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Maximum Quasi-Static Indentation Stress Analysis of Flax/Epoxy and Glass/Epoxy Polymer Composites

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Abstract: The use of fibres is constantly expanding to satisfy the demands of various industries. Both synthetic and natural fibres offer benefits that are best suited to specific applications. Synthetic fibres are preferable than the natural fibres because they have greater mechanical properties. However, in their application, synthetic fibres negatively influence the environment as they are non-biodegradable material. As a result, the demand and usage of natural fibres keep increasing as an alternative to the synthetic fibres. The usage of natural fibres reduces negative impact on the environmental, though their properties are not as good as synthetic fibres. ANSYS APDL, one of the FEA analysis software, is used to perform quasi-static indentation (QSI) test modelling in this research work. The purpose of this study is to determine the influence of fibre orientations of 0°, 15°, 30°, 45°, 60°, 75°, and 90°, as well as the effect of the supporting ply angle, 0°, on the mechanical properties of Flax FRP composite. For layup sequences of $[(+\theta, -\theta)_2]_S$ and $[(\pm\theta)_2,0_4]_S$, it was observed that maximum strength increases from 0° to 90° fibre orientation. Meanwhile, in a QSI test, the highest strength of Flax FRP was found at 45° for both $[(+\theta, -\theta)_2]_S$ and $[(\pm\theta)_2,0_4]_S$ layup sequences, with 94.20 MPa and 96.80 MPa, respectively. The effect of fibre volume fraction (Vf), such as Glass FRP composites with fibre volume fractions of 30% and 60%, shows that the fibre volume fraction for 60% has a better performance than 30%. Therefore, composites with a higher fibre volume fraction show better maximum strength and lower deformability. The results of modelling and simulation work on Flax FRP composites can aid in developing new materials that are more sustainable than conventional techniques by anticipating the mechanical behaviour of natural FRP composites.

Keywords: Fibre reinforced polymer composite, flax, quasi-static indentation, finite element analysis, ANSYS

1. Introduction

Natural fibres are known as eco-friendly materials that are used as replacement materials to conventional fibres for composite reinforcement. Natural FRP composites have lower strength than conventional fibres and have high moisture absorption rate, which are their primary disadvantages. However, Fibre Reinforced Polymer (FRP) composites are a

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group of structural materials employed or regarded as metal substitutes in many applications due to their enormous potential in various engineering sectors.

The usage of FRP composites continues to grow at an impressive rate as these materials are used more in current industries. Any combination or composition that consists of two or more materials as discrete phases, at least one of which is a polymer, is referred to as a polymer composite [1]. It is frequently feasible to develop new combinations or properties by mixing a polymer with another material, such as glass, carbon, or another polymer. FRP composite is a combination of fibre and matrix in which fibre with high modulus and strength and matrix with low strength are bonded with different interphases [2]. Natural and synthetic fibres are the most common types used in composite materials. Natural fibres are a common and easy-to-find material in nature. They reveal that excellent material properties include biodegradability, low cost per unit volume, high strength, and specific stiffness [3]. Flax is one of the most widely used natural fibres, and it is extracted from a flowering plant named Linum Usitatissimum [4].

Flax materials are viewed as a more sustainable alternative to current composites with several advantages. In addition to their environmental benefits, they have low densities, good damping, and vibration absorption [5]. Flax is one of the most durable plant fibres when compared to others. Flax FRP composite is a blend of flax fibre and matrix. Matrix is a material that transfers load between fibres while reducing mechanical abrasion on the fibre surface [6]. Excellent corrosion resistance and adhesion strength, good processing capabilities, minimal curing shrinkage, outstanding mechanical, thermal, and electrical properties, and flexible formulation flexibility are all advantages of epoxy matrix [7]. The previous study has shown that increasing the fibre volume increases the tensile and compressive modulus of unidirectional Flax FRP composite. Furthermore, it is usually weaker than tensile strength. As a result, this mechanical property is important for improving flax biocomposites [8]. Fibre volume fraction, fibre and matrix characteristics, interface bond strength, porosity and fibre misalignment are contributing factors that might influence the behaviour of composite materials. Many methods can be developed to produce Flax FRP composites such as hand lay-up, compression moulding, film stacking, vacuum infusion, filament winding, manual winding, resin transfer moulding, injection moulding, and pultrusion [9]. However, the type of polymer utilised, the volume fraction fibre, the fibre orientation, the curing procedure, and the production techniques all affect the strength of flax fibre. Table 1 shows the properties of unidirectional Flax FRP composite.

Table 1 - Properties of unidirectional Flax FRP composite [10]

Matrix	Fibre volume fraction (%)	Compressive modulus (GPa)	Compressive strength (MPa)	Tensile modulus (GPa)	Tensile strength (MPa)
Phenol formaldehyde	˜70	41.4	163	41.4	310
Phenol formaldehyde	˜75	48.3	182	48.3	414
Epoxy	43.9	24.7	136	22.8	318
Epoxy	40	15.1	137	23.9	223
Epoxy	51	30.3	127	31.4	287

Glass fibre is a synthetic fibre that has been prepared using various manufacturing techniques and is widely utilised in various applications. Glass fibres have several advantages, including great tensile strength, chemical resistance, and good insulating properties. However, glass fibre has the disadvantages of having a low tensile modulus and a high density when compared to commercial fibres, and because it is a syntactic fibre, it has a negative environmental effect. The combination of glass fibre as a reinforced element and polymer matrix elements, including epoxy, polyester, vinyl ester, and thermoplastic, is a glass fibre reinforced polymer (GFRP). Table 2 shows the physical and mechanical properties of glass fibre.

Epoxy is utilised as a matrix element in this project. The reinforced element strengthens the material, improves stiffness, and improves overall performance. From the previous research, each test was carried out on variations in the amount of fiberglass lamination CSM 300, CSM 450 and WR 600 and the variation in weight percentages of 99.5% - 0.5%, 99% -1%, 98.5% -1, 5%, 98% -2% and 97.5% -2.5% have been used [12]. The results demonstrate that the tensile strength improves as the number of laminates grows, and the tensile strength decreases when the weight of the hardener increases. The mechanical properties of GFRP vary depending on the type, orientation, matrix percentage, and fibres used. In addition, recent research has shown that the mechanical properties and performance of fibre-reinforced composites are affected not only by matrix type, fibre type, fibre volume percentage, and fibre orientation but also by matrix morphology and the fibre-matrix interface [13].

Experimentation is typically used to determine the properties. Mechanical property prediction values for natural FRP composites are relatively limited, and other modelling and simulation work is required to resolve these performance values. These simulated and projected values could be utilised in the design of natural FRP composite structures. This might lower the price of destructive testing, shorten the time required to evaluate the FRP composite component or structural performance, and result in various designs based on the desired properties. Composite mechanical properties may be affected by the orientation of fibre reinforcement. As a result, modelling and simulation work is required to investigate the influence of fibre orientation on the mechanical properties of Flax FRP composite. FEA allows for predicting potential design issues, reducing risks to research development. The modelling procedure for this project was carried out using the FEM built-in ANSYS Mechanical APDL, which is suitable for analysing the failure, deformation, and behaviour of composite materials. ANSYS was used to obtain the needed parameters for this project, such as maximum stress, deformation, and failure modes. This study aims to evaluate the effect of layer sequence on quasi-static indentation strength and deformation of flax fibre-reinforced polymer (FRP) composites. The mechanical properties of flax/epoxy were investigated in this study using ANSYS APDL software for modelling and simulation. The result of this flax/epoxy will be compared with glass/epoxy (Fibre volume fraction (Vf) = 60% and Vf = 30%).

Table 2 - Physical and mechanical properties of glass fibre [11]

Fibre	Density (g/cm3)	Tensile strength (GPa)	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion (10^{-7}/°C)
E-glass	2.58	3.445	72.3	4.8	54
C-glass	2.52	3.310	68.9	4.8	63
S_2-glass	2.46	4.890	86.9	5.7	16
A-glass	2.44	3.310	68.9	4.8	73
D-glass	2.11–2.14	2.415	51.7	4.6	25
R-glass	2.54	4.135	85.5	4.8	33
EGR-glass	2.72	3.445	80.3	4.8	59

2. Methodology

ANSYS APDL software was used to model and simulate flax/epoxy and glass/epoxy composites. The preferred option in the ANSYS software is initially set to structural analysis. Table 3 shows the dimensions used based on ASTM standards, ASTM D7264 Standard Test Method for Quasi-Static Properties of Polymer Matrix Composites Materials. The specimen consisted of flat sections with a standard thickness of 4 mm.

Table 3 - Specimen dimension and stacking sequence

Specimen Dimensions (mm)	
Width	50
Height	50
Thickness	4
Layer	16
Stacking sequence	
Symmetric angle-ply	$[0]_{16}$, $[(\theta/-\theta)_4]_S$
Supporting angle-ply	$[\theta/-\theta/\ \theta/-\theta/0/0/0/0]_S$

The modelling process begins with the Pre-processor options determining the area defined by the rectangle centre and corners. In the Shell 8 node 281 element type, all layers and the middle are selected for layer data storage. The material properties of the model are then classified as structurally linear elastic "Orthotropic". Following that, the reference properties of linear orthotropic materials for composites are filled. The Shell lay-up is then added to the laminate lay-up sequence, followed by the thickness and fibre orientation. Table 4 shows the material properties of the unidirectional flax/epoxy and glass/epoxy composites used in this study. The boundary conditions were applied at each node around the specimen, and the load was applied at the middle node for quasi-static indentation.

Table 4 - Unidirectional mechanical properties

Mechanical Properties	Symbol	Glass/epoxy (Vf = 60%) [14]	Glass/epoxy (Vf = 30%) [15]	Flax/epoxy (Vf = 43%) [16]
Longitudinal modulus (0°)	E_1 (GPa)	54.00	6.47	25.42
Transverse Modulus (90°)	E_2(GPa)	10.80	2.16	4.2
Shear Modulus	G_{12} (GPa)	9.00	2.59	2.01
Poisson's Ratio	ν_{12}	0.25	0.25	0.36
Shear Strength	S_{12} (MPa)	41.00	41.00	39.34
Tensile Strength (0°)	X_T (MPa)	1035.00	342.56	255.14
Tensile Strength (90°)	Y_T (MPa)	28.00	9.25	24.81
Compression Strength (0°)	X_C (MPa)	621.00	77.29	127.5
Compression Strength (90°)	Y_C (MPa)	103.00	10.31	13

Convergence analysis estimates how many mesh elements are needed in a model so that any changes in mesh size do not influence the analysis results. Few mesh sizes, including 2×2, 4×4, 8×8, 16×16, and 32×32, were evaluated on unidirectional glass FRP composite for fibre orientations of 0°, 45°, and 90° under the same tensile load in this convergence analysis. The applied load is the maximum stress in the failure analysis. If the failure index is one, the deformation will be evaluated in all three directions (X, Y, and Z). In the post-processing, the modelling and simulation results will be shown. The contour plot's graphic and animation may be used to view the data, deformation, and behaviour. There are two contours plotting solutions in ANSYS: nodal and element solutions. Fig. 1 depicts the meshing element of the modelled specimen with boundary conditions and loads applied. The meshing size is 8×8, and the mesh shape is quad and mapped for the specimen.

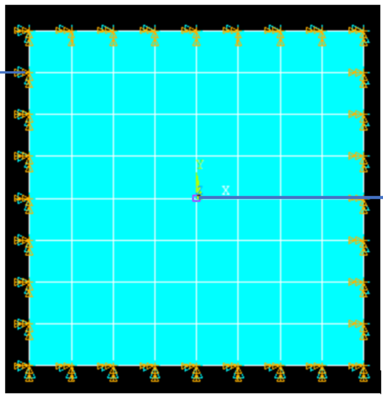


Fig. 1 - Meshing element of the modelled specimen with boundary conditions

3. Results and Discussion

This study investigated the effect of fibre ply orientation on the quasi-static indentation properties and penetration depth at failure load of flax/epoxy fibre-reinforced epoxy composites using ANSYS APDL modelling and simulation software. The flax/epoxy result will be compared to the glass/epoxy result (Vf = 60% vs Vf = 30%).

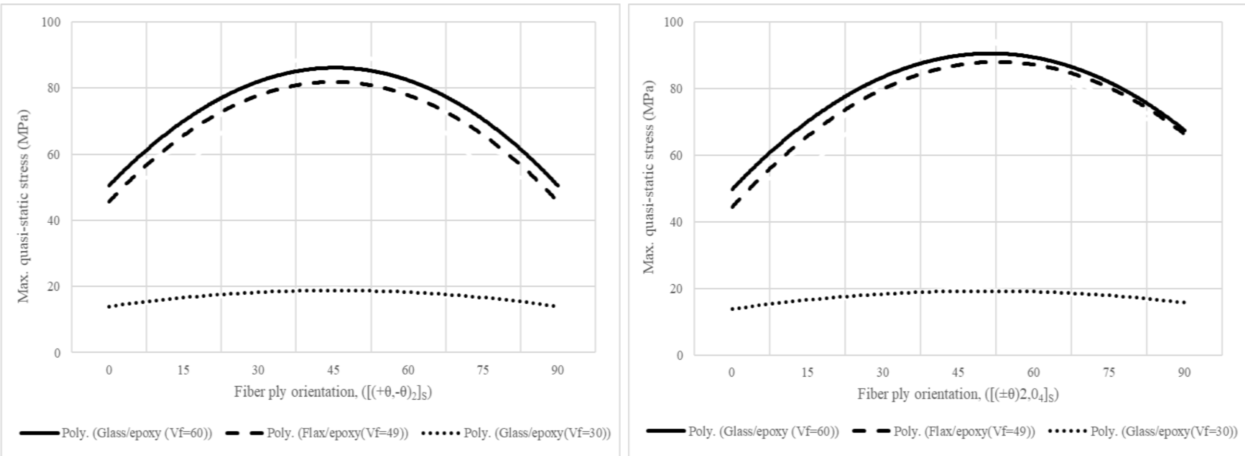
3.1 Effect of Fibre Ply Orientation on Quasi-Static Indentation (QSI) Properties

Table 5 illustrates the maximum quasi-static indentation stress of glass/epoxy (Vf=60%), glass/epoxy (Vf = 30%), and flax/epoxy (Vf = 43%) composites at 0°, 15°, 30°, 45°, 60°, 75°, and 90° fibre ply orientation using lay-up sequences of ($[(+\theta, -\theta)_2]_S$) and ($[(\pm\theta)_2,0_4]_S$). The quasi-static response at different volumes was studied at variations in the orientation, in which the maximum quasi-static stress was experienced when the orientation was 45° for glass/epoxy (Vf = 60%), glass/epoxy (Vf=30%), and flax/epoxy (Vf = 43%). When the quasi-static loading conditions are considered, there will be some crack initiation due to the loading characteristics, which increase and reach the critical load based on the formation of bridges in the fibres and flanks in the cracks [17]. These cracks in fibre increase as the loading condition reach the critical loads and decrease with the degree of orientation. The maximum quasi-static indentation stress for glass/epoxy (Vf = 30%), glass/epoxy (Vf = 30%), and flax/epoxy (Vf = 43%) composites is 94.70 MPa, 19.50 MPa, and 94.20 MPa, respectively, at 45° fibre ply orientation. The greatest maximum quasi-static indentation stress for glass/epoxy (Vf = 30%), glass/epoxy (Vf = 30%), and flax/epoxy (Vf = 43%) composites is 97.40 MPa, 19.90 MPa, and 96.80 MPa, respectively, for 45° fibre ply orientation.

Table 5 - Effect of fibre ply orientation on maximum quasi-static of glass/epoxy and flax/epoxy

Fibre Ply Orientation, θ (º)	Maximum Quasi-static Stress, σ (MPa)					
	Glass/Epoxy (Vf = 60%)		Glass/epoxy (Vf = 30%)		Flax/Epoxy (Vf = 43%)	
	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$
0	54.10	54.10	14.30	14.30	50.10	50.10
15	62.00	62.00	15.80	15.80	55.90	56.10
30	82.10	82.10	18.40	18.50	77.00	76.50
45	94.70	97.40	19.50	19.90	94.20	96.80
60	82.90	91.10	18.40	19.30	77.00	89.90
75	62.00	75.90	15.80	17.30	55.90	73.40
90	54.10	69.40	14.30	16.10	50.10	68.10

Fig. 2 shows that the maximum quasi-static indentation stress curve for each fibre ply orientation changes significantly between glass/epoxy (Vf = 60%) and glass/epoxy (Vf = 30%) composites. Fig. 2(a) illustrates that the maximum quasi-static indentation stress at 0° fibre ply orientation is similar to 90° fibre ply orientation for the lay-up sequence ($[(+\theta, -\theta)_2]_S$). A similar trend is seen in Fig. 2(b) for the ($[(\pm\theta)_2,0_4]_S$) lay-up sequence. The trend obtained by the curve fitting process provides the best fit to the curve in the data.



(a) (b)

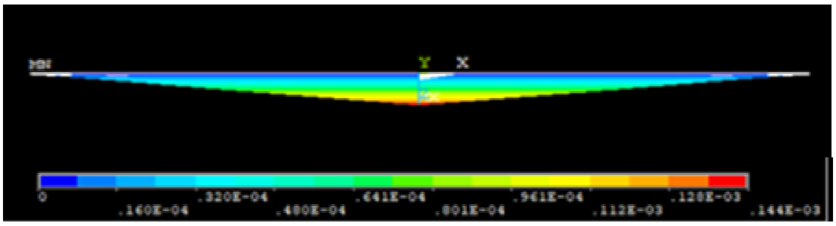
Fig. 2 - Graph of maximum Quasi-static stress against fibre ply orientation of (a) $[(+\theta, -\theta)_2]_S$ and (b) $[(\pm\theta)_2,0_4]_S$ for Glass/Epoxy (Vf = 60% and Vf = 30%) and flax/epoxy (Vf = 43%)

3.2 Effect of Fibre Ply Orientation on Penetration Depth at Failure Load of the Fibre-Reinforced Epoxy Composites

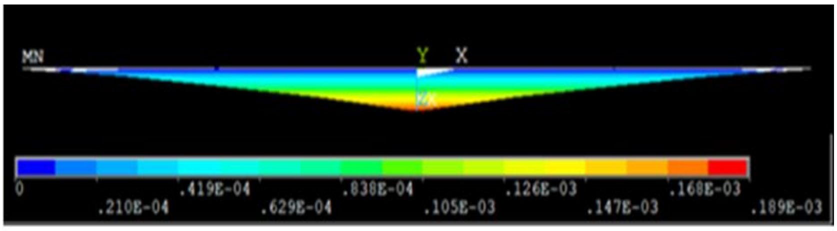
Results presented in Table 6 show that the ($[(+\theta, -\theta)_2,0_4]_S$) lay-up sequence at 45° has a larger penetration depth for all three composites than the ($[(+\theta, -\theta)_4]_S$) lay-up sequence for all three composites. At ($[(+\theta, -\theta)_4]_S$) and ($[(\pm\theta)_2,0_4]_S$) lay-up sequences for 45° fibre ply orientation, the penetration depth of flax/epoxy (Vf = 43%) composite is 0.189 mm and 0.195 mm, respectively. Meanwhile, the penetration depth of glass/epoxy (Vf = 60%) is 0.079 mm for the ($[(+\theta, -\theta)_4]_S$) lay-up sequence and 0.081 mm for the lay-up sequence ($[(\pm\theta)_2,0_4]_S$) at 45° fibre ply orientation. Finally, for lay-up sequences of ($[(+\theta, -\theta)_4]_S$) and ($[(\pm\theta)_2,0_4]_S$) at 45° fibre ply orientation, glass/epoxy (Vf = 30%) penetration depth values are 0.125 mm and 0.126 mm, respectively. The volume fraction of the fibres determines the composites' strength. The highest quasi-static indentation stress values for glass/epoxy (Vf = 60%) and glass/epoxy (Vf = 30%) composites are 94.70 MPa and 19.50 MPa, respectively, at 45° fibre ply orientation of the ($[(+\theta, -\theta)_4]_S$) lay-up sequence. In comparison to glass/epoxy (Vf = 30%) composite, glass/epoxy (Vf = 60%) composite has the greatest value. A similar trend can be seen in the ($[(\pm\theta)_2,0_4]$ S) lay-up sequence, where the maximum quasi-static indentation values for glass/epoxy (Vf = 60%) and glass/epoxy (Vf = 30%) are 97.40 MPa and 19.90 MPa, respectively. The qualities of a composite with a high fibre volume fraction are better than those with a low fibre volume fraction.

Table 6 - Effect of fibre ply orientation on maximum quasi-static of glass/epoxy and flax/epoxy

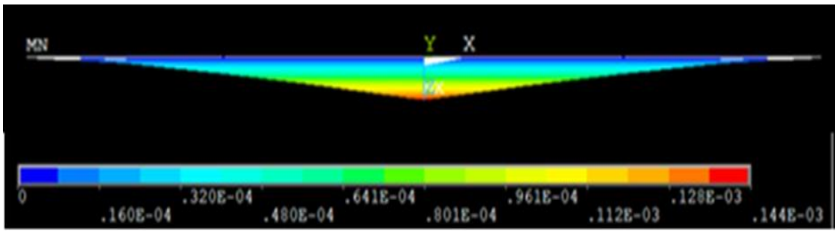
Fibre Ply Orientation, θ (°)	Penetration Depth, Δ (mm)					
	Glass/Epoxy (Vf = 60%)		Glass/epoxy (Vf = 30%)		Flax/Epoxy (Vf = 43%)	
	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$	$[(+\theta,-\theta)_2]_s$	$[(\pm\theta)_2,0_4]_s$
0	0.06	0.06	0.100	0.100	0.144	0.144
15	0.064	0.064	0.107	0.106	0.147	0.148
30	0.823	0.073	0.120	0.012	0.169	0.168
45	0.079	0.081	0.125	0.126	0.189	0.195
60	0.073	0.079	0.120	0.012	0.169	0.194
75	0.064	0.074	0.107	0.114	0.147	0.182
90	0.06	0.072	0.100	0.109	0.144	0.181



(a) Penetration depth Δ = 0.144 mm at 0°



(b) Penetration depth Δ = 0.189 mm at 45°



(c) Penetration depth Δ = 0.144 mm at 90°

Fig. 3 - Maximum penetration depth contour of the fibre-reinforced epoxy composite under quasi-static indentation for flax/epoxy (Vf = 43%) at $[(+\theta, -\theta)_2]_s$

4. Conclusions

The effect of fibre ply orientation on quasi-static indentation properties and the penetration depth at failure load of the fibre-reinforced epoxy composites of flax/epoxy were investigated in this study using ANSYS APDL software for modelling and simulation. The result of this flax/epoxy is then compared to glass/epoxy (Vf = 60% and Vf = 30%).

Based on the quasi-static indentation tests results, the flax fibre-reinforced polymer composite with $[(\pm\theta)_2,0_4]_S$ lay-up sequence exhibited greater maximum stress than the composite with $[(+\theta, -\theta)_2]_S$ lay-up sequence. The maximum quasi-static indentation stress values for glass/epoxy (Vf = 30%), glass/epoxy (Vf=30%), and flax/epoxy (Vf = 43%) composites are 94.70 MPa, 19.50 MPa, and 94.20 MPa, respectively, at 45° fibre ply orientation ($[(+\theta, -\theta)_2]_S$) layup sequence. For ($[(\pm\theta)_2,0_4]_S$) lay-up sequence, at 45° fibre ply orientation, the highest value of maximum quasi-static indentation stress values for glass/epoxy (Vf=30%), glass/epoxy (Vf = 30%), and flax/epoxy (Vf=43%) composites are 97.40 MPa, 19.90 MPa, and 96.80 MPa, respectively. The fibre volume fraction is another factor that impacts the composite's maximum stress. It is found that the glass/epoxy with a volume fraction of 60% has greater maximum stress than glass epoxy with a volume fraction of 30%. The strength reduction percentage of flax fibre-reinforced polymer composite lay-up sequence for $[(\pm\theta)_2,0_4]_S$ layup sequence is smaller than $[(+\theta, -\theta)_2]_S$ layup sequence.

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