Research article

Simplified FE model and experimental study on the tensile properties of the glass fiber reinforced polyester polymer

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ABSTRACT

This research aims to understand the simplified finite element (FE) model behavior for estimating the glass fiber reinforced polyester polymer (GFRP) structural response and studying its tensile properties. The simplified FE model has been developed using an equivalent single-ply transversely isotropic material model to estimate the multi-layer GFRP laminates tensile behavior. The linear elastic and a trilinear plasticity material formulation were adopted. The experimental study is conducted to determine the tensile properties of the equivalent single-ply model of the multi-layer laminates with the variation of layers number, stacking sequence, and fiber orientation. The tensile test specimen used E-glass fiber reinforcement and polyester resin (Yukalac 157 BQTN-EX) as the matrix. The hand layup method was used for the lamination procedure. The experimental results show that the nonlinearity might occur due to the imperfection and poor quality of the composite laminate. Therefore, the comparison of numerical simulation and the experimental results is conducted to understand the stress-strain behavior of the simplified FE model. Both models presented different characteristics and showed good agreement with the experimental results. The linear model can be adopted while the nonlinearity is not significantly identified. Furthermore, the plastic strain as a compensated constant should be defined thoroughly to conduct an accurate estimation using the trilinear plasticity model. However, neither model is suitable for predicting the composite laminate’s initial failure point.

1. Introduction

Fiber-reinforced polymer (FRP) is a popular material used in many industries. The application of fiber-reinforced polymer in a wide range of manufacturing industries because of their strength to weight, stiffness to weight ratio, high specific strength, corrosion resistance, non-magnetic and durability in seawater, [1, 2, 3]. Glass fiber reinforced polymer (GFRP), one of FRP composites types, are the most common composite material due to their performance based on cost. Therefore, their mechanical behavior, such as tensile, flexural, fatigue, and impact fracture, should be precisely recognized. Kim et al. [4] investigate the mechanical properties and failure mechanism of the GFRP marine structures by applying the hand layup and the vacuum infusion. The results show that the hybrid composites with three sets of vacuum infusion layers presented the highest tensile strength while the two established the highest compression strength. Naresh et al. [5] investigate the dynamic mechanical properties of carbon-epoxy and glass-epoxy composite panels. A neat epoxy resin, unidirectional with numerous fiber orientation angles (0°, 45°, 90°), symmetric angle ply, and quasi-isotropic were investigated. Navya et al. [6] study the tensile behavior of glass fiber composite with various strain rates. FEM simulations were conducted to understand the stress-strain behavior in the different strain rates of the composite material. The results show that the FE analysis results have a good agreement with the experimental results.

The finite element method (FEM) is a well-known and efficient numerical analysis capable of handling composite laminated structure problems. Numerous researches can be found on applying FEM in structural response study of laminated composites material, such as multiply laminate stress analysis, vibration, buckling/post-buckling, and failure and damage analysis.

The essential theories of the laminated numerical model were presented in some papers. Reddy and Robbins [7] developed the equivalent single layer and layer-wise laminated plate theories. Liu and Li [8] compare the displacement hypothesis based on laminated theories such as shear deformation theory, layer-wise theory, generalized zigzag theory, and double-superposition theory. Altenbach [9] has reviewed the...
laminates and sandwich theories. Ghugal and Shimpi [10] presented the refined shear deformation theories based on the displacement and stress of isotropic and anisotropic laminated plates. Some reviews of the laminated plate theories also can be found on [11, 12, 13, 14].

In applying the finite element method to the laminated plate structural responses, Singh et al. [15] study the FE simulation to estimate the mechanical behavior of chopped strand mat fiber with epoxy polymer. The weight fractions of glass fibers are 10% and 20%. The results show that the increased reinforcement raises the material brittleness, decreasing impact strength. The numerical results have shown a good agreement with the experimental results. Tysmans et al. [16] developed a finite element model of fiber-reinforced cement composites with a large strain hardening capacity. The developed FE model uses biaxial tension load and Concrete Damaged Plasticity (CDP). The results show that the modified CDP model can correctly simulate the nonlinear tensile strain-hardening behavior.

Furthermore, the failure behavior also can be simulated. Seifoori et al. [17] investigated the flexural strength of GFRP and Carbon Fiber Reinforced Polymer (CFRP) thin composite beams. The results show that finite element simulation accurately estimates deflection and initiation damage prediction. The increases in bending speed have gradually arisen the bending strength and failure force. This study adopted a digital image processing algorithm to detect the composite beam deflection. Banat D [18], simulated the three-point bending test of the multilayered rectangular (GFRP/CFRP) composite beam with the finite element method. The GFRP/CFRP composites beams have been configured on the length to thickness ratio and the variation of laminate stacking. The adopted failure criteria are Tsai-Hill, Hoffman, Tsai-Wu, Hashin, and Puck. The results show that the failure initiation can be detected with the defined failure criteria in the FE model. It is also indicated that the specified failure criteria significantly depend on the context of laminate material properties and the layer position.

Gliszcynski and Kubiak [19] estimate the load-carrying capacity of the C-shaped composite beam due to the pure bending. The FE models have developed with the defined failure criteria of Inverse of Tsai-Wu, Hoffman and the reduction of maximum stress to the fiber direction. The study concluded that the maximum stress reduced to fiber direction obtained the most significant numerical and experimental results convergence. A high stiffness degradation occurs when the compressive and tensile strength in the fiber direction is exceeded. Xingyu et al. [20] investigated a hybrid steel-GFRP reinforced concrete beam with FEM. The characterized FE model with bond-slip relation was developed to simulate the beam flexural behavior. The results show that the theoretical method overestimates the flexural capacity by 9%. The FE models with the defined bond-slip relation have successfully improved the estimation of the mid-span deflection. Kumar and Gangwar [21] calculate the flexural stress of the green composite using CATIA V5, ANSYS, and AGMA. The green composite was created from the reinforced coir fiber combined with polystyrene and epoxy resin. It is shown that the coir fiber reinforced epoxy resins have better durability and lifetime because of the higher stress-bearing capacity and lower deformation. The other studies on the load-carrying capacity, buckling, and post-buckling investigated using analytical and numerical methods can be found in [22, 23, 24, 25, 26]. The numerical calculations compared to the experimental results can also be found in [27, 28, 29].

Although many publications of the FE analysis on the GFRP laminated composite were conducted, a few research studies related to the simple model FE analysis compared to the experiment results of tensile properties. Positively, the simplified FE models, such as equivalent single-ply transversely isotropic, have offered a fewer material constant than the multiply orthotropic model. Furthermore, the material constant of the simplified FE model can be determined easily through the uniaxial tensile test [30]. The simplicity of the simplified FE model is suitable for commercialization. However, it might increase...
Table 1. The configurations of the laminate composite tensile test specimen.

| Specimen Type | Layer Number | Stacking sequences | Fiber orientation angle | Fiber wt% |
|---------------|--------------|---------------------|-------------------------|-----------|
| 4CSM          | 4            | mat300/mat300/mat300/mat300 | random/random/random/random/random | 32.8%     |
| 4WRC45        | 4            | mat300/wr400/mat300/wr400 | random/45/random/45/C14/random | 33.5%     |
| 4WRC          | 6            | mat300/wr400/mat300/wr400 | random/0/C14/random/0/C14 | 34.2%     |
| 6CSM          | 6            | mat300/mat300/mat300/mat300 | random/random/random/random/random/random | 34.5%     |
| 6WRC45        | 6            | mat300/wr400/mat300/wr400 | random/45/random/45/C14/random | 35.6%     |
| 6WRC          | 6            | mat300/wr400/mat300/wr400 | random/0/random/0/C14/random | 35.2%     |
| 8CSM          | 8            | mat300/mat300/mat300/mat300/mat300/mat300/mat300/mat300 | random/random/random/random/random/random/random/random/random | 36.2%     |
| 8WRC45        | 8            | mat300/wr400/mat300/wr400/mat300/wr400 | random/45/random/45/C14/random | 36.6%     |
| 8WRC          | 8            | mat300/wr400/mat300/wr400/mat300/wr400 | random/0/random/0/C14/random | 37.1%     |

Figure 2. The detail dimension of the tensile test specimens.

Figure 3. The fracture specimen of different laminate type: [a] 4CSM; [b] 6CSM; [c] 8CSM; [d] 4WRC45; [e] 6WRC45; [f] 8WRC45; [g] 4WRC; [h] 6WRC; [i] 8WRC.
computational inaccuracy for the component that does not have an isotropic behavior and ignores the multi-layer properties, which are known empirically to have a significant influence on the structural response [31]. Therefore, this study focuses on conducting a numerical simulation to understand the simplified FE model behavior to estimate the tensile characteristics of the GFRP composite material. An equivalent single-ply model was adopted to estimate the multi-layer laminate’s tensile behavior. Furthermore, the experimental study is conducted to generate the tensile properties for defining the equivalent single-ply material model.

This research started with an experimental study that measured the tensile properties of the GFRP laminated composite. The tensile test specimen was made following ASTM standard D3039. The configuration of the laminate composite was defined with the variation of layer number, reinforced fiber type, and stacking sequences. Afterward, the tensile test results data was used for the material definition of the simple FE model. An equivalent single-ply model with transversely isotropic assumption was created for the tensile test simulation. The numerical estimation compared to the experiment results to evaluate the accuracy and discrepancy of the predicted value.
2. Materials and methods

2.1. Materials

The GFRP composite laminates are made with the chopped strand mat (mat300) and woven roving (wr400) E-glass manufactured by Asahi Fiber Glass Company. The laminate composite specimens were determined using the polyester resin (Yukalac 157 BQTN-EX). The ratio range for the Methyl Ethyl Ketone Peroxide (MEKP) catalyst to polyester resin is 1%–2% of the total resin volume. Furthermore, this polyester matrix is a standard orthophthalic resin with quick-drying characteristics, thixotropic, non-waxed, and pre-accelerated. It is suitable for laminating process with hand layup and spray molding.

The composite laminate types have been configured with the variation of layer number, stacking sequence, and fiber orientation angle. The lamination procedure is conducted by placing the plies to the defined orientation. Regarding the standard technique of the GFRP laminate, the specimen was created with the hand layup method, Figure 1. The layering process of each glass fiber ply has been pressed uniformly with the hand roller to maintain the thickness of each lamina. This method uses cheap equipment and a simple way of laminating the reinforced fiber and the resin as the composite matrix.

Furthermore, the laminates were cured for two days with an ambient room temperature of 30 °C. Based on the laminate specimen type, the fiber weight percentage is 32.8%–37.1%. The stacking sequence specimens have been configured with the lamina with different fiber types: chopped strand mat 300 gr/m² (mat300) and woven roving 400 gr/m² (wr400). Furthermore, the fiber orientation angle was configured only for the woven roving fiber (wr400) with the
orientation angle of 0° and 45°. The detailed configurations of the tested specimens can be seen in Table 1.

2.2. Experimental setup

According to the ASTM standard D3039, the specimens of the tested material have been made as rectangular-shaped specimens. The standard does not explicitly determine the fixed specimen dimension. Therefore, the total length of the samples is defined as large as 200 mm with 50 mm clamped arm length at both edges. Consequently, the distance between two clamped arm lengths is 100 mm. The specimens' thickness variation depends on the number of laminate layers. Then, the width is given as 25 mm. The dimension detail can be seen in Figure 2.

The specimens were made using the configurations which are presented in Table 1. Each configuration of laminate type has three samples for the tensile test experiment. Therefore, 27 specimens were examined using the universal testing machine (Model WEW-1000B, Shanghai Luheng Instrument Co. Ltd). During the tensile test, the device was set up for a displacement rate of 0.5 – 1 mm/s. The increment characteristics of tension load are linear. The tensile test was ended while the maximum tensile test was achieved. In other words, the failures of the tested materials occurred. The relation of the tensile load increment and the elongation of the tested specimen were recorded automatically by the measurement unit of the machine. The fractured samples of the different laminates are shown in Figure 3. Furthermore, the mechanical properties such as tensile strength, modulus of elasticity, fracture strain, and maximum elongation were determined by processing the measurement output data.

2.3. Simplified FE model development

The simplified FE model was developed to estimate the tensile properties of the GFRP laminate composite. The developed FE model uses two approaches for the defined material model. Firstly, the equivalent single-ply with no plasticity definition was adopted for the material model definition. This approach represented the multi-layer composite laminate as a single linear elastic laminate. Secondly, the trilinear plasticity model was defined for the FE model. Both models were made with the transversely isotropic material. This assumption can be accepted because the tensile test is a uniaxial load case. Theoretically, the laminates' tensile properties with orientation angles of 0° and 45° are similar on both orthogonal axes. However, the simple model limitation cannot present the response behavior of each layer of laminate because the multi-layers have been defined as a single-ply laminate. This assumption still can be accepted for the structure strength assessment, where the combined overall lamina response is commonly used. The trilinear plasticity definition was formulated using the experimental result data.

The model discretization was defined using 1414 nodes and 1300 quadrilateral elements. Then, the mesh sizes were determined to be as large as 2 mm. The boundary condition was provided on the bottom edge with a fixed/clamped constraint. The top edge constraints were also defined instead of the Y-axis translation direction. Afterward, the coupling definition was given on both connected arms with the single reference point as the independent nodes. The displacement load was exerted on one of the independent points. The magnitude of the displacement load was determined regarding the maximum elongation of the tested specimen. The displacement load arises gradually with the incremental rate as large as 0.01 of maximum elongation. The developed materials occurred. The relation of the tensile load increment and the elongation of the tested specimen were recorded automatically by the measurement unit of the machine. The fractured samples of the different laminates are shown in Figure 3. Furthermore, the mechanical properties such as tensile strength, modulus of elasticity, fracture strain, and maximum elongation were determined by processing the measurement output data.

Table 2. The Maximum Ultimate Stress of the Experiment and the FE models.

| Specimen Type | Maximum ultimate stress [MPa] |
|---------------|-----------------------------|
|               | Experiment | No Plasticity | Error % | With Plasticity | Error % |
| 4CSM          | 62.526     | 62.265        | 0.42    | 61.928          | 0.96    |
| 4WRC          | 110.884    | 110.221       | 0.60    | 88.319          | 20.35   |
| 4WRC45        | 93.308     | 92.746        | 0.60    | 78.695          | 15.66   |
| 6CSM          | 109.012    | 108.489       | 0.48    | 82.925          | 23.93   |
| 6WRC          | 172.580    | 171.406       | 0.68    | 126.860         | 26.49   |
| 6WRC45        | 132.881    | 131.953       | 0.70    | 107.894         | 18.80   |
| 8CSM          | 133.665    | 132.735       | 0.70    | 107.263         | 19.75   |
| 8WRC          | 228.870    | 227.320       | 0.68    | 190.464         | 16.78   |
| 8WRC45        | 178.484    | 177.179       | 0.73    | 143.002         | 19.88   |
simulation model with boundary and loading conditions can be seen in Figure 4.

3. Results and discussion

3.1. Tensile test results

The simulation results show that the number of layers influenced the maximum tensile stress, Figure 5. Due to the additional layers, the laminates strength improvement is 23–74%. The larger number of layers has shown an enormous tensile strength. This phenomenon indicates that the increased layers provide an additional reinforced fiber that improves the laminate strength. Although these conditions have occurred in all laminate types, this mechanical behavior cannot be directly adopted for the other laminates because the additional layers can only increase the strength when the fiber fraction increases and the optimum fraction has not been achieved yet. It can be seen that the increase in the number of layers has increased the fiber content, Table 1. The maximum fiber weight percentage is the 8WRC laminate, while the minimum fiber weight percentage is the 4CSM laminate. Therefore, the increase in the layer number can improve the tensile strength of the laminates, Figure 5.

On the other factors, the orientation angle and the reinforced fiber type also influenced the tensile strength properties. The laminates strength improvement due to the orientation angle and the fibers type are 19–28% and 19–49%, respectively. The laminate showed higher tensile strength with the orientation angle of 0° and the reinforced fiber type of woven roving (WRC). Furthermore, the woven roving type (wr400) laminate has a more significant tensile strength than the chopped strand.
mat (mat300). It is indicated that the woven roving type can provide a better reinforcement than the chopped strand mat. These phenomena might have occurred because the woven roving has a uniform fiber orientation direction. A uniform fiber direction generated optimum load support on the laminates, especially for the uniaxial load, which has the same direction as the fibers. It also can be seen in the influence of fiber orientation.

The orientation effect might be obtained from the tensile strength difference between two woven roving laminates (WRC and WRC45). Furthermore, the larger orientation angle might reduce the tensile strength of the laminates. It can be explained that the larger angles have to withstand the tensile load with the inclined position of the reinforced fiber. Therefore, the maximum strength capacity cannot be achieved.

Figure 6 depicts the tensile strain characteristics of the laminates composite. The increased layer number has escalated the magnitude of the tensile strain. The increments of tensile strain due to the added layer number are 15–64%. These phenomena have shown similar behavior with the tensile strength. The influence of fiber type and orientation angle also presented identical behavior with the tensile strength. The woven roving typed fiber might improve the tensile strain characteristics of the laminates. The escalation of the tensile strain due to fiber type and orientation angle are 5–42% and 5–18%, respectively.

Figure 13. The discrepancy of the second turning point in the stress-strain curve.

Figure 14. The Stress-strain diagram of 4-layers composite laminate: [a] 4CSM; [b] 4WRC45; [c].

Figure 15. The Stress-strain diagram of 6-layers composite laminate: [a] 6CSM; [b] 6WRC45; [c] 6WRC.
The effect of fiber orientation angle on the tensile strain is similar to Naresh et al. [5] and Abd-Ali and Madeh [32]. A fiber orientation angle of 0° has shown a more significant tensile strain than 45°. However, Naresh et al. [5] show that the laminate presented the maximum tensile strain with fiber orientation of 45°/−45°/45°. In contrast, the measurement results show that the laminate with 0° woven roving fiber is the largest tensile strain. This condition might be occurred because of the insertion of mat300 fiber with a random orientation. The fiber insertion might increase the strength and influence the magnitude of specimen elongation due to the tensile load. Otherwise, the measured laminate adopted non-unidirectional fiber mat300 and wr400.

Furthermore, Naresh et al. [5] presented a distinct tendency of the orientation angle influence on tensile strain behavior of GFRP and CFRP laminates. The largest CFRP’s tensile strain have shown by 0° than the orientation angle of 45°/−45°/45°. Regarding the experimental and previous research results, it can be concluded that the difference in fiber type and orientation angle might change the tensile strain behavior of the developed laminates composite.

The modulus of elasticity of the developed laminates composite can be seen in Figure 7. Regarding the experimental measurement of the developed laminates, the modulus of elasticity was increased with the larger number of layers. The increment of modulus of elasticity due to the increase of laminate layers number is 6%–23%. Although the larger number of layers might increase the maximum tensile strain, the fracture tensile strength significantly arises. The modulus of elasticity has shown an increment tendency. Otherwise, the presented modulus of elasticity was defined as the ratio of the fracture stress to the fracture strain constant. Therefore, the significant increment of tensile stress can increase the magnitude of the modulus of elasticity.

Theoretically, adding lamina with the same fiber configuration to the existing layer would not increase the laminate stiffness. However, these phenomena might occur because the additional lamina has changed the laminate fiber content. It can be seen that the fiber content has arisen about 1%–2% due to the increase in layer number, Table 1. Regarding the condition, it can be explained that the increase in modulus of elasticity is caused by the increment of fiber content induced by the additional layer. Moreover, the more extensive fiber content increased the tensile strength and compensated for the modulus of elasticity increment. The larger fiber content effect on the increment of modulus of elasticity and laminate stiffness was also presented by Kim et al. [4] and Elkazaz et al. [33].

Furthermore, the fiber type and orientation angle influenced the modulus of elasticity. The woven roving with 0° fiber orientation angle has increased the laminate’s stiffness. The increments of the elastic modulus due to fiber type and orientation angle are 1%–22%. These results are reasonably accepted since the woven roving with 0° orientation angle might increase the strength of developed laminates. The tensile strength is escalated because the reinforced fiber provides optimum support while the orientation is parallel to the tensile load direction. Otherwise, the fiber content of the WRC type laminates is larger than the other types (CSM and WRC45).

The tensile properties of the developed laminates can also be presented in the stress-strain diagram, Figure 8. It can be seen that the stress-strain relation characteristic of the developed laminates is an almost linear line up to the maximum/ultimate tensile stress. The sudden drop in the near ultimate stress indicates that the laminates undergo brittle failure. Otherwise, the nonlinearity characteristics are observed in the strain zone below 0.04. The changed slope of stress-strain curves represents that the modulus of elasticity was altered when the specimen was stretched in the tensile test. These phenomena might be occurred because of the lamina’s premature failure and delamination. When one of the laminas prematurely failed, the elongation rate would escalate due to decreased laminate stiffness. Furthermore, delamination might generate fiber-resin interface crack, which also reduces the stiffness of the composite. Based on the fracture specimens’ observation, the imperfection of the lamination process is predicted as the primary cause of premature failure and delamination.

Comparing this measurement results with the other studies has found that the nonlinear characteristic of the stress-strain relation of GFRP composite also can be seen in Kim et al. [4]. However, the stress-strain relation can be estimated as a linear line. However, in the study, Kim presented that the stress-strain curve of the hand layup laminate has more significant convexity than vacuum infusion laminate. This condition represents that the better layering method might reduce the nonlinearity of the stress-strain relation. Therefore, it can be concluded that the imperfection of the lamination process might generate nonlinearity in the stress-strain relation. Otherwise, the defect might decrease the laminate tensile strength.

### 3.2. Numerical simulation results

The simulations have been made with two kinds of material models. Firstly, the model has adopted the linear elastic material model. The linear elastic models have been defined with no plasticity region. Secondly, the material model was determined to represent the laminate’s nonlinear behavior of the stress-strain relation. The material model with plasticity definition is adopted to define nonlinearity. In the linear model, no plasticity has been described with the assumption of yield stress equal to the maximum tensile stress (ultimate/fracture stress). Therefore, the magnitude of plastic strain was determined as zero value. This assumption is reasonably acceptable since the laminate composite has been...
Table 3. The experiment and numerical estimation of the laminates fracture load.

| Specimen Type | Fracture Load [N] | Error % | With Plasticity | Error % |
|---------------|-------------------|---------|-----------------|---------|
| 4CSM          | 7190              | 0.42    | 7122            | 0.95    |
| 4WRC          | 16355             | 0.59    | 13027           | 20.35   |
| 4WRC45        | 13763             | 0.60    | 11608           | 15.66   |
| 6CSM          | 12839             | 1.14    | 14512           | 13.03   |
| 6WRC          | 21573             | 0.68    | 15858           | 26.49   |
| 6WRC45        | 16278             | 0.70    | 13217           | 18.80   |
| 8CSM          | 21721             | 0.70    | 17430           | 19.76   |
| 8WRC          | 23459             | 1.60    | 19523           | 16.78   |
| 8WRC45        | 29896             | 0.73    | 23953           | 19.88   |

Table 4. The experiment and numerical estimation of the laminates maximum elongation.

| Specimen Type | Max. Elongation [mm] | Error % | With Plasticity | Error % |
|---------------|----------------------|---------|-----------------|---------|
| 4CSM          | 3.375                | 0.41    | 3.238           | 4.06    |
| 4WRC          | 5.646                | 0.60    | 5.905           | 4.59    |
| 4WRC45        | 4.795                | 0.60    | 4.519           | 5.76    |
| 6CSM          | 5.546                | 0.49    | 5.284           | 4.72    |
| 6WRC          | 7.226                | 0.68    | 7.324           | 1.36    |
| 6WRC45        | 6.430                | 0.70    | 6.140           | 4.51    |
| 8CSM          | 6.361                | 0.69    | 6.699           | 5.31    |
| 8WRC          | 7.794                | 1.62    | 8.518           | 9.29    |
| 8WRC45        | 7.409                | 0.73    | 7.801           | 5.29    |

Table 5. The experiment and numerical estimation of the laminates modulus of elasticity.

| Specimen Type | Modulus of Elasticity [MPa] | Error % | With Plasticity | Error % |
|---------------|-----------------------------|---------|-----------------|---------|
| 4CSM          | 1853                        | 0.00    | 1913            | 3.24    |
| 4WRC          | 1964                        | 0.00    | 1946            | 23.83   |
| 4WRC45        | 1946                        | 0.00    | 1741            | 10.53   |
| 6CSM          | 1966                        | 0.00    | 1569            | 20.19   |
| 6WRC          | 2388                        | 0.00    | 1732            | 27.47   |
| 6WRC45        | 2066                        | 0.00    | 1757            | 14.96   |
| 8CSM          | 2101                        | 0.00    | 1601            | 23.80   |
| 8WRC          | 2097                        | 0.00    | 2236            | 23.87   |
| 8WRC45        | 2409                        | 0.00    | 1833            | 23.91   |

recognized as a brittle material. Theoretically, the failure of a brittle material can be identified through a slight plastic deformation characteristic of the fractured body. The second model is defined similarly to the first transversely isotropic model. However, the plasticity behavior was provided using the trilinear approach. The trilinear formulation was determined by adjusting the slope of the stress-strain diagram curve.

The first slope can be obtained by finding the first yield point where the curve slope starts to decrease. Furthermore, the plastic strain of this point was determined as zero strain. Afterward, the second and the third slope were determined with the second turning slope (second yield point) and the fracture point. Furthermore, the second plastic strain was defined as the difference between the first and the second yield point strain value. The final plastic strain value of the fracture point is the maximum elongation that has been reduced with the extension on the second yield point. Therefore, the second approach has three regions on the stress-strain curve. The first region is represented by the line with the first slope (elastic zone), while the second and the third region are represented by the line with the second and the third slope (the plastic zone).

Regarding the numerical results, the ultimate stress was presented as Von Mises’s effective stress. It is acceptable because the models are loaded by a uniaxial tensile force with no shear stress response. The stress distributions were presented using the color contour. All FE models with no plasticity definition showed a similar color contour with different peak stress values at the maximum time step of the simulation. Therefore, only the color contour of the 4CSM laminate type was presented as a representation of the other linear models, Figure 9. The maximum Von Mises stress (estimated ultimate strength) of each specimen type can be seen in Table 2. In the linear no plasticity formulation, maximum stress initially appears before achieving the fracture strain. The maximum stress is continuously expanded on the initial point by continuing the tensile load increment. Therefore, the red color can be seen almost in all of the body parts of the specimen. The simulation was completed when the fracture strain was achieved. These estimated tensile characteristics are similar to the elastoplastic material model. While the maximum stress has been achieved, the increment of displacement load merely increased the tensile strain response.

On the other hand, the FE model’s stress distribution with plasticity definition has shown a few different color contours. The Von Mises effective stress distribution was presented in Figures 10, 11, and 12, categorized by the number of layers. The maximum Von Mises stress has shown underestimated value compared to the experiment results, Table 2. These phenomena might have occurred because the defined trilinear plasticity has generated a smaller slope than the measured material properties. Otherwise, the estimated second turning point position was not accurately located on the measurement data point location, Figure 13. Therefore, the magnitude of maximum tensile stress is significantly distorted. The maximum stress can be obtained on the node adjacent to the point of the boundary condition. It is indicated that the boundary conditions still influence the stress distribution of the FE model. Otherwise, the boundary condition constraint point can be identified as the stress concentrator on the numerical estimation.

Consequently, the hot spot stress does not represent the point at which the initial failure starts. It is a normal condition since the developed model is a simple structure object with a uniaxial load. Therefore, the boundary condition point has influenced the stress distribution results. Otherwise, the material model is a transversely isotropic material without flaw condition. Regarding the simulation results, it is indicated that both equivalent single-ply models with transversely isotropic material can be used to estimate the stress response of the GFRP structure. Nevertheless, the simplified FE models are not suitable for determining the initial point of failure of the GFRP composite laminate. It can be explained that, in the actual case, the initial fracture of the GFRP laminates commonly occurred in the region where the material flaw is located. The material defects frequently found are crack, delamination, porosity, incomplete laminating penetration, and trapped bubble. However, both equivalent single-ply is still acceptable for estimating structure response.

The generated stress-strain relation diagram is presented in Figures 14, 15, and 16. The stress-strain values obtained from the experimental test and numerical estimation have been plotted concurrently on the same coordinate axis. The plotting values have identified discrepancies between the numerical computation and the measurement data. All curves have presented that the linear no plasticity material model was significantly different from the measured data on the low strain region. However, the discrepancy was gradually decreasing when the stress was increased. The precision estimation was made when the failure stress reached or entered the adjacent zone’s failure limit. It is a normal response since the linearity of the material model has been defined according to the slope formulated from the fracture stress and strain. Therefore, a large discrepancy was found due to the nonlinear behavior of the low-strain zone.
Otherwise, the FE model with trilinear plasticity has accurately estimated the low-strain zone. The accuracy level gradually decreases exponentially when the plastic zone’s slope increases exponentially. It can be seen that the discrepancy occurred because the estimated second turning point was not accurately located in the actual location. This error might have happened because the defined plastic strain as a compensated constant to determine the initial point of the trilinear plasticity model’s third line is inaccurate. Therefore, the FE model with the plasticity material model significantly differs in estimating stress-strain behavior in the fracture limit adjacent zone. However, the trilinear plasticity models have effectively estimated the nonlinearity characteristics of the stress-strain relation curve.

For this reason, the trilinear plasticity model might be capable of predicting the nonlinearity behavior of the laminate composite. Although the proposed trilinear model still does not accurately estimate the fracture stress value, modifying the defined plasticity model constants might improve the third line slope and generate better estimation results. This effort can be seen on the stress-strain curve of 4CSM laminates, Figure 14a. The trilinear model accurately estimates the fracture point with the suitable constant for the slope definition.

Both simplified FE models have presented different estimation results behavior. The first model, the linear no plasticity, delivered an excellent accuracy in predicting the failure point and the global tensile properties determined from the fracture stress point value. Therefore, the fracture load and maximum elongation have been estimated accurately, Tables 3 and 4. Furthermore, in Table 5, the numerical estimations of the modulus of elasticity have shown the same values as the experiment data (zero relative error). This condition can be explained that the estimated modulus of elasticity constant is generated by the entered experimental data constant. Therefore, the stress-strain relation of the simulation model is controlled by the given modulus of elasticity constant.

Due to the nonlinear behavior, the first approach has missed its accuracy in the low-strain zone. However, the linear approach can be adopted when the nonlinearity behavior is not significantly appeared in the tensile test results. Otherwise, applying the linear model can also accurately estimate the problems with the generated stress located adjacent to the fracture limit point.

The second model, the trilinear plasticity, presented an accurate estimation of the low-strain zone but lacked the estimation of the fracture limit point. The trilinear plasticity model might solve the accuracy problem of the linear one. Therefore, it can be recommended that the trilinear plasticity formulation is suitable for the nonlinearity behavior in estimating multi-layers laminate structural response. However, the selection of the plasticity constants should be thoroughly examined for a precision result.

The proposed trilinear models have shown an underestimated fracture stress. Although the fracture stress limit was underestimated, the defined plasticity model is still acceptable. This recommendation is reasonable because the structural strength assessment was generally made by considering the small displacement and elastic behavior assumptions. The trilinear plasticity model has an excellent tensile properties estimation on the nonlinear zone. However, the definition of an accurate plasticity model should be supported by valid experimental data.

Finally, comparing the estimation performance of the developed FE simplified models with the other previous FE model [15, 34, 35, 36] have shown that both models have generated an acceptable level of accuracy with a relative error between 0 and 27.3%. Singh et al. [15] estimated the glass fiber reinforced epoxy composite (GFREC) tensile properties using a 3D solid FE model with isotropic material definition. The relative error of the 3D solid model is between 0 and 27.3%. Nurhanizah et al. [35] estimated the stress-strain value of GFRP composite with unidirectional E-Glass using a multi-layer laminate FE model. The developed multi-layer laminate FE models have shown that the level of accuracy is regularly between 10% and 25%. However, it is identified that the relative errors were slightly large in some cases. The excellent levels of accuracy have been presented by The Monte-Carlo simulation based on finite element analysis [34] and The multi-scale modeling of 3D composites [36]. Although both models have shown excellent accuracy, the two models are complex FE models that should be supported by sophisticated experimental series to determine the numerical constants of the material model.

4. Conclusions

Numerical simulation was carried out on the glass polyester composites with a configuration of layer numbers [4, 6, and 8 plies], fibers type [mat300 and wr400], and orientation angle such as [random/random/random], [random/45/45], and [random/0/random/0°] to understand the simplified FE model behavior to estimate the tensile behavior of the composite laminate. To accurately understand the simplified FE model behavior in assessing multi-layer composite structural response, the material model was designed with two kinds of formulation, linear elastic and trilinear plasticity. The following conclusions are drawn from the present work:

- Regarding the experimental study, the nonlinearity of the stress-strain relation might occur in the tensile properties of the GFRP laminate composite. The lamina’s premature failure and delamination might change the elongation rate and the slope of the stress-strain curve. Furthermore, delamination generates fiber-resin interface crack that reduces the composite stiffness. The imperfection of the laminated procedure is predicted as the primary cause of premature failure and delamination. Therefore, nonlinear behavior occurs because of the composite laminates’ defects and poor quality.
- The linear elastic with no plasticity model has shown an excellent estimation of the ultimate stress, the fracture load, and the maximum elongation. However, the estimation accuracy was decreased in the nonlinear low-strain zone. Therefore, the linear model can be adopted when the tensile test result does not significantly identify the nonlinearity behavior.
- The trilinear plasticity model can capture the nonlinear behavior on the stress-strain curve. However, a significant discrepancy is identified in estimating stress-strain relation at the fracture limit adjacent region. Inaccurate results on the estimated second turning point have decreased the quality of tensile properties estimation. The modification of the plastic strain constant might improve the estimation accuracy. Therefore, determining the plastic strain constant to define the trilinear slope should be examined thoroughly.
- Both simplified FE models have a good agreement with the experimental results and present the capability to estimate the tensile behavior with different characteristics. However, it is not suitable to predict the initial failure point of the laminate composite. Since both models have been defined with no flaw material assumption, both models have limitations in accurately determining the initial failure point. Otherwise, the initial fracture point commonly occurs on the point where the material flaw is located and is not defined in the simulation model.

Declarations

Author contribution statement

Ahmad Fauzan Zakki: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed materials, analysis tools or data; Wrote the paper.
Aulia Windyandari: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

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Data included in article/supp. material/referenced in article.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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