material Notation	D/W	σ_n,MPa	σ_o, MPa
	0.1	408.8	
SS1	0.2	365.1	442.9
	0.5	199.7	
	0.1	203	
SS2	0.2	187.7	222.7
	0.5	161.4	
	0.1	79.8	
SS3	0.2	70.2	109.3
	0.5	52.3	

hole according to point stress criterion according to Whitney-Nuismer Mathematical Model. It is indicated that the stress concentration is almost more localized for smaller radius hole than the larger ones as clear from (Fig. 5) for different D/W ratios. Some researchers [3, 39] have been used the characteristic distance principle to determine the notch sensitivity of the composites.

It is well known that higher characteristic distance do means lower sensitivity and vice versa and as indicated in (Fig. 5) that the characteristic distance of SS3 composites is lower compared with SS1 and SS2 composites for different D/W ratios. Therefore, the notch sensitivity of SS3 composites is more sensitive than SS1 and SS2 composites. Moreover, the tensile strength of the plain woven fiber reinforced polymer composites depends on the strength of longitudinal glass fibers which withstand most of the tensile stresses. Therefore, more localized concentrated residual stresses result around the hole or the notch in plain-woven fiber reinforced polymer composites due to the discontinuity of the fibers as reported by Elbadry *et al.*[40] for jute fiber reinforced polymer composites.

Moreover, for angled ply orientation, when the fibers are not pulled in the loading direction, the cumulative effect of twist is expected to be predominant, as it has been explained previously, so more concentrated residual stresses may result



(a) (b)

(c)

Fig. 5. Stress distribution around the hole for (a) SS1 (b) SS2 and (c) SS3 composites

around the notch as in SS3 composites. As a result of that the notch sensitivity of SS3 is higher than that of SS1 and SS2 at different D/W ratios as shown in (Figs. 4 and 5). It was found as reported in [41], the reorientation of fibers near the hole edge in the notched (45) plies facilitates the redistribution of stresses. Therefore as expected, (±45º) layers in the inner mid plane layers of S2 composites helps in redistribute the stresses results from (0/0) mid layer as explained before and so the stress concentration decrease around the hole in the middle layers . As result of that the notch sensitivity of the glass composites with S2 stacking sequence is lower compared to that of the composites with S1 and S3 stacking sequence as indicated in (Fig. 4).

In summary, from these results it is recommended to use the stacking sequence of 0/45/90 (SS2) to obtain the optimum condition for using as joining bolts for assembling structural mechanical parts for all hole diameter compared to those of SS1 and SS3, whereas it is recommended to use SS1 as joining bolts than SS3 for smaller hole diameters (D/W=0.1and 0.2).

Fig. 6 shows the visual view of the failure damage as an example of the notched samples for D/W=0.2 at different stacking sequences. Similar fracture mechanisms were observed for open hole specimens as in unnotched specimens as was shown in (Fig. 3). It can be observed that the failed specimens were failed across the hole due to the stress concentration induced by the hole. Moreover, the fracture surface of composite laminates shows five typical failure modes fiber breakage, fiber pull out, delamination, matrix cracking and debonding. The most common failure modes of S1 composites with $[(0, 90)]_5$ cross ply composite laminates are fiber breakage and fiber pull out, while most common failure modes for angled ply orientations in S2 and S3 with $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ stacking sequences, respectively are delamination and matrix cracking. This is due to the fact that the fibers with cross ply orientations in S1 carry most of the tensile loads whereas, for angled ply orientation the matrix carries the highest tensile load in S2 and S3. Fig. 7 indicates SEM images of the side view fracture surface of the open hole specimens with different stacking sequences through the thickness, it can be observed that the fracture surface of S1 composites with $[(0, 90)]_5$ shows less delamination as shown in (Fig. 7a) on the other hand, the most common failure modes for S2 and S3 stacking sequences are clear and more significant delamination and matrix cracking than that of S1 and the delamination is more severe in S3 than that in S2 due to the fact that the fibers for angled ply orientation the matrix carries the highest tensile load as shown in (Fig. 7 b and c). Fig. 8 indicates SEM images of the fracture surface of the open hole specimens with different stacking sequences, it can be observed that the fracture surface of S1 composites are oriented perpendicular to the tensile loading direction and therefore fiber breakage and fiber pullout is dominated because the fibers carry most of the tensile loading as shown in (Fig. 8a). On the other hand, the matrix carries more of the tensile strength than the fiber in S2 and S3 than that of S1, therefore fiber pull out is significantly predominant due to misdirected fibers to the tensile loading as shown in (Fig. 8 a and b).

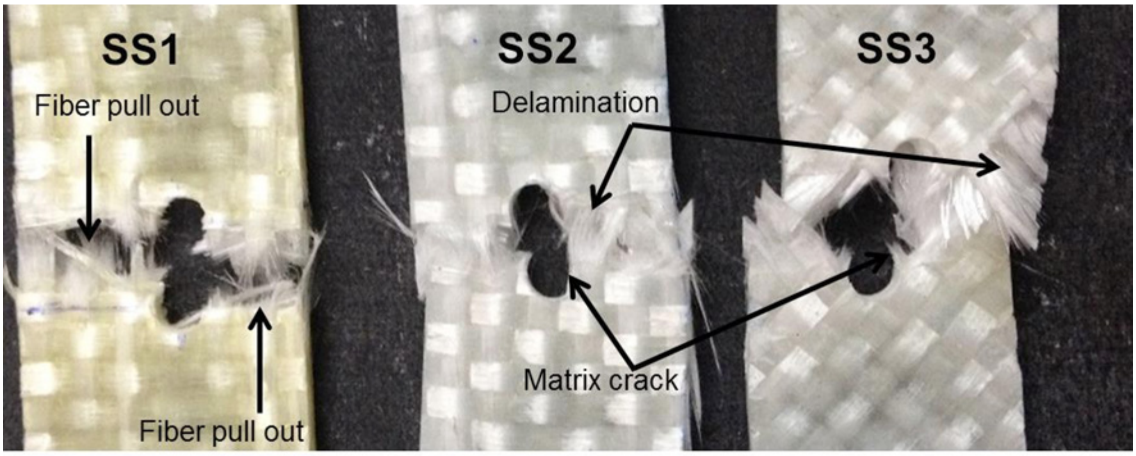


Fig.6. Fracture surface of notched specimens with D/W=0.2 for different stacking sequences.

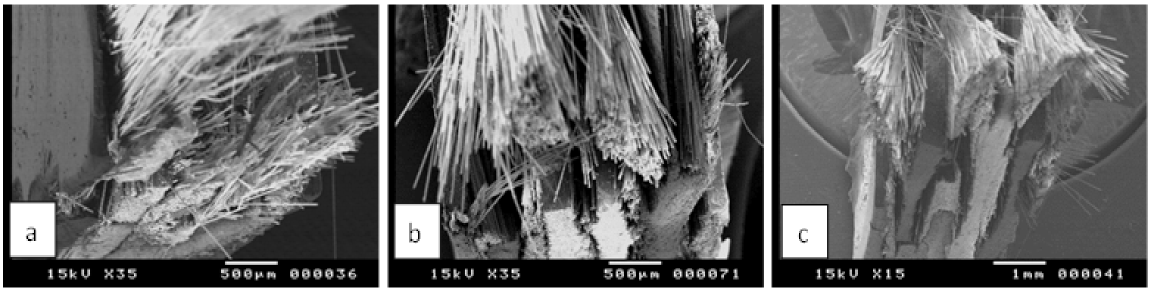


Fig. 7. SEM micrographs of side view of notched composite specimens for different stacking sequences (a) SS1, (b) SS2, and (c) SS3.

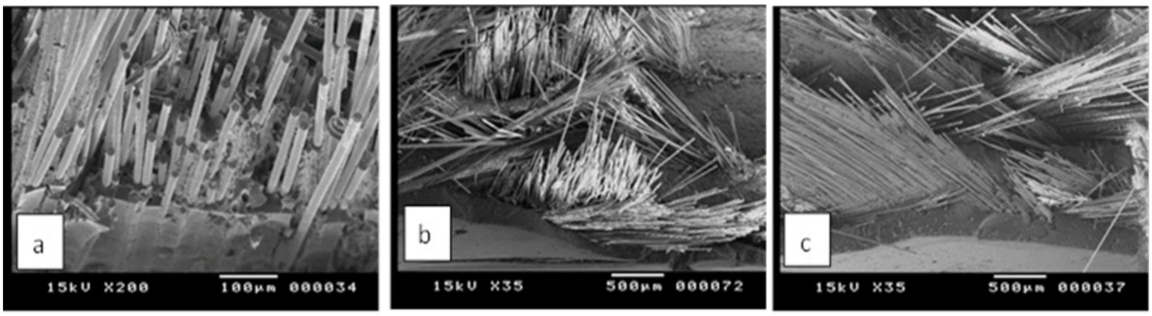


Fig. 8. SEM micrographs of surface fracture of notched composite specimens for different stacking sequences (a) SS1, (b) SS2, and (c) SS3.

Conclusions

Comparing the effect of stacking sequence of glass fiber on the notched and unnotched tensile strength of glass fibers plies reinforced epoxy matrix composites, it can be concluded that:

1. The composites with $[(0/90)]_5$ stacking sequence displays the highest unnotched tensile strength, whereas the composites with $[\pm 45°]_5$ stacking sequence displays the least one.

2. The characteristic distance of $[\pm 45°]_5$ composites is lower compared with $[(0/90)]_5$ and [(0/90), (45/-45),]s composites for different W/D ratios.

3. The notch sensitivity of $[\pm 45°]_5$ composites is almost higher than those of other stacking sequences composite structures with different D/W ratios.

4. Notched and unnotched composite laminates displays similar fracture behavior which showed five typical failure modes including fiber breakage, fiber pull out, delamination, matrix cracking and debonding.

5. Failure modes of notched composites with $[(0, 90)]_5$ are fiber breakage and fiber pull out, while most common failure modes for notched angled ply orientations with $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ sequences are delamination and matrix cracking.

6. The most common failure modes for $[(0/90), (45/-45), (0/0)]_s$ and $[(45/-45)]_5$ stacking sequences are clear and more significant delamination and matrix cracking than that of $[(0, 90)]_5$ and the delamination is more severe in $[(45/-45)]_5$ than that in $[(0/90), (45/-45), (0/0)]_s$.

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