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Effect of Open Hole on Tensile Properties of Kenaf/Epoxy Composite via ANSYS Simulation

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Abstract

The open hole tensile (OHT) test determines the force required to tear a fibre-reinforced polymer composite laminate specimen with a hole located in the centre. In this study, continuous kenaf/epoxy composite laminates with 0o, 15o, 30o, 45o, 60o, 75o, and 90o fibre orientations were modelled and simulated via ANSYS software. The effect of the open hole on the tensile properties of kenaf/epoxy composite laminates was investigated. It was found that kenaf/epoxy composite laminate with 0o fibre orientation, [0]8, exhibits the highest tensile stress in presence of an open hole with a reduction percentage of 17% when compared to the composite laminates without a hole. Meanwhile, Kenaf/epoxy composite laminate with 90o fibre orientation, [90]8, showed the lowest tensile stress and the highest reduction percentage up to 68% in the presence of an open hole. The effect of open hole size (6 mm, 8 mm, and 12 mm diameter) on kenaf/epoxy composite laminate with 0o fibre orientation, when subjected to tensile load, was simulated and analysed. It was observed that the maximum tensile stress of kenaf/epoxy composite laminates reduces with the increase of open hole size. Research on the effect of open holes is important to predict damage resistance and tolerance of composite systems when flaws, damaged areas or drill holes are present.

Discipline: Mechanical Engineering.

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1 Introduction

Increasing awareness of the effects of the production of inorganic materials on the environment in recent years causes the rise of interest towards the application of natural fibres and their potential to replace synthetic fibres in various applications (Keya et al., 2019). Kenaf (*Hibiscus cannabinus* L.) is a herbaceous plant that has recently been commercialized in industries as natural fibre reinforcement for composite due to its appealing mechanical properties such as low in density but high in specific strength and modulus. Compared to other natural fibres, kenaf fibre is preferred to be developed due to its properties and better performance such as its impact strength, storage modulus, and thermal stability (Sreenivasan et al., 2013). Great mechanical properties such as higher storage modulus and better thermal stability which affect the elasticity of composites can be achieved through the addition of natural fibres to epoxy composites (Sanjay et al., 2016; Saba et al., 2015).

Conventionally, hole drilling is mostly unavoidable for joints and bolts which are commonly used as mechanical fastening methods for composite materials due to their simplicity (Davoodi et al., 2010). However, the presence of a hole in composites will induce discontinuity and development of great stress concentrations in the region nearby the hole causing strength reduction of the composite (Shaari et al., 2017; Kannan et al., 2012). Studies on the open hole or notch strength of composite materials have been widely carried out over the past decades. A previous study on open-hole tensile properties of Kenaf composites reported that the hybridization of kenaf and woven glass composite provides better resistance to crack growth compared to kenaf composite (Salleh et al., 2013). A study on the effect of open hole tension on unidirectional flax yarn reinforced composite found that the tensile properties of the composite are influenced by the hole size and the fibre orientation in which 0^{o} oriented flax reinforced composite produces greater performance compared to $\pm 45^{o}$ oriented flax reinforced composite (Kannan et al., 2012).

The previous study showed that the strength and modulus of elasticity of unidirectional kenaf/epoxy composite increase as the fibre volume increases which indicates that composite with higher fibre volume is stiffer and able to withstand greater load (Mahjoub et al., 2014). It is also suggested that the alignment of continuous kenaf fibre affects the strength of the composite since it shows better properties compared to chopped kenaf fibre. In continuous fibre, the loads from the matrix are easily transported along the fibre length in an effective way compared to short fibre which strengthens the fibre (Sapiai et al., 2014). Earlier studies indicated that the tensile strength and tensile modulus of fibre-reinforced composites are determined by the fibre orientation, especially on continuous composite. When evaluated under tensile loading parallel to the unidirectional FRP (0^{o} fibre orientation), the specimens start failing with tensile rupture of the reinforced fibre followed by the debonding of the fibre-matrix interface. Meanwhile, under transverse tensile loading at 90^{o} fibre orientation, the specimen fails by the tensile rupture of the fibre-matrix interface which shows the importance of properties of matrix in FRP composite with 90^{o} fibre orientation (Bakar et al., 2014; (Manap et al., 2015).

This paper aims to report the effect of the open hole on the tensile properties of kenaf/epoxy composite through modelling and simulation using ANSYS software. Factors that influence the strength of the composite such as fibre orientation and open hole size were investigated in this study. This research will contribute to a new piece of information in predicting component failure and performance of kenaf composite using the simulation technique.

2 Method

2.1 Open Hole Tensile (OHT) Test

The specimen dimensions follow the ASTM standards for tensile of unhole and open-hole specimens (D5766) as shown in Figure 1. The specimen dimension and the lay-up sequence used for the OHT simulation are shown in Table 1.

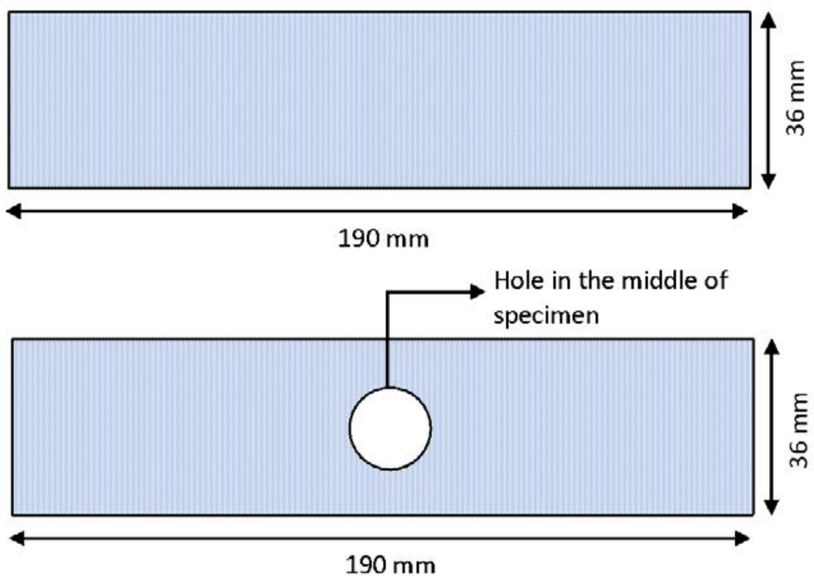


Figure 1: Specimen dimensions for tensile test and OHT test (ASTM D5766).

Table 1: Specimen dimension and stacking sequence used for both test.

Test	Tensile	Open hole Tensile
Width	190	190
Height	36	36
Thickness	2	2
Layer	8	8
Hole size	-	6
Stacking sequence	[0]8, [(θ/-θ)2]s *	[0]8, [(θ/-θ)2]s *

*Where θ is 15°, 30°, 45°, 60°, 75°, and 90°

2.2 Finite Element Method

In this study, 20% fibre volume fraction (vf=20%) of kenaf/epoxy composite alongside 60% and 30% fibre volume fractions (vf=60% and vf=30%) of glass/epoxy composites was analysed using modelling and simulation techniques via ANSYS Mechanical APDL software. The mechanical properties of these composites were obtained through a literature review as listed in Table 2.

The Finite Element Model (FEM) method was done for the modelling and simulation work which involved pre-processing, processing, and post-processing stages as shown in the flowchart (Figure 2). In the pre-processing, the preference setting of the ANSYS software was set to structural analysis. The element type was defined as "Shell 8 node 281" with the storage of layer data, and "all layers and middle" was selected. The material properties of the model were then defined as structural of linear elastic "Orthotropic." The reference of linear orthotropic material properties for the composite was then filled up following the input data as listed in Table 2. The modelling process started by selecting the area which was defined using the centre and corners of the rectangle in the Pre-processor options. The lay-up sequence of the laminates was then defined by adding the Shell lay-up according to the thickness and fibre orientation of the specimen. The details on boundary conditions and the loading type are provided in Figure 2.

In the processing stage, the finite element equations were assembled and solved, and thus, the analysis results were obtained. The results were checked to ensure the failure index had reached "1" in order to obtain the maximum stress value through the calculation using the maximum stress equation. If the failure index is lesser than 1, this shows that the specimen has not reached failure, thus a higher loading value is required. The results data were then extracted and analysed in the post-processing stage.

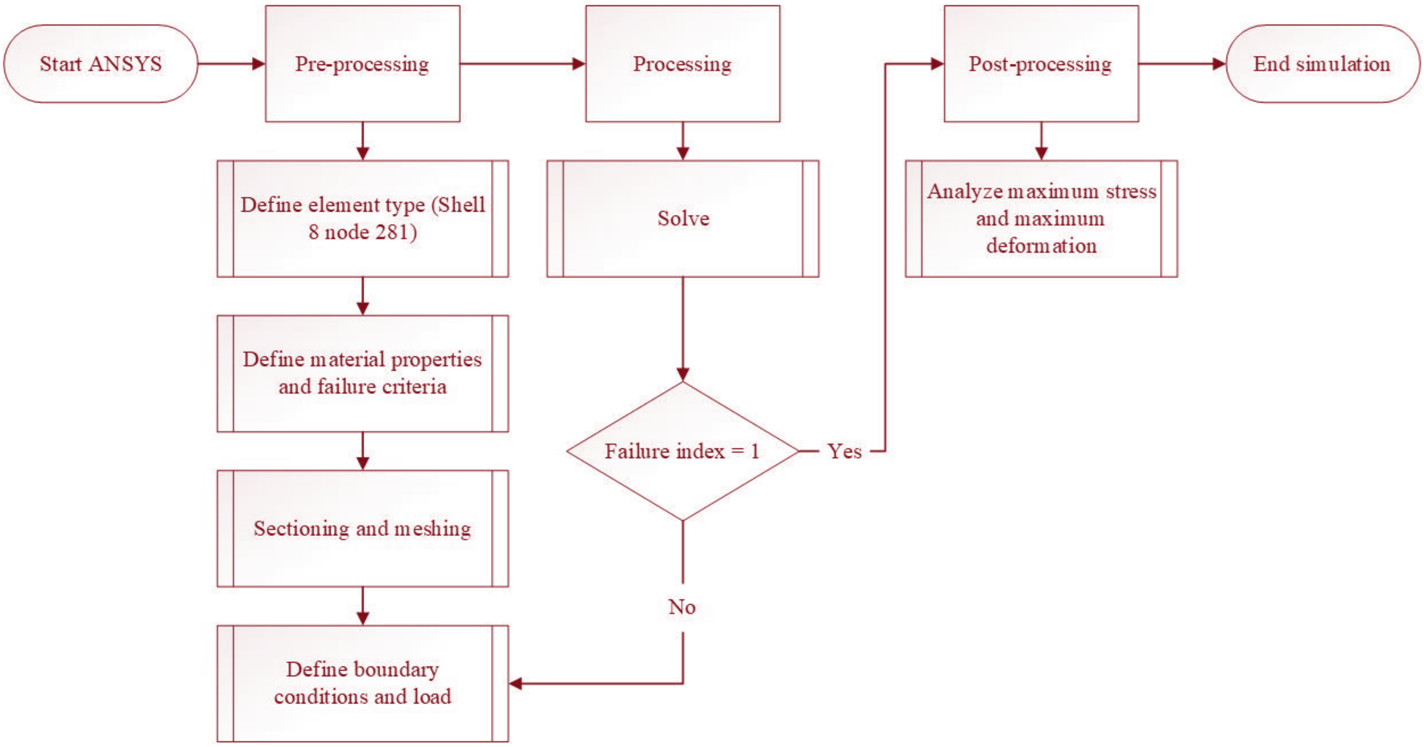


Figure 2: Simulation work flowchart.

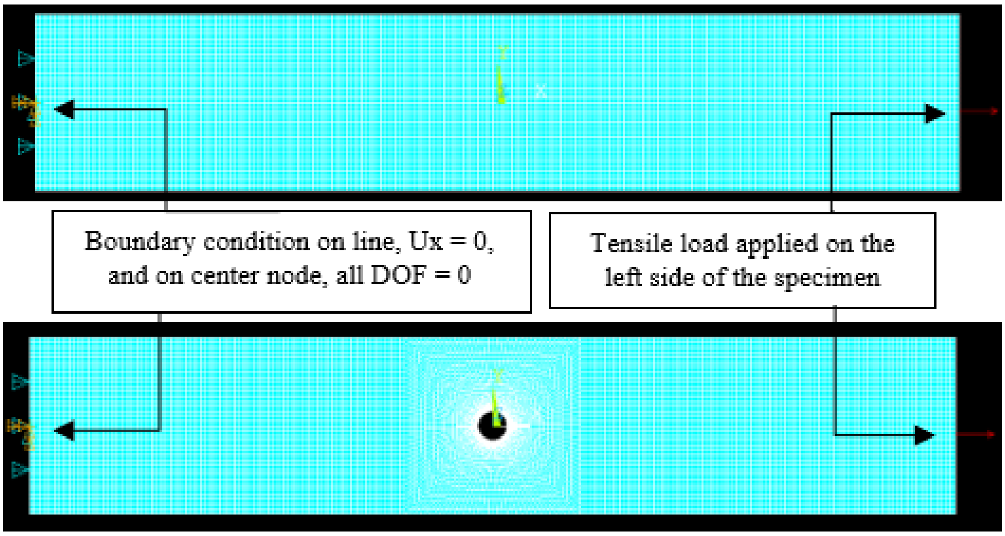


Figure 3: Boundary conditions and loading type for tensile test and OHT test.

Table 2: Material properties of Kenaf FRP and Glass FRP composites.

Mechanical Properties	Symbol	Glass/Epoxy (Vf=60%) [a]	Glass/Epoxy (Vf=30%) [a,b]	Kenaf/Epoxy (Vf=20%) [c,d]
Longitudinal Modulus (0^0) (GPa)	E1	54.00	6.47	5.45
Transverse Modulus (90^0) (GPa)	E2	10.80	2.16	1.12
Shear Modulus (GPa)	G12	9.00	2.59	1.20
Poisson's Ratio	V12	0.25	0.25	0.30
Shear Strength (MPa)	S12	41.00	41.00	11.41
Tensile Strength (0^0) (MPa)	XT	1035.00	342.56	49.48
Tensile Strength (90^0) (MPa)	YT	28.00	9.25	11.41
Compression Strength (0^0) (MPa)	XC	621.00	77.29	68.78
Compression Strength (90^0) (MPa)	YC	103.00	10.31	13.76

Note. [a] Jones (1999), [b] Hashim et al (2021), [c] Sapiai et al (2020), [d] Sapiai et al (2018)

2.3 Numerical Validation

By comparing the finite element analysis results with the analytical results, a numerical validation was conducted to evaluate the accuracy of the results from the modelling and simulation approach. Kenaf/epoxy solid plate with stacking sequences of $[0]_8$, $[45/-45]_{2s}$, and $[90]_8$ was simulated using ANSYS APDL to predict the maximum displacement values for both x-direction and y-direction under uniaxial tension loadings of 1 kN. The percentage of error was calculated, and the comparison was tabulated as shown in Table 3. The percentage of error calculated was used to evaluate the accuracy of the finite element analysis. The modelling and simulation techniques used for the test are acceptable as the overall percentage of error is less than 0.2%.

Table 3: Comparison between results from finite element analysis and an analytical method for Kenaf/Epoxy composite under tensile load.

Stacking sequence		[0]8	[45/-45]2s	[90]8
Simulation (ANSYS)	Max x (m)	0.0000091700	0.0000172000	0.0000446000
	Max y (m)	0.0000004950	0.0000006550	0.0000004950
Analytical	Max x (m)	0.0000091743	0.0000171931	0.0000446429
	Max y (m)	0.0000004954	0.0000006552	0.0000004954
Error (%)	Max x	0.05	0.04	0.10
	Max y	0.08	0.04	0.08

3 Result and Discussion

This section displays the results obtained and discusses the effect of open hole and open hole size on the maximum tensile stress of Kenaf/epoxy and Glass/epoxy composites. The simulations were done on specimens with a thickness of 2 mm. The thickness of each layer was 0.25 mm. The layup sequence used was $[+\theta,-\theta]_{2s}$ in which θ was 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The simulation outcomes include maximum stress and deformation analysis contour.

3.1 Effect of Open Hole on Maximum Tensile Stress

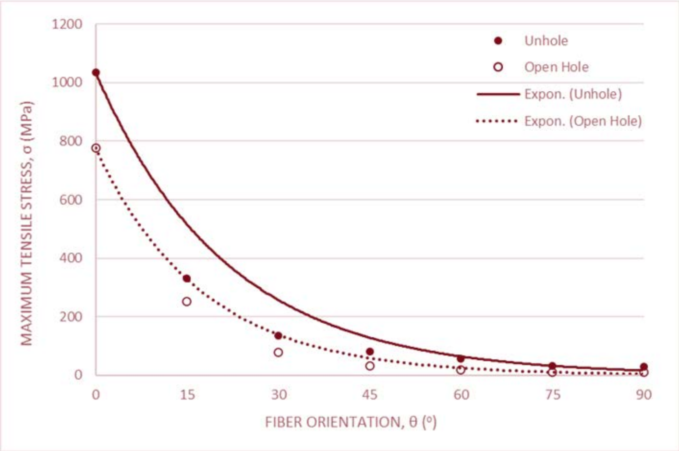
The effect of the open hole on the maximum tensile stress of composites was studied by subtracting a circle with a diameter of 6 mm in the middle of the specimen. As seen in Table 4, the maximum tensile stress decreases in the presence of an open hole in the specimen. The highest maximum tensile stress of open-hole kenaf/epoxy is 40.93 MPa. Meanwhile, its lowest maximum tensile stress is 3.62 MPa. This shows that the effect of the open hole is influenced by the fibre orientation. 0° fibre orientation exhibits the least reduction and the highest maximum stress in the presence of an open hole due to the high amount of fibre that exists in the direction of the load exerted on the specimen (Abdul Nasir et al., 2019). The highest reduction is displayed at 90° fibre orientation, which shows that transverse fibre orientation is highly affected by the open hole and possesses the lowest strength in retaining stress in the tensile direction.

Table 4: Effect of the open hole on maximum tensile stress of glass/Epoxy and Kenaf/Epoxy

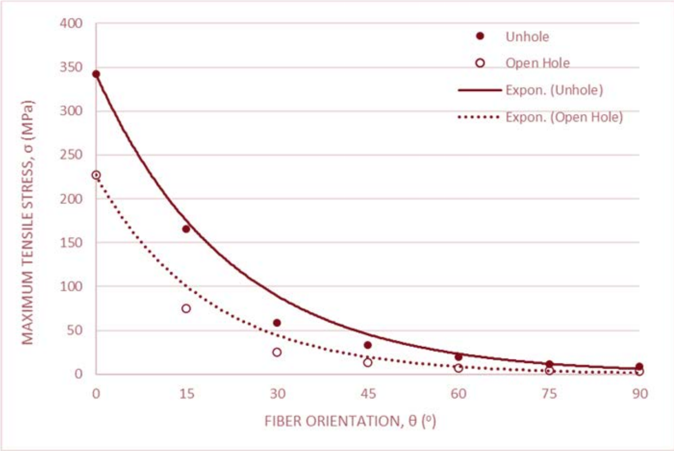
Fibre Ply Orientation θ (°)	Maximum Tensile Stress, σ (MPa)								
	Glass/Epoxy (V_f = 60%)			Glass/epoxy (V_f = 30%)			Kenaf/Epoxy (V_f = 20%)		
	Unhole	Open Hole	R.P	Unhole	Open Hole	R.P	Unhole	Open Hole	R.P
0	1034.9	776.07	25%	342.56	227.01	34%	49.48	40.93	17%
15	330.88	253.00	24%	165.45	75.22	55%	50.09	35.69	29%
30	134.14	77.26	42%	59.12	25.58	57%	34.79	18.77	46%
45	82.00	33.08	60%	33.27	13.05	61%	22.82	9.22	60%
60	56.00	18.72	67%	19.72	7.09	64%	18.78	6.47	66%
75	33.23	10.70	68%	11.89	3.97	67%	14.35	4.62	68%
90	28.00	8.99	68%	9.25	3.00	68%	11.41	3.62	68%

*R.P stands for strength reduction percentage

Figure 4 and Figure 5 show the effect of the open hole on specimens of glass/epoxy (V_f=60%), glass/epoxy (V_f=30%), and kenaf/epoxy (V_f=20%), respectively under tensile loading. Between the three composites, it showed that glass/epoxy (V_f=30%) is the most influenced by the presence of an open hole in the specimen, followed by glass/epoxy (V_f=60%) and kenaf/epoxy composite. A significant drop of maximum stress at 0° fibre orientation was observed from glass/epoxy (V_f=30%) for both tests while kenaf/epoxy showed the least maximum stress drop.



(a)



(b)

Figure 4: Effect of the open hole on maximum tensile stress of (a) glass/epoxy with V_f = 60% (b) glass/epoxy with V_f = 30%

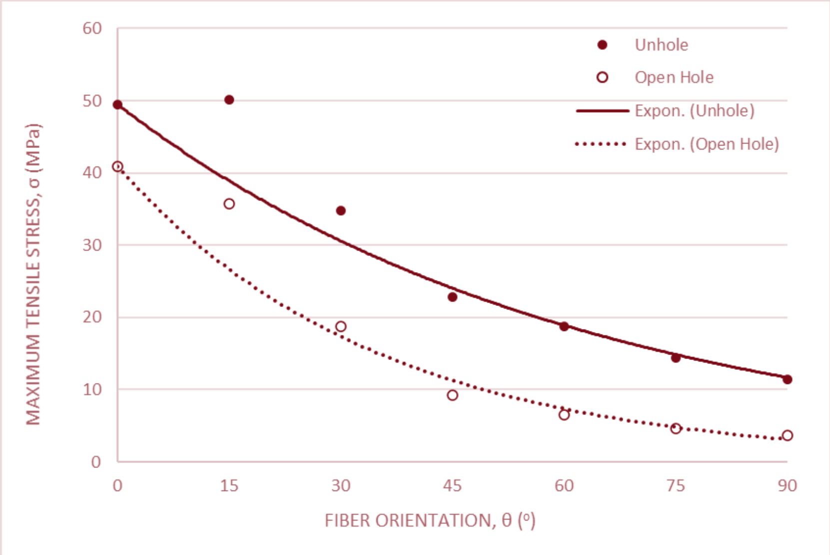


Figure 5: Effect of the open hole on maximum tensile stress of kenaf/epoxy (V_f = 20%)

The effect of the open hole on the maximum deformation of composites is displayed in Table 5, in which the highest deformation can be seen at 0° fibre orientation for the OHT test. Glass/epoxy (V_f=30%) exhibits the highest maximum deformation, followed by glass/epoxy (V_f=60%), and kenaf/epoxy with 6.378 mm, 2.903 mm, and 1.499 mm, respectively. The deformation contours of open hole kenaf/epoxy composite in Figure 6 display the effect of the open hole on its deformation behaviour under tensile load at 0° fibre orientation. It can be seen that the specimen elongates, and the circle shape of the hole stretches into an ellipse shape in the tensile direction.

Table 5: Effect of the open hole on maximum deformation of glass/epoxy and kenaf/epoxy.

Fibre Ply Orientation, θ (°)	Maximum OHT Deformation (mm)		
	Glass/epoxy (V_f = 60%)	Glass/epoxy (V_f = 30%)	Kenaf/epoxy (V_f = 20%)
0	2.903	6.378	1.499
15	1.000	2.069	1.344
30	0.372	0.715	0.800
45	0.220	0.414	0.507
60	0.177	0.290	0.508
75	0.133	0.227	0.518
90	0.123	0.208	0.479

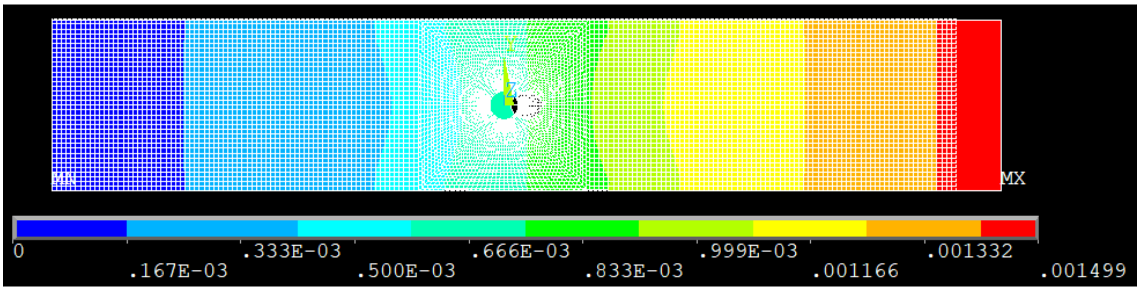


Figure 6: Effect of the open hole on maximum OHT deformation contour of kenaf/epoxy composite.

3.2 Effect of Addition of Supporting Ply-Angle (0°) In Layup Sequence

The effect of open hole size on maximum tensile stress was studied on specimens with unidirectional 0° fibre orientation as the highest maximum stress was observed on 0° fibre orientation compared to other fibre orientations. The open hole size tested was 6 mm, 8 mm, and 12 mm on each composite specimen. Table 6 shows the effect of the increase in open hole size on maximum tensile stress. It was observed that as the diameter of the hole size increases, the maximum stress decreases. This behaviour is observed on maximum tensile stress towards the increase in hole size diameter on kenaf/epoxy composite with a reduction percentage of around 17% for 6 mm hole size, 34% for 8 mm hole size, and 53% for 12 mm hole compared to unhole specimen. The results indicated that a specimen with a larger hole size lessens the stress-supporting region whereas in specimen with a smaller hole size contains a larger region in which stress could be disseminated; thus, reducing the damage to the specimen (Shaari et al., 2017).

Table 6: Effect of open hole size on maximum tensile stress of glass/epoxy and kenaf/epoxy

Hole Diameter (mm)	Maximum Tensile Stress, σ (MPa)		
	Glass/epoxy (V_f = 60%)	Glass/epoxy (V_f = 30%)	Kenaf/epoxy (V_f = 20%)
0 (unhole)	1034.98	342.56	49.48
6	776.07	227.01	40.93
8	679.88	203.02	32.45
12	587.04	179.73	23.15

Figure 7 shows the bar graph of maximum tensile stress against hole size. Glass/epoxy (V_f=60%) is displayed to be the most influenced towards increasing hole dimension. The reduction in the maximum stress due to the increase in open hole diameter exhibited by the composite is more significant compared to glass/epoxy (V_f=30%) and Kenaf/epoxy composites.

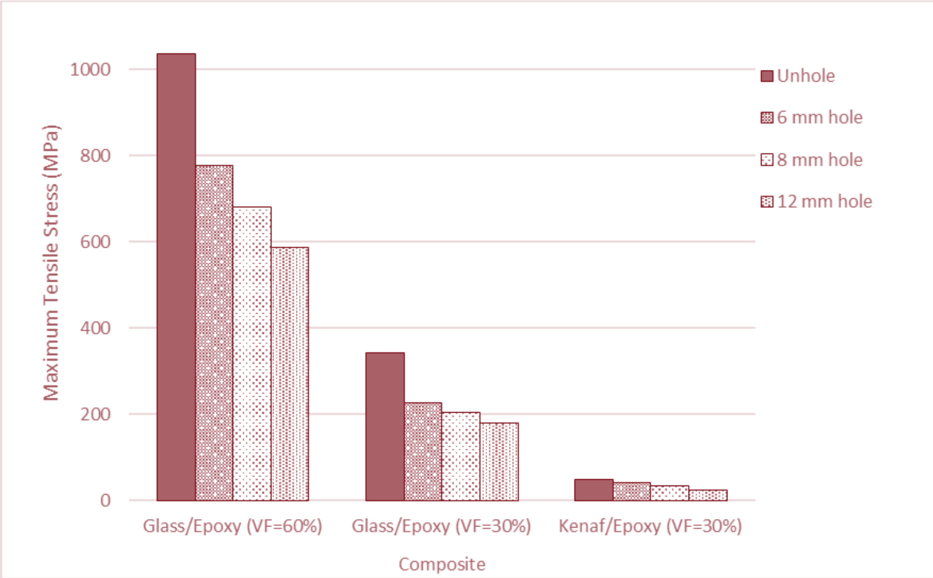


Figure 7: Effect of open hole size on maximum tensile stress.

Figure 8 and Figure 9 show the effect of open hole sizes of 8 mm and 12 mm on its deformation behaviour under tensile load at 0° fibre orientation of kenaf/epoxy composite. It was observed that the specimen with a smaller diameter of the open hole possessed better deformability before failure compared to the specimen with a bigger diameter of the open hole. This is due to the presence of a highly stressed region around the hole which reduces the specimen strength, especially for a hole that is larger than 8 mm (Morais, 2000; Whitney et al., 1974).

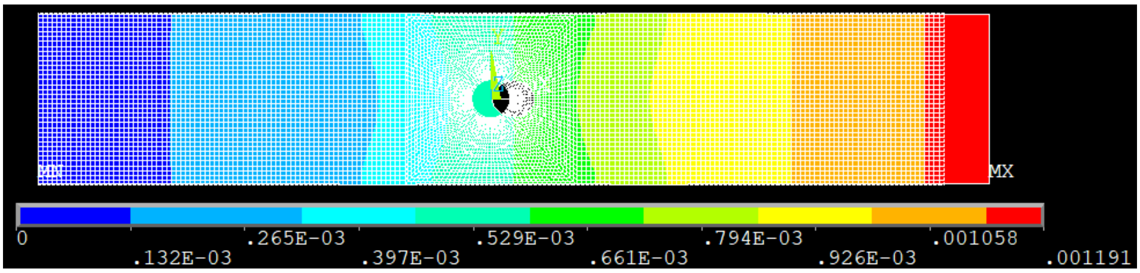


Figure 8: Effect of 8 mm open hole on maximum OHT deformation contour of kenaf/epoxy composite.

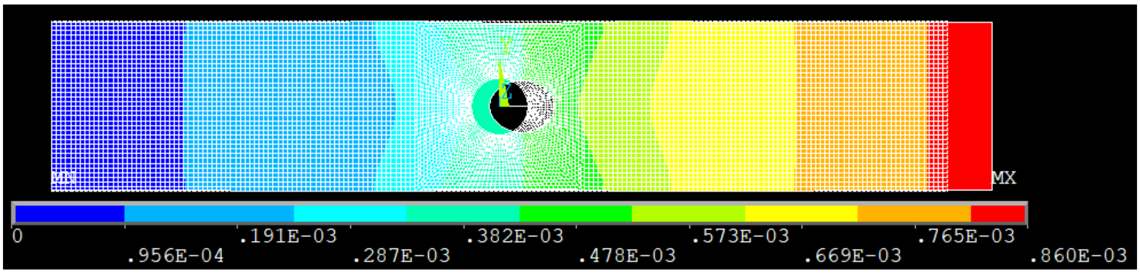


Figure 9: Effect of 12 mm open hole on maximum OHT deformation contour of kenaf/epoxy composite.

4 Conclusion

The effect of the open hole on the tensile properties of the kenaf/epoxy composite was successfully investigated through modelling and simulation methods using ANSYS software. Fibre orientation and size of the hole influence the tensile or notch strength of a composite material. It was found that kenaf/epoxy with unidirectional longitudinal laminate, 0° fibre orientation, exhibits the least strength reduction percentage and also the highest maximum tensile stress with 40.93 MPa in the presence of an open hole, owing to the presence of more fibre to carry the load exerted on the composite. Meanwhile, kenaf/epoxy with transverse laminate, 90° fibre orientation possesses the highest strength reduction percentage and the lowest maximum tensile stress with 3.62 MPa in the presence of an open hole. The diameter of the open hole is found to affect the stress-supporting region of the specimen which also influences the tensile strength of composites. Kenaf/epoxy composite has a reduction percentage of around 17% for 6 mm hole size, 34% for 8 mm hole size, and 53% for 12 mm hole compared to unhole specimen. The results show that a specimen with a smaller open hole diameter possesses a greater stress-supporting region which allows stress to be disseminated; thus, reducing the damage to the specimen.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

6 Acknowledgement

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