©2022 International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

ISSN 2228-9860 eISSN 1906-9642 CODEN: ITJEA8

TuEngr Group

International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

http://TuEngr.com

Modelling and Simulation of Quasi-Static Indentation of Kenaf/Epoxy Composite

Ilya Izyan Shahrul Azhar[1], Aidah Jumahat[2,3*], Sabreena Wam[2], Ramzi Khiari[4]

[1] College of Engineering, Universiti Teknologi MARA, Cawangan Johor, Kampus Pasir Gudang, Johor, MALAYSIA.

[2] School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA.

[3] Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA (UiTM) Shah Alam, Selangor, MALAYSIA.

[4] Laboratory of Environmental Chemistry and Cleaner Process, Faculty of Science Monastir 5000, Monastir, TUNISIA.

**Corresponding Author (Tel: +60122290890, Email: aidahjumahat@ uitm.edu.my).*

Paper ID: 13A13F

Volume 13 Issue 13

Received 23 July 2022
Received in revised form 18 October 2022
Accepted 25 October 2022
Available online 01 November 2022

Keywords:
Penetration depth; Kenaf fibre; Glass fibre; Fibre reinforced polymer composites; Fibre volume fraction; Fibre orientation; Polymer composite; ANSYS; Quasi-static indentation (QSI).

Abstract

The performance of composites loaded in quasi-static indentation is influenced by properties of reinforcement fibres, fibre volume fraction, fibre orientation and layup sequence of the composites. The effect of fibre orientation of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, and layup sequence of $[(+\theta,-\theta)_4]_s$ and $[\pm\theta_2,0_4]_s$ on quasi-static indentation properties of fibre-reinforced polymer (FRP) composites were determined through modelling and simulation analysis using ANSYS software. The effect of fibre types, Kenaf and Glass fibre, and the effect of fibre volume fraction on quasi-static indentation properties and penetration depth properties were simulated and analysed. It is found that as the fibre orientation angle increases from 0° to 45°, the maximum quasi-static indentation strength increases, and then starts to decrease until 90°. The maximum quasi-static indentation strength of Kenaf FRP composite was observed at 45° fibre orientation with 39.2 MPa and 40.3 MPa for layup sequence of $[(+\theta,-\theta)_4]_s$ and $[\pm\theta_2,0_4]_s$, respectively. The maximum penetration depth of the composite was observed at 45° fibre orientation with 0.312 mm and 0.315 mm for both layup sequences. The addition of 0° fibre orientation into the layup sequence of $[\pm\theta_2,0_4]_s$ helps in increasing the curve of maximum quasi-static indentation stress of Kenaf FRP composite by 25%.

Discipline: Mechanical Engineering, Materials (Polymer Composites, Engineering Materials, Advanced Materials).

Cite This Article:

Azhar, I. I. S., Jumahat, A., Wam, S., Khiari, R. (2022). Modelling and Simulation of Quasi-static Indentation of Kenaf/Epoxy Composite. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 13*(13), 13A13F, 1-9. http://TUENGR.COM/V13/13A13F.pdf DOI: 10.14456/ITJEMAST.2022.258

1 Introduction

In the present years, people have become more conscious of the impact of the production of inorganic materials on the environment causing the rise of interest in the application of natural fibres and their potential to replace the usage of synthetic fibres in various fields (Kamrun, 2019). Fibres as a reinforcing agent contribute to quasi-static indentation strength, enhanced strength, and stiffness of polymer composites while minimizing their weight. The performance of fibre-reinforced polymer (FRP) composites is influenced by the properties of fibre used as the reinforcing agent, the properties of the polymer matrix, the ratio between the fibre and polymer matrix in the composite as well as the orientation of fibre in the composite. Kenaf (Hibiscus cannabinus L.) is a herbaceous plant that has recently been commercialized in industries as natural fibre reinforcement for composite for its appealing mechanical properties such as being low in density but high in specific strength and modulus.

Compared to other natural fibres, Kenaf fibre is preferred and developed for its properties and better performance such as its impact strength, storage modulus, and thermal stability (Sapiai, 2014). Epoxy resins exhibit high strength, low shrinkage, excellent chemical, and heat resistance. Composite materials are extremely vulnerable to impact, which can cause damage and even cause the components to break (Yunus, 2018). The addition of natural fibres to epoxy composites shows great mechanical properties such as higher storage modulus and better thermal stability which affect the composite's elasticity (Ching Hao Lee, 2021). The quality of the fibre-matrix interface and the matrix stiffness is important to the strength of the FRP composite especially for Natural FRP (NFRP) composites as the mechanical strength of NFRP relies on the effectiveness of the stress transfer between the fibre and the matrix, while the toughness of the composite is governed by adhesion (Saba, 2015).

The previous study shows that the tensile strength and modulus of elasticity of unidirectional Kenaf/Epoxy composite increases as the fibre volume increases indicating composite with higher fibre volume is stiffer and able to withstand more significant load (Purohit, 2017). The bending strength of the Kenaf FRP composite suggested Kenaf/Epoxy composite exhibits excellent flexural strength when compared to other natural fibres; Kenaf fibres show great properties in polymeric composites as fibre reinforcement when loaded under varied flexural loading conditions (Bakar, 2014). However, Kenaf/Epoxy composites fabricated through the hand-layout technique with high fibre content convey greater disintegration rates and load-carrying capacity, implying the fatigue life of the composite is affected by the fibre content (Purohit, 2017). It is also suggested that the alignment of continuous Kenaf fibres affects the strength of the composite which shows better properties compared to chopped Kenaf fibre. In continuous fibre, the load is effectively transported along the fibre length in an effective way, compared to short fibre which strengthens the fibre (Sapiai, 2014).

Studies on natural FRP composites such as Kenaf/epoxy are very beneficial to encourage more applications of these biodegradable composites in the future. Results obtained through

ANSYS simulation can be compared with results obtained from the experimental method, which enables a comparison between actual and target processes in respect of practicability and efficiency. The objectives of the study are to conduct modelling and simulation to analyse the performance of quasi-static indentation Kenaf FRP composite using ANSYS software. The study on the effect of fibre orientation and layup sequence on FRP composites loaded in quasi-static indentation (QSI) allows the prediction of mechanical values. Since no similar research has been done, this new approach can be used to support the production of various designs of composites based on desired properties in engineering industries.

Quasi-static indentation (QSI) test is one of the mechanical tests which measures the behaviour of composites under low-velocity impact. QSI test is useful to analyse the behaviour of composites such as their sequence and interaction during a low-velocity impact. In this study, the quasi-static indentation properties of Kenaf FRP composites were determined using finite element modelling and simulation analysis using ANSYS software. The effect of fibre orientation of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, and layup sequence of $[(+\theta,-\theta)4]_s$ and $[\pm\theta 2,04]_s$ on quasi-static indentation properties of Kenaf FRP composite was investigated. A simulation was also done on a Glass FRP composite with two different fibre volume fractions (V_f=30% and V_f=60%) for comparison and validation purposes.

2 Method

2.1 Quasi-Static Indentation (QSI) Test

The dimension used for QSI Test is 50 mm × 50 mm. It was set up following the ASTM D6424 standard dimension for modelling and simulation using ANSYS software. The reference of linear orthotropic material properties for the composite was then filled up following the input data as listed in Table 1.

Table 1: Material properties of Kenaf FRP and Glass FRP composites.

Mechanical Properties	Symbol	Glass/Epoxy (Vf=60%) [55]	Glass/Epoxy (Vf=30%) [55][56]	Kenaf/Epoxy [47][57]
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

2.2 Finite Element Method

In this study, the symmetric angle-ply sequence of $[0]_{16}$, $[(+15/-15)4]_s$, $[(+30/-30)4]_s$, $[(+45/-45)4]_s$, $[(+60/-60)4]_s$, $[(+75/-75)4]_s$ and $[90]_{16}$, and supporting angle-ply sequence of $[(\pm15)2/04]_s$, $[(\pm30)2/04]_s$, $[(\pm45)2/04]$s, $[(\pm60)2/04]_s$, $[(\pm75)2/04]_s$, and $[(\pm90)2/04]_s$ were implemented across all types of FRP composite laminate sequence. A meshing size of 8 x 8 is used and shapes for meshes are quad and mapped for the specimen. Displacement on nodes (All Degree of Freedom to be constrained at a constant value of 0) placed at all outer nodes of the specimen while quasi-static indentation load is introduced on the node at the middle point of the specimen. The type of meshing, boundary conditions, and loading type is provided in Figure 1.

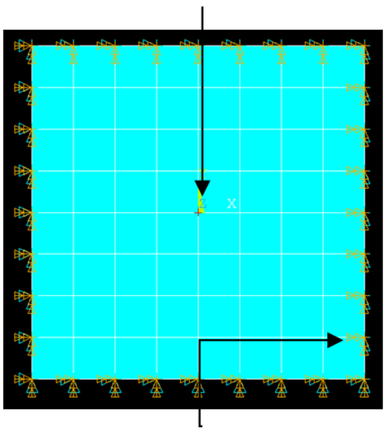


Figure 1: Meshing, boundary condition, and loading direction of the specimen under quasi-static indentation loading.

2.3 Numerical Validation

A numerical validation was done to assess the accuracy of the results from the modelling and simulation approach by comparing the finite element analysis results with the analytical results. 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 comparison is shown in Table 2. The accuracy of the finite element analysis was determined through the percentage of error calculated. The overall percentage of error for both loadings is lesser than 0.2%, thus the modelling and simulation methods used are acceptable.

Table 2: 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 chapter displays the results obtained and discusses the effect of fibre orientation and the addition of supporting ply angle on layer sequence, the effect of fibre type, and fibre volume fraction under quasi-static loading. The simulations were done on specimens with a thickness of 4 mm. The thickness of each layer for every specimen is 0.25 mm. The layup sequences used are

$[(+\theta,-\theta)_4]_s$ and $[(+\theta,-\theta)_2,0_4]_s$, in which θ is 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The simulation outcomes include maximum stress and deformation analysis contour.

3.1 Effect on Fibre Orientation

Table 3 shows the effect of fibre orientation with symmetric angle-ply of $[(+\theta,-\theta)_4]_s$ under quasi-static loading on the maximum stress and maximum deformation or indentation depth of Glass/epoxy (V_f=60% and V_f=30%) and Kenaf/epoxy composites. It can be observed that the highest maximum QSI stress can be seen on the specimen with a 45° fibre orientation while the lowest maximum quasi-static indentation stress is seen on specimens with 0° and 90° fibre orientation. The highest maximum QSI stress of Kenaf/epoxy obtained is 39.2 MPa at 45° fibre orientation. Figure 2 shows the QSI behaviour towards fibre orientation and a dome-shaped graph was obtained in which the tip of the dome indicated the highest maximum QSI stress.

Table 3: Effect of fiber orientation on maximum QSI stress and the indentation depth.

Fibre Orientation, θ (°)	Glass/Epoxy (Vf=60%)		Glass/Epoxy (Vf=30%)		Kenaf/Epoxy	
	σ (MPa)	Δ (mm)	σ (MPa)	Δ (mm)	σ (MPa)	Δ (mm)
0	54.1	0.060	14.3	0.100	22.1	0.222
15	62.0	0.064	15.8	0.107	25.5	0.238
30	82.1	0.073	18.4	0.120	35.0	0.291
45	94.7	0.079	19.5	0.125	39.2	0.312
60	82.9	0.073	18.4	0.120	35.0	0.291
75	62.0	0.064	15.8	0.107	27.4	0.256
90	54.1	0.060	14.3	0.100	23.6	0.237

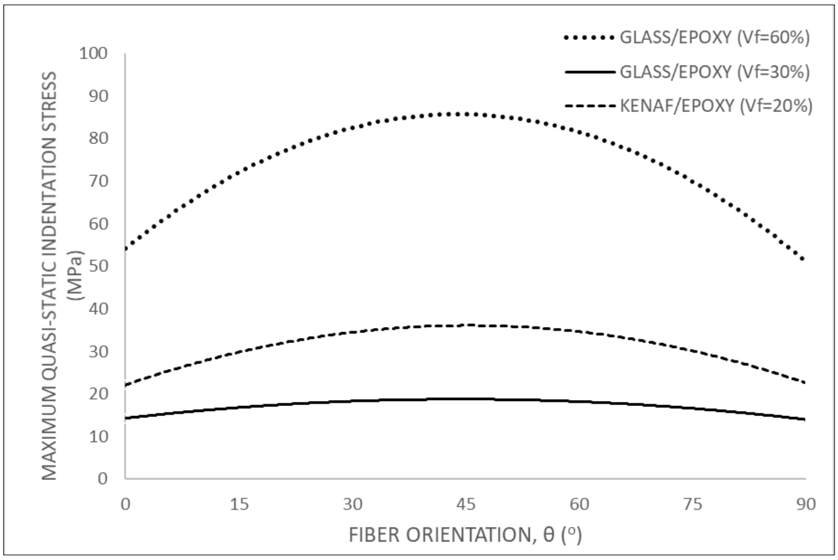


Figure 2: Polynomial graph of maximum QSI stress against fibre orientation.

As shown in Figure 2, the maximum QSI stress increases with the fibre ply orientation from 0° to 45° orientation with the highest peak of the curve indicating the highest maximum QSI stress at 45° fibre orientation. Meanwhile, from 45° to 90° fibre ply orientation shows decreasing in the maximum QSI stress. A previous study by Suresh Kumar revealed that 45° angle ply laminates offered higher linear stiffness compared to 0° and 90° ply laminates (Norazean Shaari, 2017). This suggests that at 45° fibre orientation, both fibres and matrix play a significant role in the resistance offered to shear-induced damage thus causing it to possess the highest maximum QSI stress. Figure

3 shows that deformation contours show their deformation behaviour. The highest indentation depth was observed at the middle node of the specimen where the QSI load was introduced to the specimen.

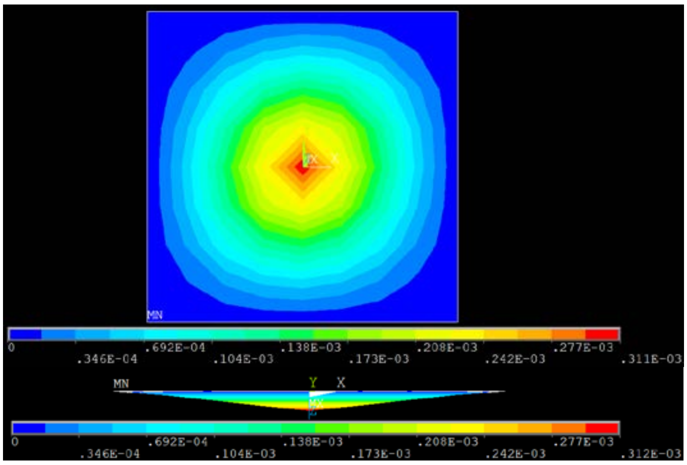


Figure 3: Effect of fibre orientation on maximum deformation and indentation depth contour of Kenaf/epoxy (V_f=20%)

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

Table 4 shows the effect of the addition of supporting ply angle (0°) on the maximum stress of Glass/epoxy (V_f=60% and V_f=30%) and Kenaf/epoxy composites under QSI loads. It can be observed that the maximum stress elevated with the addition of 0° fibre orientation in the $[+\theta,-\theta,0,0]_s$ layup sequence compared to the $[(+\theta,-\theta)2]_s$ layup sequence.

Table 4: Effect of addition of supporting ply angle (0^o) on maximum QSI stress of Glass/epoxy and Kenaf/epoxy.

Fibre Orientation, θ (°)	Maximum QSI Stress, σ (MPa)								
	Glass/Epoxy (V_f=60%)			Glass/Epoxy (V_f=30%)			Kenaf/Epoxy (V_f=20%)		
	LS 1	LS 2	EP (%)	LS 1	LS 2	EP (%)	LS 1	LS 2	EP (%)
0	54.1	54.1	-	14.3	14.3	-	22.1	22.1	-
15	62	62	0.00	15.8	15.8	0.00	25.5	25.5	0.00
30	82.1	82.1	0.00	18.4	18.5	0.54	35.0	32.9	-6.00
45	94.7	97.4	2.85	19.5	19.9	2.05	39.2	40.3	2.81
60	82.9	91.1	9.89	18.4	19.3	4.89	35.0	38.1	8.86
75	62	75.9	22.42	15.8	17.3	9.49	27.4	32.3	17.88
90	54.1	69.4	28.28	14.3	16.1	12.59	23.6	29.5	25.00

*LS 1: Layup sequence number 1 ($[(+\theta,-\theta)_2]_s$)
LS 2: Layup sequence number 2 ($[+\theta,-\theta,0,0]_s$)
EP (%): Elevation Percentage

Figure 4 shows the effect of the addition of supporting ply-angle (0°) on the maximum stress of Kenaf/epoxy under QSI load. The figures display that the addition of a supporting ply angle (0°) into the layup sequence elevates the maximum stress significantly at 90° fibre orientation. At 90° fibre orientation, maximum QSI stress elevated from 23.6 MPa to 29.5 MPa with a percentage increase of 25%. Results indicate that the addition of supporting ply-angle (0°) into the layup sequence give a significant influence on Kenaf/epoxy.

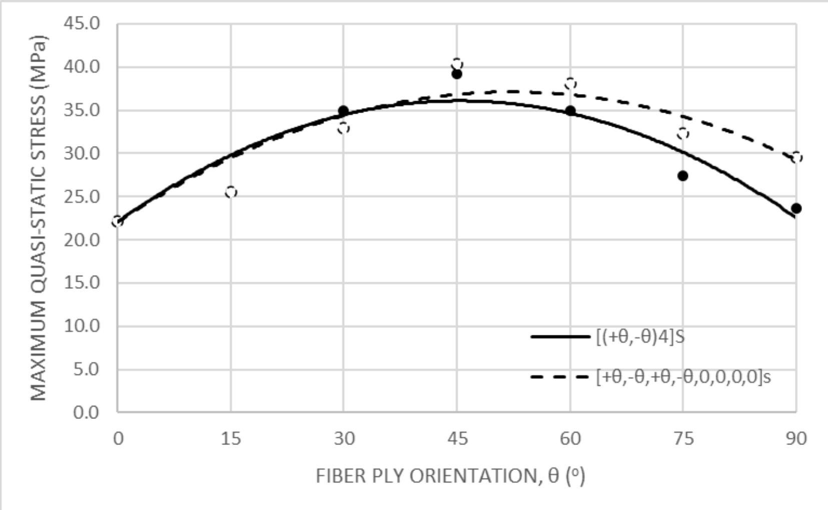


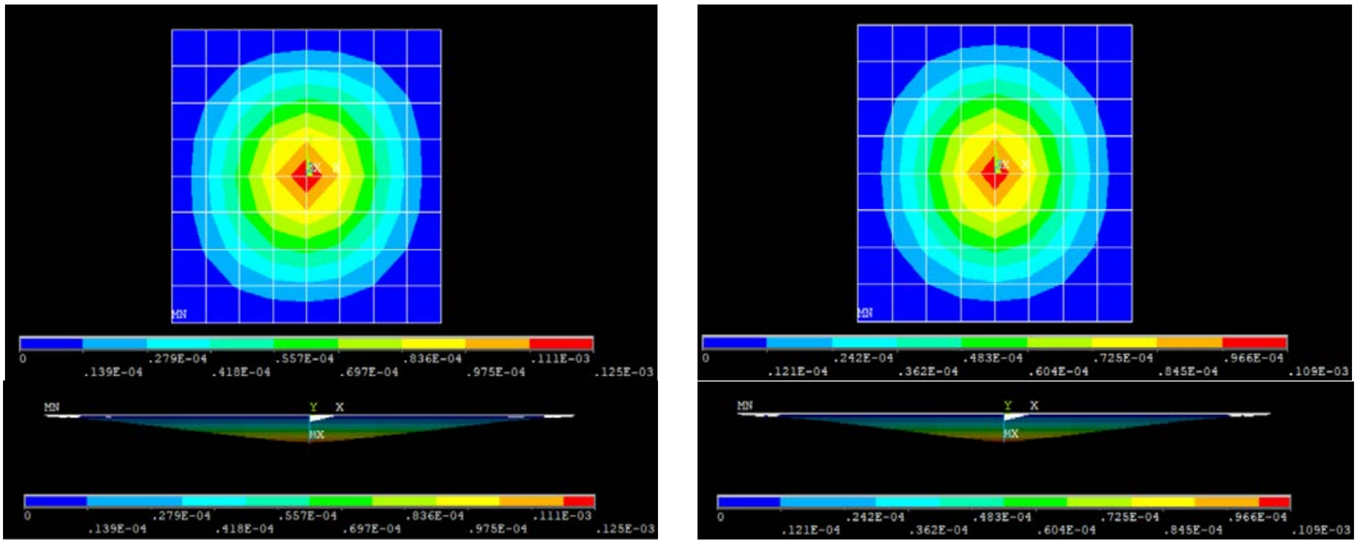
Figure 4: Effect of additional supporting ply-angle on maximum QSI stress of Kenaf/Epoxy

Table 5 shows the maximum deformation of Glass/epoxy (V_f=60% and V_f=30%) and Kenaf/epoxy composites with various layup sequences loaded in quasi-static. This implies that fibre volume fraction affects the deformability of the composites, in which as fibre volume fraction increases, the composite becomes stiffer, thus decreasing the deformability of the composite (H. Salmah, 2011).

Table 5: Effect of addition of supporting ply angle (0^o) on maximum indentation depth of Glass/epoxy and Kenaf/epoxy.

Fibre Orientation, θ (°)	Maximum QSI Stress, σ (MPa)								
	Glass/Epoxy (V_f=60%)			Glass/Epoxy (V_f=30%)			Kenaf/Epoxy (V_f=20%)		
	LS 1	LS 2	EP (%)	LS 1	LS 2	EP (%)	LS 1	LS 2	EP (%)
0	54.1	54.1	-	14.3	14.3	-	22.1	22.1	-
15	62	62	0.00	15.8	15.8	0.00	25.5	25.5	0.00
30	82.1	82.1	0.00	18.4	18.5	0.54	35.0	32.9	-6.00
45	94.7	97.4	2.85	19.5	19.9	2.05	39.2	40.3	2.81
60	82.9	91.1	9.89	18.4	19.3	4.89	35.0	38.1	8.86
75	62	75.9	22.42	15.8	17.3	9.49	27.4	32.3	17.88
90	54.1	69.4	28.28	14.3	16.1	12.59	23.6	29.5	25.00

*LS 1: Layup sequence number 1 ($[(+\theta,-\theta)_2]_s$)
LS 2: Layup sequence number 2 ($[+\theta,-\theta,0,0]_s$)
EP (%): Elevation Percentage



(a) [(+45,-45)2] (b) [+90,-90,0,0]s

Figure 5: Indentation depth contour of Kenaf/epoxy (V_f=20%)

Figure 5 shows the maximum indentation depth contour of Kenaf/epoxy (V_f=20%) with $[(+45,-45)2]_s$ and $[+90,-90,0,0]_s$ laminates when loaded in quasi-static. The results reveal that Glass/epoxy composite with a lower volume fraction (V_f=30%) exhibits greater maximum deformation compared to Glass/epoxy composite with a higher volume fraction (V_f=60%).

4 Conclusion

The influence of geometrical alterations such as fibre orientation and addition of supporting ply angle, 0° on the mechanical behaviour of composites in terms of their quasi-static indentation properties was investigated. It was found that the highest maximum QSI stress can be found at 45° fibre orientation, where both fibres and matrix resist shear-induced damage from the load. The addition of 0° fibre orientation into the lamination scheme shows a significant elevation effect on the maximum stress at 90° fibre orientation for all four tests. Moreover, the fibre volume fraction also affected the maximum stress, in which a composite with a higher fibre volume fraction exhibit greater maximum stress. It was noted that the type of fibre used in FRP composites also affected its performance. Generally, synthetic fibre such as glass fibre is more advantageous compared to natural fibre. However, between Glass/epoxy (V_f=30%) and Kenaf/epoxy, there are times when the NFRP composite shows better performance, especially at higher fibre orientation. This shows the importance of the fibre-matrix interface in influencing the stiffness of the composite. Thus, the Kenaf FRP composite shows great potential to be implemented as a partial substitute for conventional FRP composite due to its valuable properties such as good mechanical properties, biodegradability, low cost, and sustainability.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

6 Acknowledgement

The authors would like to thank the School of Mechanical Engineering, Universiti Teknologi Mara (UiTM), Shah Alam, and the Ministry of Higher Education, Malaysia for the research support. This research work is financially supported by the Strategic Research Partnership (SRP) Grant no: 100-RMC 5/3/SRP (001/2020) and DINAMIK grant No. 600-RMC/DINAMIKPOSTDOC 5/3 (004/2020) Universiti Teknologi MARA (UiTM) Malaysia.

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Ilya Izyan Shahrul Azhar is a PhD student at the School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor, Malaysia. She obtained her Masters' degree from Universiti Teknologi Malaysia (UTM), Skudai, Johor. Her Master's degree involved creep characteristic of austenistic stainless steel. Currently, her study focuses on enhancing fibre-reinforced polymer composites with thermoplastic thin film.

Prof. Dr. Aidah Jumahat has a PhD degree in Mechanical Engineering from the University of Sheffield United Kingdom, a MSc (Mechanical Engineering) degree and a B.Eng. (Hons.) Mechanical and Materials Engineering degree from the Universiti Kebangsaan Malaysia. She has been lecturing on Composite Materials, Finite Element Method, Mechanics of Materials, Manufacturing Processes, Product Design and Advanced Materials, which happens to be her areas of research interest.

Sabreena binti Wam completed her Bachelor Degree (Hon.) in Mechanical Engineering from the College of Engineering, Universiti Teknologi MARA (UiTM) in 2022. Her main research of interest is in fibres reinforced composites. Her final year project involved investigation on the effect of several geometrical alterations on the mechanical behaviour of kenaf and glass fibres reinforced composites in terms of its tensile, compression, flexural, and quasi-static indentation properties

Prof. Dr. Ramzi Khiari is a professor at the Higher Institute of Technological Studies in Ksar-Hellal (Monastir, Tunisia) in the department of Textile Engineering. He is a permanent member of Laboratory of Environmental Chemistry and Clean Process (LCE2P- LR21ES04) research group in the Faculty of Sciences of Monastir of the University of Monastir in Tunisia. His research interests focus on the valorization of biomass at multi-scale levels namely: fibers, nanocellulose, lignin, hemicelluloses and their used as potential raw materials in several industrial applications (Textile, papermaking, polymeric materials, composites and nanocomposites). A particular focus is given to vegetal biomass from annual plants, and particularly agricultural residues and industrial wastes"