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Numerical Simulation of Cross-Ply R-Pet Laminated Composites Subjected to Quasi-Static Indentation Test

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Abstract: Polyethylene Terephthalate (PET) is the most popular thermoplastic that is frequently employed as a reinforcement material in laminated composites due to its lightweight and high strength qualities. In this study, a Finite Element Analysis (FEA) was used to carried out the numerical simulation of quasi-static indentation on r-PET/Epoxy laminated composite. The results from simulation were compared with experimental study which obtained from the secondary data. The FE model for laminated composite panel 100.00 mm x 100.00 mm and a 12.70 mm diameter hemispherical tip for indenter was designed and developed for testing using ANSYS R2 2021 software. The materials and layer of r-PET mats were defined in the ANSYS Composite PrePost (ACP) as a single-plate with different stacking orientation. Experimental testing and simulation results were compared to analyze the behavior of the laminated composite. The findings evidenced that the simulation results have different trends with the experimental test. The simulation results show to have larger deformation on the composite panel and 44.00 % higher energy absorption with 8% different for maximum indentation force in comparison with experimental. However, these differences are not very significant and still logically acceptable. In shorts, both results demonstrated the high potential of r-PET/Epoxy laminated composite as reinforcement material in the engineering application

Keywords: Finite Element Analysis, Laminated composite, Numerical Simulation, Quasi-Static Indentation, Recycled Polyethylene Terephthalate

1. Introduction

Laminated composites have grown in popularity as a material for a variety of engineering structures, including aerospace, mechanical, automotive, marine as well as civil engineering structures. This is

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**Corresponding author: azrin@uthm.edu.my* because the material is capable of combining layers with varied degrees of rigidity. These structures are often employed to sustain bending, torsional, and transverse loads. The investigation of behaviors on laminated composites has been carried out over the course of the past year. Researchers attempted to use recycled or waste materials as reinforcement materials for laminated composites in their experiments. Multilayer or laminated composites are extremely durable and can be used to create lightweight composite panels [1]. A research of numerical and experimental was conducted to study the deformation analysis under mechanical loading of r-PET/wood laminated composites [2]. It can be concluded that the additional of PET layers decreased the bending strength and the modulus of elasticity. Thus, r-PET layers can be used as an alternative to manufacture the laminated composite for various application. Combined material can produce unique properties while also reducing the weaknesses inherent in each of the composite's constituent materials1.1 Introduction subheadings optional

Consequently, recycled polyethylene terephthalate (r-PET) is being considered as a possible reinforcement material for use in conjunction with manufacturing composite [3]. This describes how r-PET has strong material properties and has demonstrated a high degree of resistance to impact loading. In addition, using recycled materials is one way to use environmentally friendly materials while also adding value to this research. As public awareness of plastic pollution grows, researchers around the world are looking for processes that combine the use of recycled materials with the production of high-quality end products. As a result, efforts have been made in research and development to reduce the amount of waste generated by recycled PET.

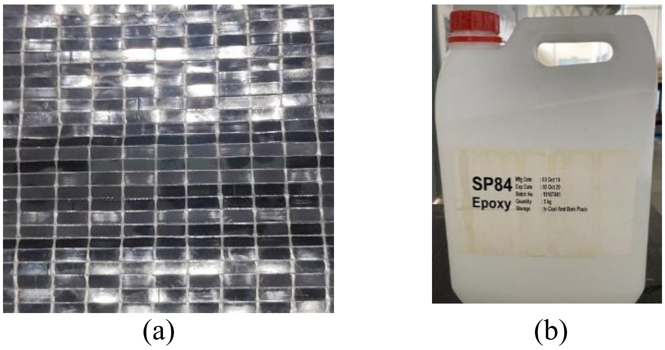
Several researchers have investigated the sturdiness impact response of PET composite as reinforcement for composite material using both experimental and numerical simulation methods [4]–[6]. Numerical simulation, in which the computational simulation was carried out using a commercial code based on finite differences, and the values obtained were compared with experimental data in order to evaluate the outcomes [7]. Based on the development of previous research to reduce the waste of plastic bottle, as well as numerical simulation for prediction and validation with experimental studies, the goal of this study was to investigate the energy absorption of laminated composite material panels made up of r-PET laminated composite and epoxy as matrix by conducting a simulation of a quasi-static indentation test using a computer simulation. Furthermore, by using secondary data from experimental testing and simulations, the impact response of different configurations of panels with different boundary conditions was investigated in greater detail.

2. Materials and Methods

This chapter was focusing on the presentation of the collected data and results that had been obtained from the numerical simulations. The results from the experimental (secondary data) was compared with analysis from simulation. The results are presented in various types of charts in order to makes it more understandable for the readers.

2.1 Material

The experimental work, which was obtained from secondary data, was carried to evaluate the quasi-static indentation impact performance of the r-PET/Epoxy laminated composite. Recycled polyethylene terephthalate (r-PET) was bonded together as a laminated composite, to create a composite structure with resin epoxy as binder. The dimension of a single r-PET mat is 100.00 mm X 100.00 mm with 0.04 mm thickness. Figure 1 shows the cross-ply r-PET mat and resin epoxy.



(a) (b)

Figure 1: (a) cross-ply r-PET mat and (b) resin SP84 Epoxy

2.2 Quasi-static indentation

A quasi-static indentation test was performed on r-PET/Epoxy laminated composites using a Universal Testing Machine in accordance with ASTM D6264. The laminated composite was cut to a 100 mm × 100 mm dimension. Throughout the indentation test, a quasi-static cross-head displacement rate of 1.27mm/min was maintained. The indenter was a hemispherical diameter tip with 12.7 mm diameter. The experiment setup is illustrated in Figure 2 below.

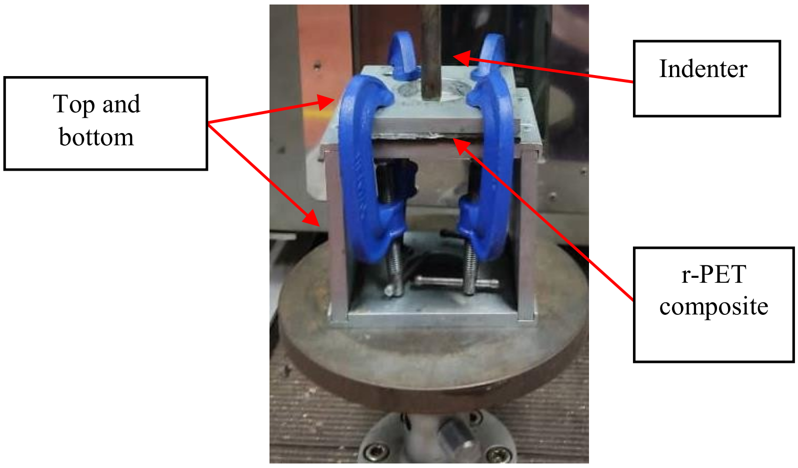


Figure 2: Setup of quasi-static indentation test

2.3 Methods

All the geometry for indenter and r-PET layer mats model were generated by using Design Modeler. The design was built simplified to save the computational times for solving and rendering. The model was then transferred into finite element code ANSYS R2 2021 for numerical simulation. The materials were first designed in the ACP (Pre) in ANSYS Workbench. Figure 3 shows the methodology flow chart of this research.

2.4 Geometry modelling

The FE model of the r-PET mat was model as a single-plate structure with dimension 100mm x 100mm. The geometrical model was shown on Figure 4 consists of 12.70 mm diameter hemispherical tip indenter and a support fixture with 127.00 mm^2 square central opening for simply supported configuration

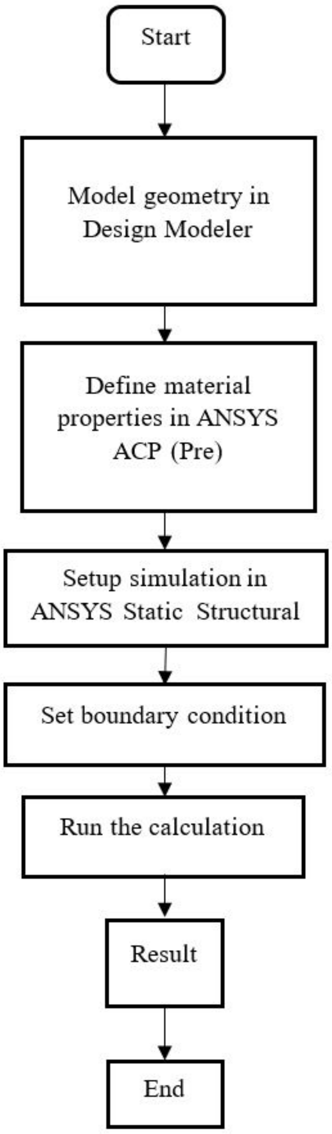


Figure 3: Methodology flowchart

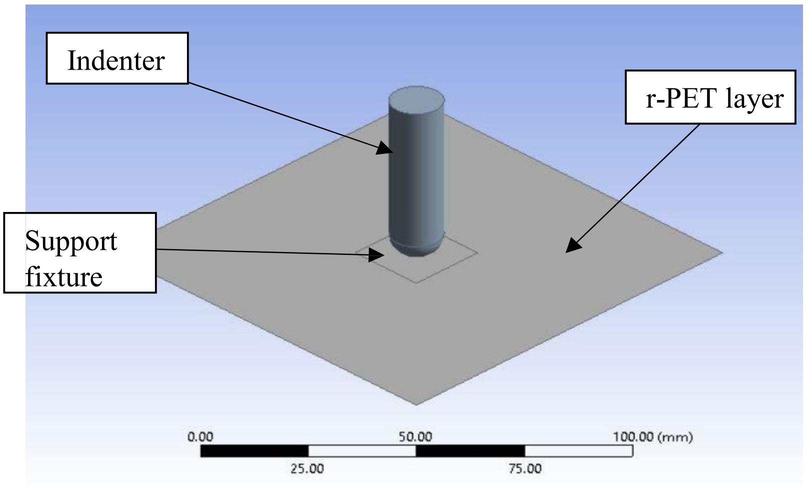


Figure 4: The geometrical of r-PET mat and indenter

2.5 Material properties

Mechanical properties of r-PET and resin epoxy were defined in the material assignment and combined as Material Combination in geometry setup. Table 1 and Table 2 are the mechanical properties of each material. The material properties of each layer were obtained from ANSYS Granta materials data for simulation.

Table 1: Mechanical properties of r-PET

Property	Value	Unit
Density	1339	kg.m^{-3}
Isotropic Thermal Conductivity	0.1702	W.m^{-1}C^{-1}
Specific Heat Constant Pressure, C_p	1199	J.kg^{-1}C^{-1}
Isotropic Secant Coefficient of Thermal Expansion		
Coefficient of Thermal Expansion	0.000117	C^{-1}
Isotropic Elasticity		
Young’s Modulus	2.898e + 09	Pa
Poisson’s Ratio	0.3887	
Bulk Modulus	4.3396e + 09	Pa
Shear Modulus	1.0434e + 09	Pa
Tensile Strengths		
Tensile Yield Strength	5.244e + 07	Pa
Tensile Ultimate Strength	5.745e + 07	Pa

Table 2: Mechanical properties of Resin Epoxy

Property	Value	Unit
Density	1160	kg m^{-3}
Tensile Yield Strength	5.46e + 07	Pa
Isotropic Elasticity		
Young’s Modulus	3.78e + 09	Pa
Poisson’s Ratio	0.35	-
Bulk Modulus	4.2e + 09	Pa
Shear Modulus	1.4e + 09	Pa

Model from Design Modeler was transferred to Ansys Composite PrePost (ACP) to defined the material on the plate. Before, the model was designed as a single layer. Therefore, in ACP, the model was assigned as 4-ply layer r-PET and matrix epoxy was used to bind the material. ACP has a pre- and post-processing mode. In the pre-processing mode, all composite definitions were created and mapped to the geometry (FE mesh). The stacking sequence for cross-ply r-PET laminated composites was defined in the stackup properties in ACP (Pre) as cross-ply orientation with angle 0 °, 90 °, 0 °, 90 °.

2.6 Geometry meshing

The accuracy of the output model was determined by the quality of the mesh. The model was meshed with the help of Ansys Static Structural. The formation of the mesh is seen in Figure 5. In order to maintain the model’s simplicity, the hexahedron technique was used to mesh it. In the case of global meshes, general mesh formation is employed, whereas in the case of local meshes, manual mesh generation is used. Face meshing was employed into the area of contact between indenter and plate with 6.1602e^{-3} m element size. Figure 5 depicts the meshing of geometry. The FE model consists of 42699 nodes and 29815 elements.

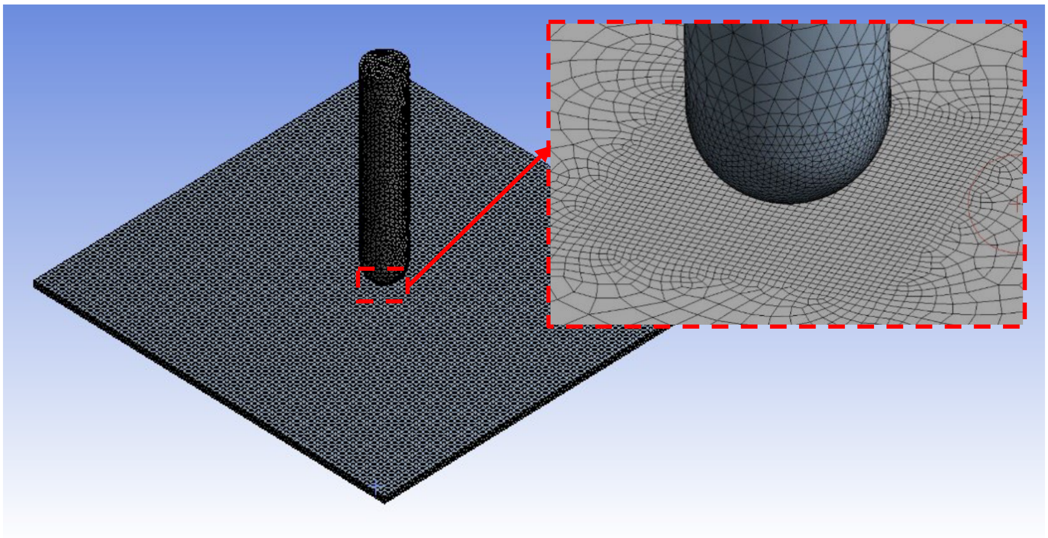


Figure 5: Geometry meshing of FE models

2.7 Contact interaction model

The accurate modelling of contact interfaces between parts has a significant impact on the prediction capability of a FE simulation. The appropriate treatment of contact is a critical component of many large-deformation problems. To address these issues, ANSYS provides a large number of contact algorithms. A contact in ANSYS is defined by recognizing the destinations to be checked for potential penetration of a contact bodies through a contact targets, which is searched for at each time step during the evaluation. For most impact analyses, the 'automatic surface to surface' method, a two-way contact treatment, is recommended [8]. This contact algorithm examines not only the target bodies but also the contact bodies for penetration through the target segments. Alternatively, the treatment can be symmetric, and the definitions of the slave and master surfaces are arbitrary because the results will be the same. This contact treatment is beneficial when a model undergoes large deformations and the orientation of its parts relative to each other cannot always be predicted. This contact pattern is used to determine the contact between the indenter and target plate of r-PET mats. In this research, 'Surface Body to Solid' was used and set frictional with 0.2 coefficient. Figure 6 shows the contact condition for the model. The tip of indenter was the target bodies and plates were the contact bodies.

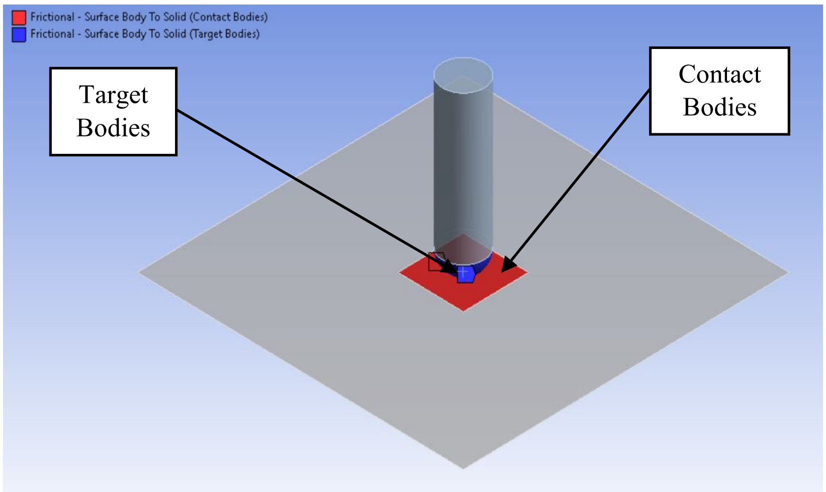


Figure 6: Contact condition

2.8 Boundary conditions

One of the most crucial aspects that was revised to acquire correct results is the boundary condition. Boundary conditions are essential to defined before running the simulation. [9] found that the impact velocity of fabric was highly dependent on the sample size. The boundaries conditions ensure that the indenter can only move along the Y-axis. A rigid body was assumed for the indenter due to no deformation produced by the materials during impact meanwhile all the r-PET layers was assigned as flexible. Projectile velocity along the Y-axis was assigned at 1.27 mm/min. The initial velocity of the indenter was assigned in the initial condition. Fixed supports were added at each side of the layer mats to prevents all degrees of freedom from being used, resulting in a specified component of the model being unable to move at all. The step end time of the analysis was set to 60 s with a maximum number of substeps equals 200. Bonded contact region was added automatically between the indenter and r-PET layers in the Ansys model simulation settings to stimulate the contact condition between the layers of the samples.

3. Results and Discussion

3.1 Quasi-static indentation (secondary data)

The quasi-static indentation test was conducted on laminated composites of r-PET cross-ply mat with different epoxy/hardener ratio as the composite matrix. Figure 7 shows the results obtained from experiment of quasi-static indentation. The figure represented force-displacement curves to evaluate the energy absorption and maximum indentation force of the laminated composites. The total of 5 different samples of r-PET laminated composite was constructed with matrix ratio 4:1, 5:1, 6:1, 7:1 and 8:1 each. The force-displacement curves of the r-PET composite laminate showed a very similar trend regardless of the matrix ratio. The trend indicated that the indentation force increased along with displacement until a maximum indentation force was attained. Based on the graph, the higher ratio of epoxy influences the maximum indentation force. This is because the properties of epoxy which is flexible and have excellent strength can absorb more force before reach failure. Table 3 shows the maximum indentation force and total energy absorption of r-PET laminated composites under quasi-static indentation.

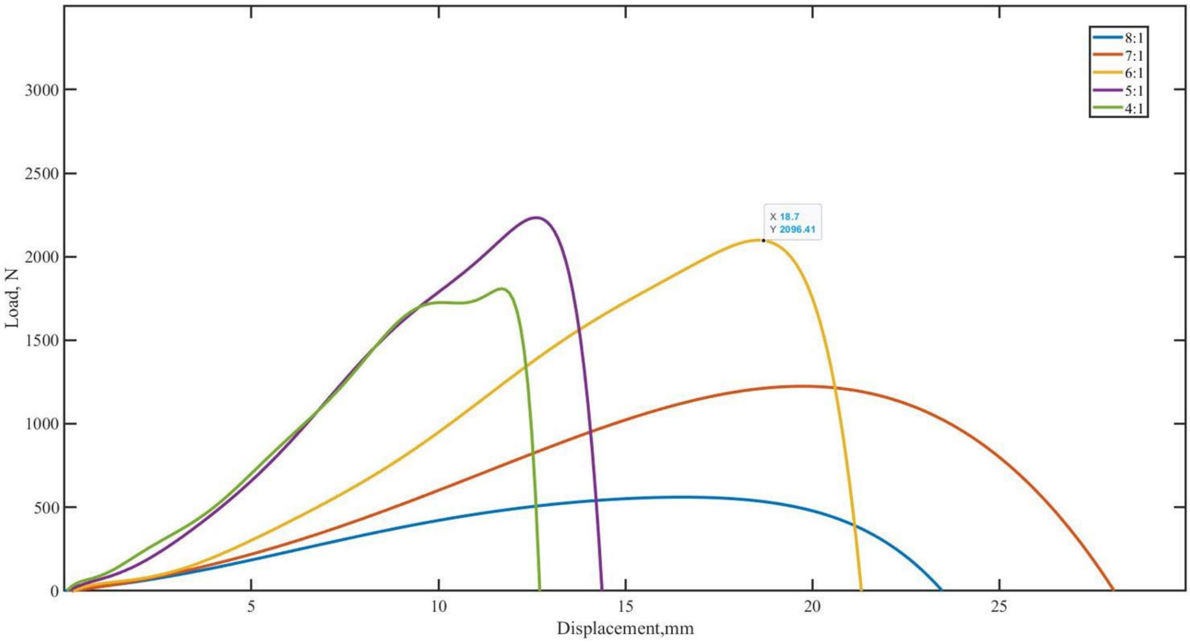


Figure 7: Force-displacement curves of r-PET/Epoxy laminated composite in different ratio 8:1, 7:1, 6:1, 5:1, and 4:1

Table 3: Maximum indentation force and total energy absorption of r-PET laminated composite

Sample configuration	Maximum Indentation Force (N)	Total Energy Absorption (J)
cP4 (8:1)	5.21	8.49
cP4 (7:1)	11.83	19.11
cP4 (6:1)	17.14	21.54
cP4 (5:1)	13.04	15.75
cP4 (4:1)	11.87	12.10

The experimental energy absorbed is obtained by calculating the area under the experimental force–displacement history curve using the trapezoidal method [4].

3.2 Validation numerical results

The FE model was capable of simulating the QSI response and to predict the force–displacement. The force-displacement graph was obtained from the ANSYS Static Structural post-processing results as portrayed in Figure 8. The graph shows almost similar trend with the experimental results. The load was increasing along at the initial stage with the increasing of displacement until the peak point where the maximum indentation force was reached.

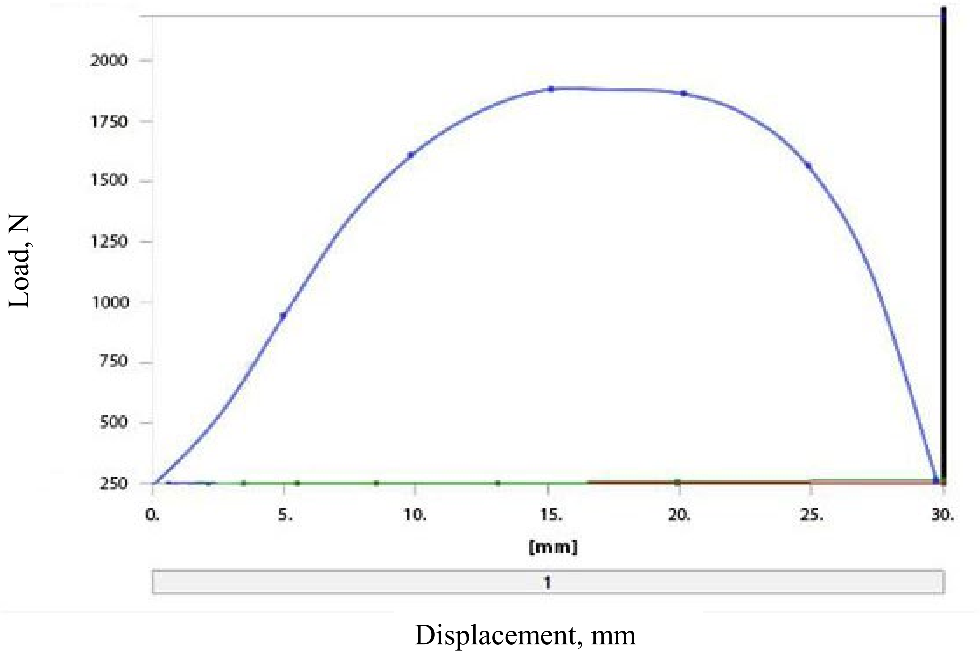


Figure 8: Simulation result of force-displacement curves of r-PET/Epoxy laminated composite

Figure 9 shows two-line graph from the simulation and experimental result. The stacking configuration of r-PET/epoxy laminated composite with matrix ratio 6:1 was selected to compare with the numerical result. The sample configuration of cross-ply r-PET (6:1) shows the highest maximum indentation force and total energy absorption among the other samples as stated in Table 3. The validation of the FEA simulation results were performed by comparing the present study by selecting the highest of the maximum energy absorption in the experimental. Therefore, this sample was selected as the best result to obtain from experimental. Both simulation and experiment were conducted with quasi-static cross-head displacement rate of 1.27 mm/min that was fixed throughout the indentation test.

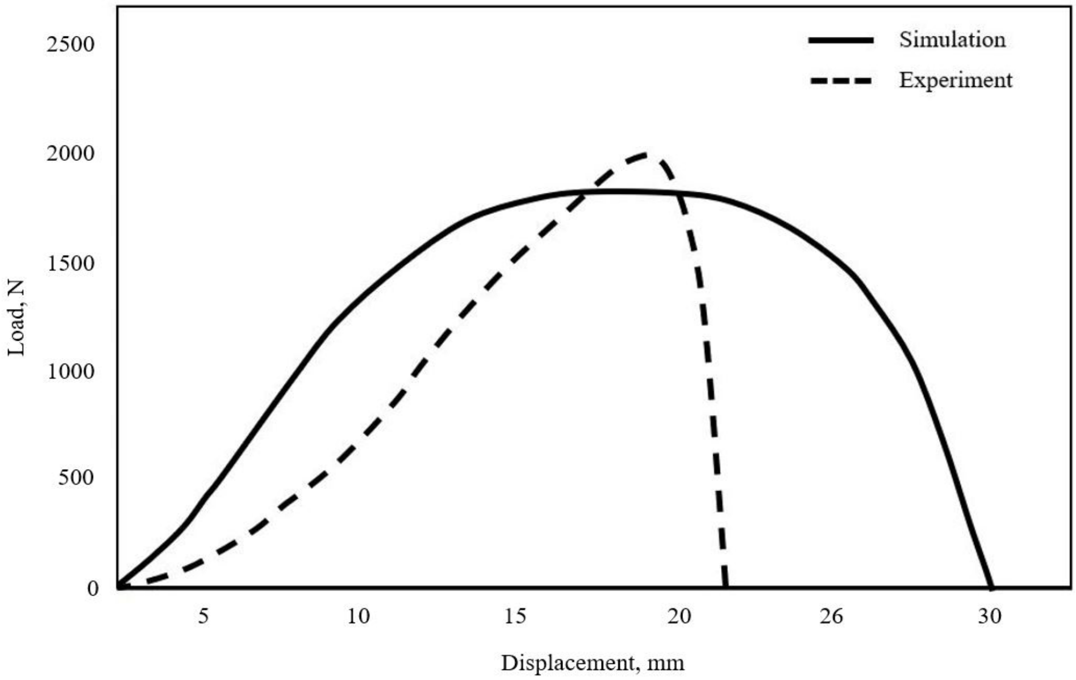


Figure 9: Force-displacement curves two-line graph of r-PET/Epoxy laminated composite

3.3 Energy absorption

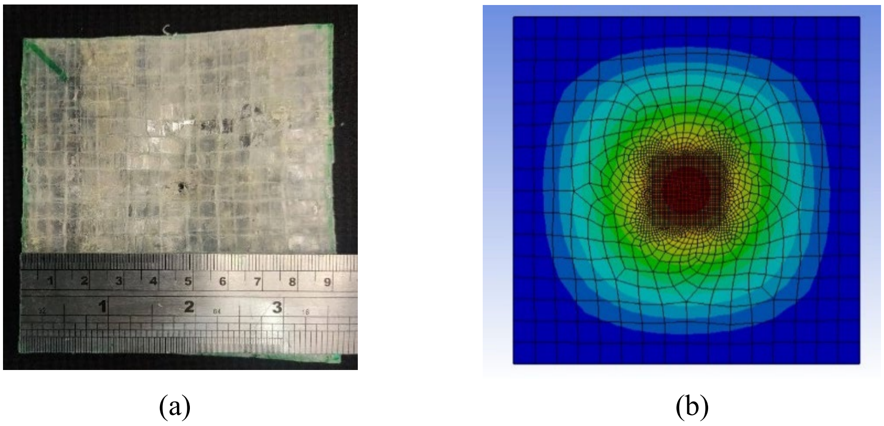
The experimental energy absorbed is obtained by calculating the area under the experimental force–displacement curve using the trapezoidal method of integration, whereas the energy absorbed by the FE model is the model's total mechanical strain energy. The results from simulation were expected to have similar results from the experiment. Table 4 shows the tabulated data from the experimental and simulation. The simulation test of laminated composite r-PET withholds higher maximum indentation force compared to simulation. The total energy absorption for simulation was also more than the experimental. The different results between both simulation and experimental happened due to the configuration of the parameter setting in the ANSYS. The FE models was modelled as single-plate rather than the original model which is 5 mm strip unidirectional mat in the DesignModeler. The original model was too complex and it takes a lot of time to do the computational results with average time 100 hours. Therefore, the model was simplified into single-plate and was defined as four-ply layer mats with different orientation in order to save the computational time.

Table 4: Indentation properties of r-PET/Epoxy laminated composites

Sample	Maximum Indentation Force (N)	Total Energy Absorption (J)
Experimental	17.14	21.54
Simulation	18.56	38.16

3.4 Damage assessment

The damage assessment of the reinforced composite was carried out by observing the laminated composite surface. The impact damage of the front side of the laminate composites were shown in Figure 10. Figure 10 (a) and 10 (b) show the total deformation of the sample in both the experimental (on the left-hand side) and simulation (on the right-hand side) conditions, respectively. From Figure 10 (b), the centre of the model shown the highest deformation from the indentation loading. A circle was drawn in the FE model to indicates the part affected by the indentation loading.



(a) (b)

Figure 10: Total deformation condition of composite panels; (a) Experiment, (b) Simulation

Additionally, when comparing the deformation from experimental with the simulation, Figure 10 (a) displayed similar damage behavior with Figure 10 (b), where the deformation occurs at the center of laminated composite. However, a budge can be seen in Figure 10 (a) which distort the r-PET surface and formed a ring-crack. On removal of the indenter, the pressure was released and elastic recovery was allowed to ensue. During this process, any crack openings attempted to close, but are prevented from doing by the presence of matrix. This shows the laminated composite has reach its maximum indentation force before the indenter completely went through the composite panel with help of matrix epoxy that assisted the laminated composite to withstand the indentation force. In short, the size of the deformation damage can be seen clearly in both experimental and simulation. However, the damage was more severe compared in the simulation of quasi-static loading because of large deformation compared to experimental test.

4. Conclusion

Composite materials and geometry design were developed using composite laminate material for quasi-static indentation. In this research, a 100.00 mm^2 sample of a laminate plate consists of two different materials with four-ply mats. Composite laminate structures with r-PET-Epoxy were modelled with ANSYS simulation program to investigate the technical feasibility of the composite design. Experimental testing data was obtained from secondary data to compare with the simulation. The result shows that laminated composite from simulation can absorb more maximum indentation force and total energy absorption with slight deformation. The force-displacement history obtained from FE model fall within 60 % to 90 % different with the mean force-displacement history obtained from the QSI experimental test. This slightly different results may occur because of some errors during the simulation setup. The simulation may not always produce accurate results. However, the results obtained fulfil the logical data with experimental results.

Acknowledgement

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