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Compressive Failure Behaviour of Kevlar Epoxy and Glass Epoxy Composite Laminates Due to the Effect of Cutout Shape and Size with Variation in Fiber Orientations

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Abstract: The increasing trend of constructing components made of composite laminates is due to the flexibility in tailoring their properties and high strength-to-weight ratio. Nevertheless, most practical components involve cutout features for fastening and these cutouts could significantly reduce the strength of the laminate. Due to its importance, many studies were conducted to study the effect of circular cutouts however, there is lack of information regarding the effect of various cutout shapes. Therefore, this study aims to investigate the compressive failure behaviour of Kevlar Epoxy and Glass Epoxy composite laminates due to different cutout shapes and sizes with variation in fiber orientations. Finite element software, ANSYS were used to simulate the deformation and failure behaviour of the laminates under compressive load. Prior to that, mesh convergence analysis and numerical validation were performed. Failure analysis was conducted for various cutout shapes (square cutout, diamond cutout, and circular) and size, based on Maximum Stress Theory. The results show that the existence of the cutouts on the composite laminates have reduced up to ten times the strength of the laminated composite plates. This information regarding the failure behaviour is important when designing components made of composite laminates under compression.

Keywords: Kevlar epoxy, glass epoxy, composite laminates, plate with cutout, failure analysis

1. Introduction

The utilisation of composite laminates has expanded from only for defense and aeronautical industries towards the civil and consumer usage such as construction, sports equipment, and automotive parts [1]. The increase in usage is because of the advantage of this material in terms of its mechanical properties. This material is also labelled as a new generation material since it can fulfill the requirement for both rapid growth of the industry and change in technology [2]. Since strength of material is an important property in the selection of material for design of any structure [3], this material has become more popular because of its tailorable properties as well the adequate strength to weight ratio [4] compared to other material.

Since the strength is also a key property for composite material, physical test is always required on the newly developed composite material or new part using this material. However, physical tests are expensive, tedious and time consuming due to the numerous repetitive tests and sufficient samples. To overcome this limitation, researchers have started using more favorable numerical methods to conduct the failure analysis [5]. By the development of computer, the use of commercial software for material failure analysis has increased significantly. Many researchers such as

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Rahimi et al. [6], Samsudin et al. [7], and Mali et al. [8] contributed new composite laminates data by performing failure analysis using the commercial software.

2. Literature Review

In structures and machines, various shape of cutouts has been designed to satisfy certain requirements [9] such as access to internal systems and structures, system integration, or to decrease weight. This is unavoidable even though the presence of this cutout weakens the structural elements or the machine parts [10]. Using the finite element software, a study was conducted by Priyadharshani et al. [11] to analyse the effect of rectangular cutout on glass fiber reinforced polymer stiffened composite plates. The study concluded a significant reduction in strength compared to the plate without a cutout. To strengthen the data produced by the finite element software of this study, the result was also compared with the findings obtained from the test carried out at the Department of Civil Engineering, IIT Madras which produced a good agreement. Similar study with more various types of cutouts was conducted by Kumar & Singh [12]. Also using various lamination schemes in the study, Kumar and Singh investigated the effect of post buckling strength on composite laminate. The study concluded a similar decrease in strength effect with the contribution of numerous failure curves.

Kevlar is one of the composite materials chosen in industries especially in aircrafts due to its versatility [13]. This has made various researchers such as Talib et al. [14] studied the influence of cutout hole on multilayer composite laminated plates. The study was conducted using finite element analysis which managed to provide important information that can be used in the design of such composite structures. Since Kevlar was often found widely used in bulletproof vests and helmets, Majzoobi & Zaheri [15] conducted a numerical and experimental study of ballistic response of Kevlar fabric and Kevlar epoxy composite. The study compared the mechanical behaviour of two materials which contributed new data too. The study also concluded a reasonable agreement was achieved between the numerical and experimental results. Another comparison study between two different Kevlar materials was conducted by Mali & Mahmud [16]. The study was carried out using finite element analysis (FEA) between unidirectional (UD) Kevlar epoxy and woven Kevlar epoxy under compression load and various fiber orientations. The study also included the effect of cutout in both study materials and managed to contribute various failure behaviour of Kevlar epoxy.

Even though many studies have been carried out on the failure analysis of Kevlar fiber cutouts such as the study conducted by Abu Talib et al. [13], Mali & Mahmud [16], and Ibrahim et al. [17], there are still not enough studies conducted on the effect of various cutout shapes such as square cutout, diamond cutout and circular cutout in relation to Kevlar epoxy respectively. Thus, the behaviour of these properties is not fully understandable.

This paper aims to study the effect of square, diamond and circular cutouts towards the failure behavior of Kevlar epoxy composite laminate with various angles of fiber orientation. Failure analysis is conducted with finite element analysis (FEA) and using Maximum stress theory for the failure criteria. Data obtained from this study should help to provide a proper selection of Kevlar epoxy with suitable cutout shape based on the design requirement.

3. Method

In general, this study used commercially available finite element software, ANSYS (v1, 2021) to model the Kevlar epoxy composite laminate with square, diamond and circular cutout shapes being applied under uniaxial compression load. Utilizing the available built-in failure criteria function, the first ply failure load was predicted using Maximum stress theory. For better organization and clarity, the methodology adapted in this study is explained in three stages.

- Stage 1: Mesh Convergence Analysis
- Stage 2: Numerical Validation
- Stage 3: Failure Analysis

3.1 Mesh Convergence Analysis

The selection of correct mesh size can produce accurate results without increasing the processing time which can optimize the work of this study [2]. To identify the correct mesh size for the study, convergence analysis was performed before the model for the study was validated. Models with and without cutout were developed using material properties of Kevlar epoxy before it was applied with first five meshing sizes of (2x2), (3x3), (4x4), (6x6), (8x8), (12x12) and (16x16). The displacement in x-direction of model was studied with specific uniaxial tension, 80,000 Newton/meter.

Fig. 1 and Fig. 2 show the maximum displacement results in x-direction at three angle variations (0, 45, and 90 degrees) of all cutouts for Kevlar epoxy and Glass epoxy composite laminates plate. From Fig. 1 and Fig. 2, the results on plate without the cutout for both Kevlar epoxy and Glass epoxy converged from start (2x2) but the plate with square, diamond and circular cutouts started to converge after mesh size (4x4). Therefore, from the results, it can be concluded that the mesh size used throughout this study was acceptable.

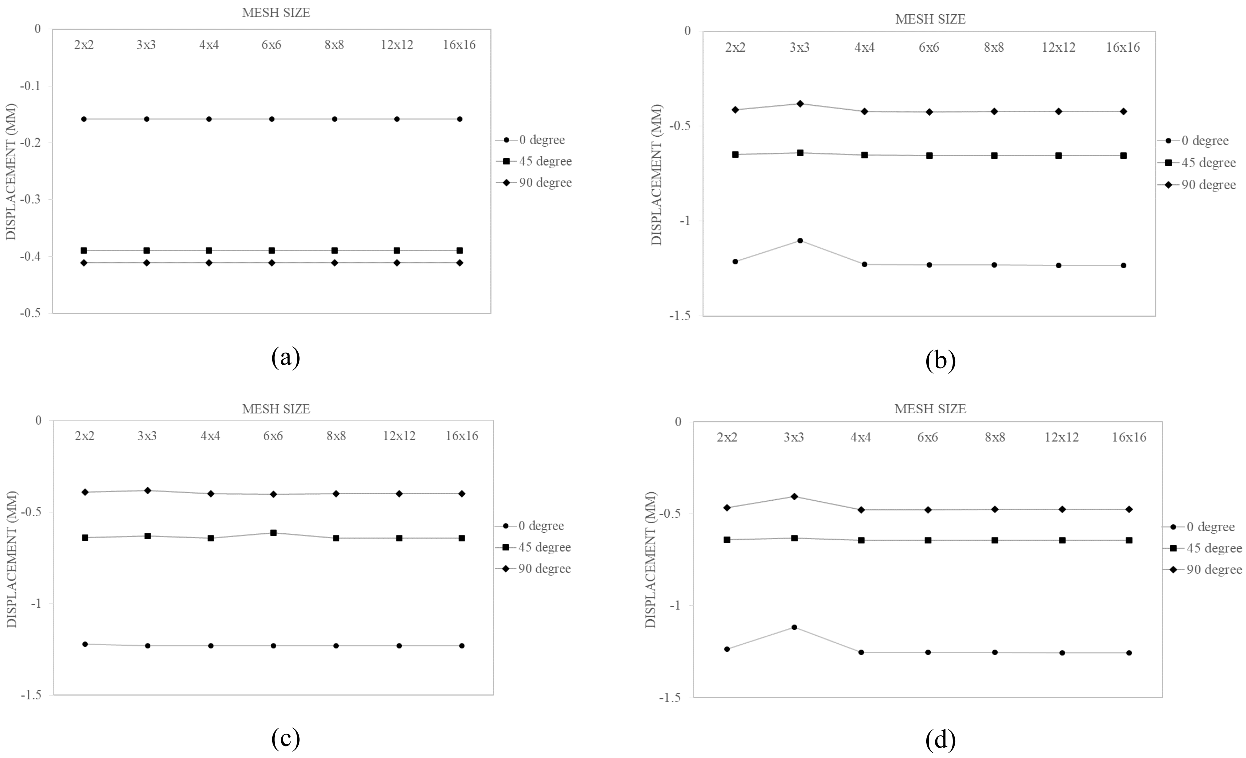

Fig. 1 - The displacement in x-direction of Kevlar epoxy composite laminates (a) without cutout; (b) with square cutout; (c) with diamond cutout; (d) with circular cutout

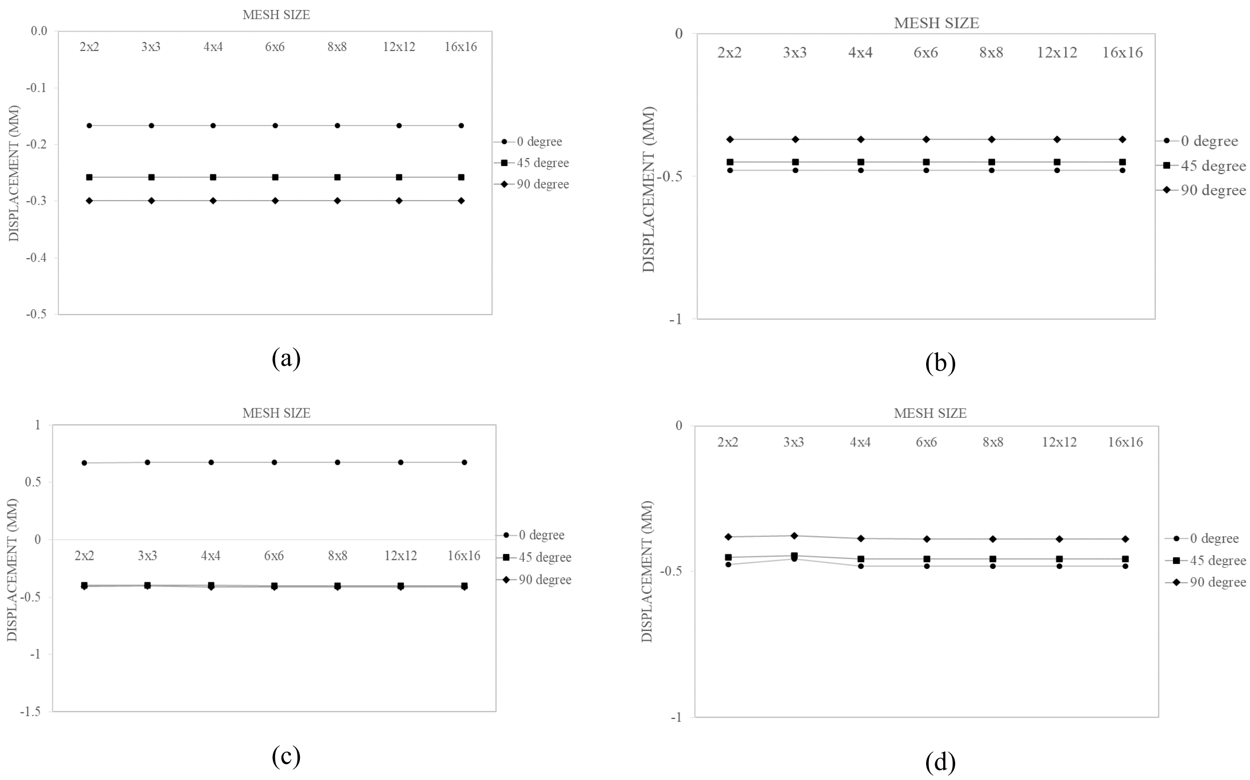

Fig. 2 - The displacement in x-direction of glass epoxy composite laminates (a) without cutout; (b) with square cutout; (c) with diamond cutout; (d) with circular cutout

3.2 Numerical Validation

Models by the geometry as shown in Fig. 5 and the material properties as shown in Table 1 were developed with stacking sequence $[\theta_4/0_4/\theta_4]_s$ where the variations in fiber orientation were θ = 0 to 90 degrees. Model was simulated using finite element to predict the maximum displacement in both x-direction and y-direction under the effect of uniaxial tension applied load of 50,000 Newton/meter.

Results of simulation were compared with results from analytical approach as shown in Table 2. The model developed for this study is validated with the comparison percentage error is identified to be less than 0.5%.

Table 1 - Material properties and strength data for Kevlar epoxy [18]

Properties	Values	Properties	Value
E_1	76.0 GPa	X_T	1380 MPa
$E_2 = E_3$	5.5 GPa	X_C	276 MPa
$G_{12} = G_{23}$	2.1 GPa	Y_T	28 MPa
G_{13}	2.1 GPa	Y_C	138 MPa
$\upsilon_{12} = \upsilon_{23}$	0.34	S	44 MPa
υ_{13}	0.34		

Table 2 - Comparison of maximum displacement in between FE simulation and analytical results

θ	Simulation (ANSYS)		Analytical		Error	
(Degree)	x-dir (m)	y-dir (m)	x-dir (m)	y-dir (m)	x-dir (%)	y-dir (%)
0	9.87 x10-5	1.68 x10-5	9.87 x10-5	1.68 x10-5	0.02	0.14
10	1.04 x10-4	3.02 x10-5	1.04 x10-4	3.02 x10-5	0.21	0.02
15	1.13 x10-4	4.66 x10-5	1.13 x10-4	4.66 x10-5	0.31	0.03
20	1.27x10-4	6.79 x10-5	1.27 x10-4	6.79 x10-5	0.08	0.02
30	1.75 x10-4	1.07 x10-4	1.75 x10-4	1.07 x10-4	0.21	0.43
40	2.26 x10-4	1.08 x10-4	2.26 x10-4	1.08 x10-4	0.20	0.22
45	2.43 x10-4	9.38 x10-5	2.43 x10-4	9.38 x10-5	0.15	0.05
50	2.53 x10-4	7.59 x10-5	2.53 x10-4	7.59 x10-5	0.14	0.02
60	2.60 x10-4	4.28 x10-5	2.60 x10-4	4.28 x10-5	0.01	0.08
70	2.59 x10-4	2.04 x10-5	2.59 x10-4	2.04 x10-5	0.16	0.16
75	2.59 x10-4	1.33 x10-5	2.59 x10-4	1.33 x10-5	0.18	0.36
80	2.58 x10-4	8.35 x10-6	2.58 x10-4	8.35 x10-6	0.10	0.05
90	2.57 x10-4	4.58 x10-6	2.57 x10-4	4.58 x10-6	0.02	0.05

3.3 Failure Analysis

Failure analysis was conducted on material to identify its strength. Since mechanical properties of composite material such as composite laminate was tailorable by altering the fiber direction, failure analysis of this study was conducted on a plate of Kevlar epoxy (Table 1) and Glass epoxy (Table 3) with 24 layers of lamination scheme $[\theta_4/0_4/-\theta_4]_s$ where the θ =10, 15, 20, 30, 40, 45, 50, 60, 70, 75, 80, and 90 degrees. The model in this study was made into plate in square shape as shown in Fig. 3 with length and width plate of 0.279 meter. Using the aspect ratio (S=a/h) of 150, the thickness of plate (h) was 1.86 x10-3 meter, and the cross-sectional area (A=ah) was 5.189 x10-6 cubic meter.

Models with square cutout, circular cutout, diamond cutout, and without cutout were developed for both composite laminates to act for the plate with cutout and applied with compression unidirectional load to study the effect of various cutout shapes under the compression. The study also developed three sizes of cutout in each shape denoted as A1, A2, and A3 to observe the effect of cutout size in every cutout shape.

This study used similar cutout size as proposed by Kumar & Singh [12], where A1, A2, and A3 represented the aspect ratio of cutout size of each shape as shown in Fig. 6. In the figure, the ratio for A1 was equal to 0.14, A2 was equal to 0.28, and A3 was equal to 0.42. The cutout in the model was made by A1, A2, and A3 cutout sizes from the dimensions provided in Table 3 based on the geometries shown in Fig. 4.

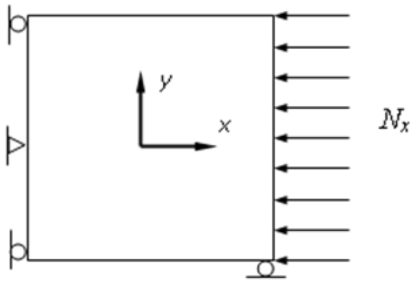

Fig. 3 - Geometry of model with boundary condition and compression load

Table 3 - Material properties and Strength data for Glass epoxy [18]

Properties	Values	Properties	Value
E_1	54.0 GPa	X_T	1035 MPa
$E_2 = E_3$	18.0 GPa	X_C	1035 MPa
$G_{12} = G_{23}$	9.0 GPa	Y_T	28 MPa
G_{13}	9.0 GPa	Y_C	138 MPa
$\upsilon_{12} = \upsilon_{23}$	0.25	S	41 MPa
υ_{13}	0.25		

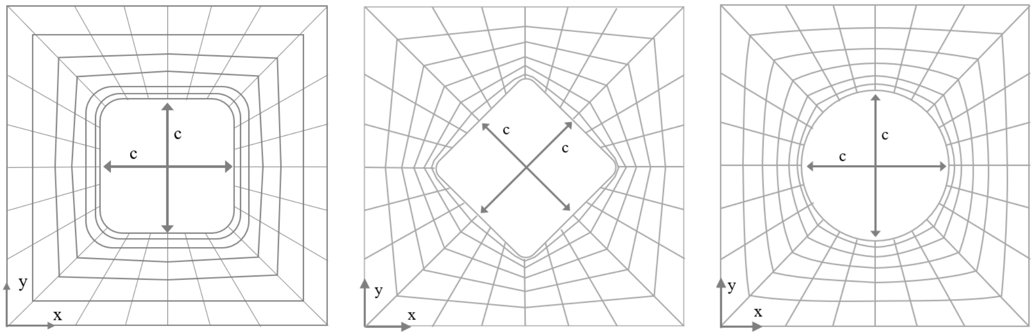

Fig. 4 - (a) Square cutout; (b) Diamond cutout; (c) Circular cutout

Table 4 - Material properties and Strength data for Glass epoxy [18]

Cutout Shape		A1	A2	A3
Square	Ratio, c/b	0.140000	0.280000	0.420000
	Length, c (m)	0.039060	0.078120	0.117180
Diamond	Ratio, c/b	0.140000	0.280000	0.420000
	Length, c (m)	0.039060	0.078120	0.117180
Circular	Ratio, c/b	0.158000	0.316000	0.474000
	Length, c (m)	0.044082	0.088164	0.132246

4. Results and Discussion

The failure curves for Kevlar epoxy and Glass epoxy with and without the cutout were tabulated and presented in Fig. 5 to Fig. 10. In those figures, based on the enormous gap between the result of plate without cutout and the result of plate with cutout, it can be concluded that the significant strength was reduced by the existence of cutout in the plate. This happened for both Kevlar epoxy and Glass epoxy composite laminates in which the finding was similar to the result presented in past study [19]. The comparison of strength in the plate without cutout for A1 was 69% for Square, Diamond, and Circular cutouts of Kevlar epoxy, while 92% for Square and Circular cutouts and 96% for Diamond cutout of Glass epoxy.

Observing the behaviour of plate towards the change in fiber orientation, the strength for both Kevlar epoxy and Glass epoxy decreased by the increase of degree of fiber orientation. The failure curves for all three cutouts shapes were somehow not very much affected by the change of fiber orientations and this happened for both composite laminates. The reduce in strength between the plate without cutout and all cutout sizes and shapes was significantly affected at 0-degree fiber orientation compared to the reduce in strength at 90-degree fiber orientation. All plates with cutouts did not show any significant activities except for Kevlar epoxy plate with cutouts which experienced a decrement starting from 0-degree fiber orientation and increased back at 20-degree fiber orientation before the strength was reduced back until 60-degree fiber orientation and remained constant. Although it was not much, based on the figures, the square cutout shape was the most affected compared to the diamond and circular cutout. On the other hand, the failure curves for Glass epoxy showed a separation for all three cutout sizes which indicated a clearly different strength of material based on the size of cutout. Another finding in Glass epoxy plate with cutout was the strength of the Square and Circular cutouts which was higher than the strength of Glass epoxy plate with Diamond cutout.

This proves that the strength of material is affected by the size of cutout. The shape of cutout; however, does not much affect the strength of composite laminates plate. This finding matches the past data on the influence of open holes shape on the failure facture of composite laminates under compressive loading [20].

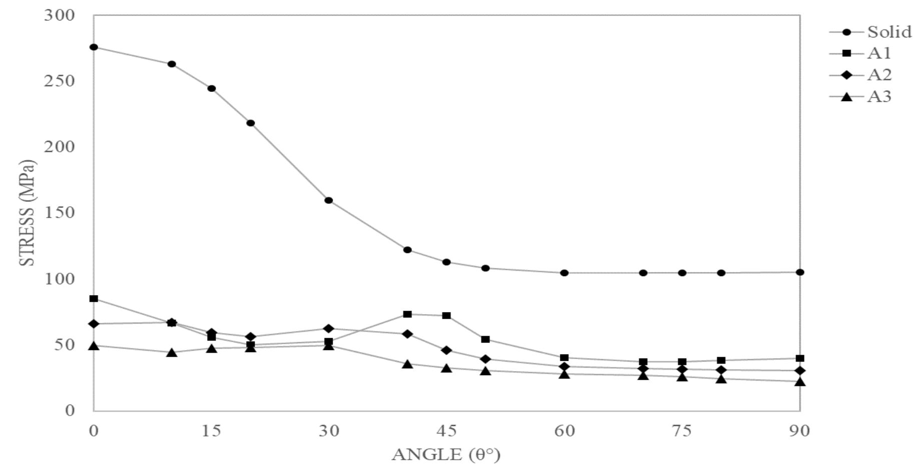

Fig. 5 - Failure curves of Kevlar epoxy with and without the square cutout shape

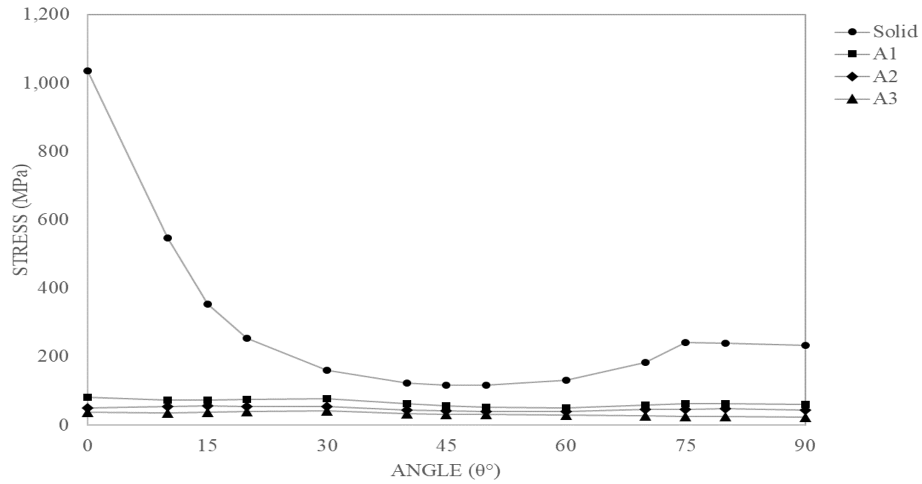

Fig. 6 - Failure curves of Glass epoxy with and without the square cutout shape

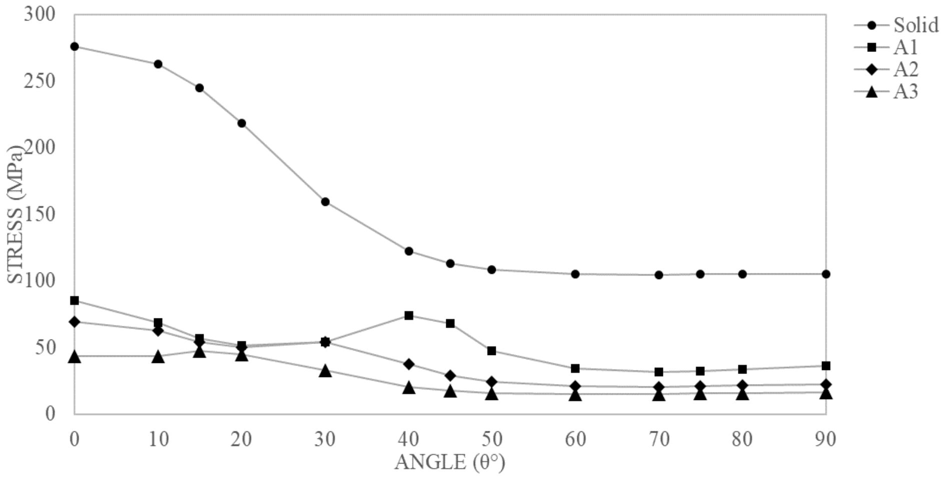

Fig. 7 - Failure curves of Kevlar epoxy with and without the diamond cutout shape

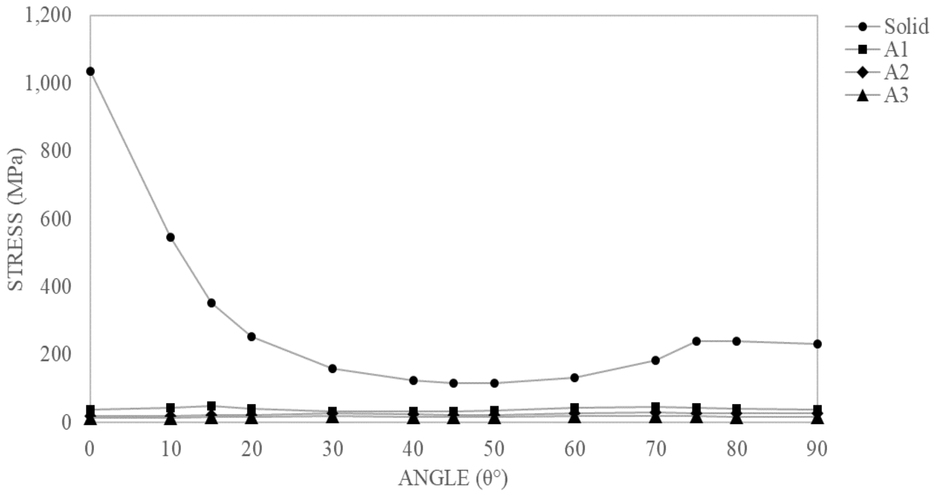

Fig. 8 - Failure curves of Glass epoxy with and without the diamond cutout shape

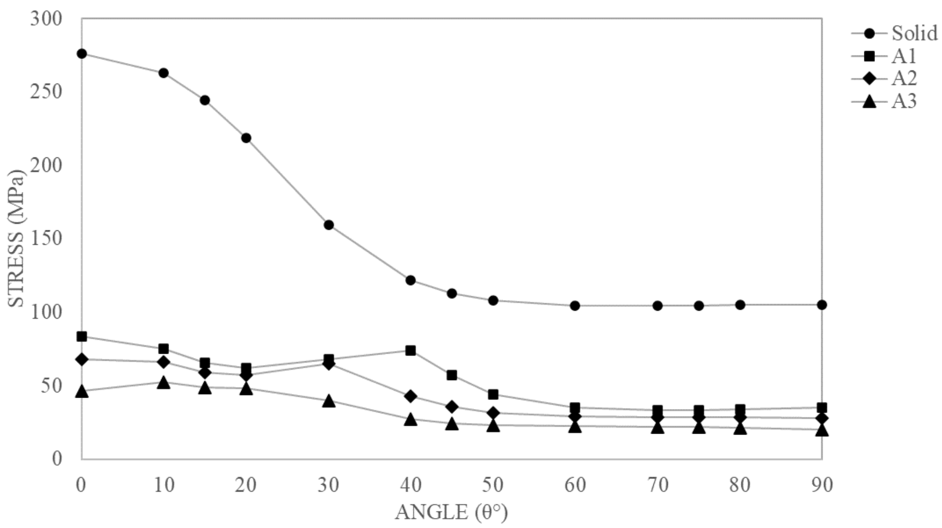

Fig. 9 - Failure curves of Kevlar epoxy with and without the circular cutout shape

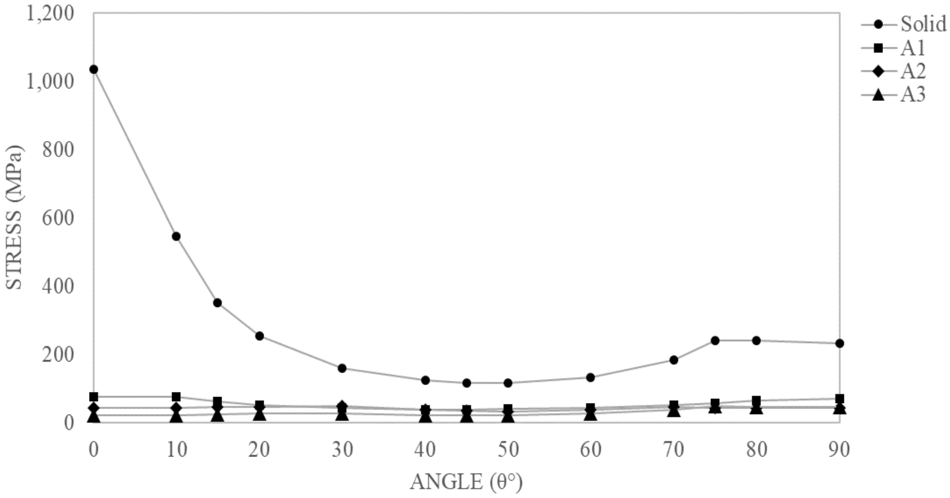

Fig. 10 - Failure curves of Glass epoxy with and without the circular cutout shape

5. Conclusions

This paper has presented and discussed on the effect of fiber orientation angle towards Kevlar epoxy and Glass epoxy composite laminates plates with square, diamond and circular cutouts and without cutout, and cutout sizes. The results show a significant effect towards the reduce in strength from the plate without cutout as compared to the three cutout shapes and sizes. The main finding that can be deduced from the study is that material removal due to cutout very much affects the strength of material as in this case of composite laminates. The cutout size and shape also prove to have an influence on the failure behaviour of composite laminates. Although the direction of fiber orientation does affect the material with plate without cutout, it does not have much effect on the plate with square, diamond and circular cutouts. From the results, it is proven that the current study is important in understanding the failure behaviour of composite plate which can be useful in contributing the knowledge for further study.

Acknowledgement

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