

ORIGINAL ARTICLE

Numerical Analysis of Unidirectional GFRP Composite Mechanical Response Subjected to Tension Load using Finite Element Method

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ABSTRACT – Composite material is a well-known structural material which is increasingly adopted as an engineering structure material. Glass fiber reinforced polymer offers the lightweight and high strength characteristics that is required for the modern industry, such as aviation, automotive, wind power, and marine technology. One of the important mechanical characteristics of the composite materials are the tensile properties, because it is well known as the material strength. Therefore, the investigation of mechanical response on the glass fiber reinforced polymer (GFRP) tensile test using numerical analysis is important for the estimation of structural response of the GFRP complex structure, such as boat construction. The objective of this research is to assess and estimate the mechanical response of the GFRP composite material subjected to tension load using finite element method. The linear transversely isotropic model is developed to estimate the unidirectional glass fiber GFRP with the configuration of fiber orientation angles of 0°, 30°, 45°, 60° and 90°. The results show that FE simulation are capable to detect the specimen response during the tensile test. The maximum discrepancy of the estimated stress strain diagram is about 16.5% to 32% compared to experimental data. The larger orientation angle has shown the larger discrepancy value. It is found that the increment of discrepancy value is generated by the nonlinearity behavior of the material due to the domination of polymer material behavior on the large orientation angle. Otherwise, the FE models have estimated accurately the ultimate strength, maximum displacement and fracture load. It can be concluded that the linear transversely isotropic model is adequately accepted as the estimation method of the GFRP composite structure response.

ARTICLE HISTORYReceived: 29th Sept. 2021Revised: 8th March 2022Accepted: 28th June 2022Published: 4th July 2022**KEYWORDS***GFRP composite;**Tensile properties;**FE modeling;**Transversely isotropic;**Stress-strain diagram***INTRODUCTION**

Recently, composite materials have been frequently used as structural materials for significant developments in the aeronautics, automotive, manufacturing, and marine industries. This trend occurs because of the increased requirement for lightweight material and high tensile strength to meet the immediate demands of the present industry. The rapid development and application of composite materials were initially conducted when synthetic adhesive resins as the essential material were progressively developed to fabricate multilayer laminates. The polymer binder allows one to fabricate reinforced fiber plastics (FRPs), Figure 1, which are assembled using a variety of the most common laminates, including glass fibers reinforced polymer (GFRP) or carbon fiber reinforced (CFRP). The glare typed composite made of the unidirectional glass fiber reinforced laminates combined with aluminum alloy sheets were adopted in the aviation industry. Furthermore, when combined with composite, such materials generate high tensile strength, high impact toughness, and improved damage tolerance.



Figure 1. Glass fiber reinforced polymer laminates.

Fiber-reinforced material also offers an improvement in the tensile strength and bending stiffness, especially when it is compared to other structural materials on the basis of weight units. Significantly, the fiber orientation can be arranged to generate better structure stiffness in the selected direction. These characteristics provide a significant advantage for boat builders and shipyards [1]. Consequently, these composite materials are broadly applied as structural materials in many modern industries, especially in aviation and marine activities [2],[3]. This condition has motivated many

researchers and naval architects to investigate the mechanical behavior of composite due to specific loading conditions [4-9].

One of the essential mechanical characteristics of the composite is flexural strength and stiffness. Such studies conducted the optimization analysis to find the optimum configuration for improved flexural strength [10]. The tension and bending load on the composite structure concurrently generate tensile, compressive, and shear stresses. The composite failure is initiated when one of the stresses or the combined stresses exceeds the strength limit [11]. Otherwise, the effect of stress concentration and the particular stresses change is also usually observed [12]. Therefore, the failure criteria should be implemented to evaluate the bending and shear stresses simultaneously and consider the combined stress effect on the structural strength [13]. Various failure criteria are adopted in an isotropic material, such as the Huber-Mises-Hencky criterion [14]. However, in orthotropic composite material, the failure criteria became more complicated [15]. The quadratic failure criteria were known for FRP strength analysis, where the specific factors are defined to enable the direct failure assessment [16]. Therefore, the development of an advanced concept for failure analysis of composite material should be investigated [17].

Nowadays finite element method is commonly used to evaluate the structural strength of the industrial product. However, in propagation analysis of multi failure mode of composite, the finite element method still does not provide satisfying results [18-19]. Although, some examples of thin-walled composite column failure subjected to compression test using numerical analysis can be found [20-23]. However, in the study on failure mechanism of composite structures subjected to tensile test with the numerical analysis still relatively few can be found. Otherwise, the numerical analysis using complex composite failure criteria should be supported by sophisticated experimental data. Therefore, the investigation of mechanical behavior for tensile properties using the simplified FE model is essential. This research investigated the unidirectional GFRP composite laminate mechanical behavior subjected to tension load using the linear transversely isotropic FE model.

LITERATURE REVIEW

Glass fiber reinforced polymer (GFRP) has been applied extensively in marine industries such as fishing boats, racing boats, recreational boats, lifeboats, and floating structures. With outstanding mechanical properties and relatively lightweight compared with metal material, the GFRP is very suitable for constructing small boats and crafts. Furthermore, the GFRP properties can be customized by arranging some influencing factors: the angle of orientation of the glass fiber, the stacking sequence of the lamina, the number of layers, and the procedure of the lamination process. In the study of numerical modeling of composite structure, the articles mainly reviewed deal with applying the finite element method to estimate the structure response behavior of the composite material structures. Some references can be found for the numerical modeling element of polymer matrix composite as follows.

Moumen et al. [24] develop a numerical model to investigate the tensile properties of a bio-composite material using the finite element method. The microscopic level model is adopted to obtain the thermo-mechanical behavior. The results show that the numerical model able to define the elasto plastic properties with the temperature variation. It is also can be found that the young modulus and the fracture stress increase by the escalation of the horn fiber contents. Styles et al. [25] develop the FE model to estimate flexural strength characteristics of a sandwich structure with an aluminum foam core. The two thickness of core which is 5 and 20 mm were observed. A comparison between FE results and experimental work was made. The results show that the predicted strain has reasonably good agreement with the experimental result. Input parameters for the foam core have been modified to generates an adequate estimation.

Vacik et al. [26] optimized the simple structures made from carbon fiber-reinforced polymer and cork in the composite laminates. The numerical model was made using the finite element method software MSC Marc. The Pareto front algorithm was conducted for the optimization work. Zemcik et al. [27] investigate the mechanical characteristics of the polyurethane foam cored sandwich panels. The tensile strength, bending, compressive test, dynamic modal, and impact test were investigated by the experimental study. The material properties were defined directly from the result of the experimental test. The three-point bending test was experimentally performed and numerically estimated using the finite element method with MSC Marc software. The progressive Hashin failure criterion was adopted for the simulation calculation.

Ullah et al. [28] study the deformation behavior and damage of composite laminates due to quasi-static bending. The investigation of the characteristics of woven CFRP material has conducted experimental work for the large-deflection bending. The numerical calculation was made using a two-dimensional finite element model with commercial software Abaqus/Explicit. The numerical analysis results show that the initiation and growth of material damage are sensitive to the mesh size of cohesive-zone elements. The top and bottom layers have shown mode-I failure, while the core material experienced mode-II failure behavior. The results of the simulation have shown a good agreement with experimental data.

Klasczorny et al. [29] developed a numerical model of riveted (RN-B) with in/out plane single lap joint clearance. The finite element 3D model was defined to examine the RN-B joint tensile properties to determine translational stiffness coefficients. The experimental work was conducted for validation and examined the full loss of load capacity. The results show that the translational stiffness coefficient was correctly presented for the 3D joint model. The estimated stiffness coefficient can be used for the 2D model of the shell segment flanges connection with the same ply sequence of the lamina. In the other study, Klasczorny et al. [30] developed a numerical model of static process GFRP laminates, including the progressive failure. The mixed sequence layers of laminate with E-glass chopped strand mat and woven roving were examined. The focus of this study is to determine the parameters option/value for numerical modeling and simulation of

the static process, which includes the failure for beam, plate, and shell composite structures using MSC Marc. The results show that the quasi-linear and progressive failure have a good agreement with the experimental result.

Nycz et al. [31] develop the methodology of numerical modeling and simulation of single wave glass-polyester laminate segments using the MSC Marc program. The three-point bending test was made experimentally for the validation of computational results. The composite segment of glass fiber and polyester resin laminate was developed with the sequence laminate layer of CSM450/STR600. The elastic and material strength properties were derived experimentally from laminates type of M (5xCSM450) and F (4xSTR600). It is obtained that Bilinear Thick Shell provides an outcome similar to the real experimentally result.

Urbaniak et al. [32] present the experimental buckling and post-buckling behavior analysis of square cross-section tubes due to pure bending load. The beams were made of glass fiber reinforced polymer unidirectional prepregs tape in the autoclaving procedure. The eight-layer laminate was made for the experiment test. The result indicates that in bending, the angular arrangement of layers influences the buckling and failure strength. The increase of longitudinal direction layers might decrease the buckling load. However, it might increase the failure load. This influence is visible when longitudinal direction layers with fiber are added close to the middle surface of the lamina. Gliszczynski et al. [33] estimate the load capacity of C-shaped cross-section composite beams under the pure bending load. The eight layers GFRP laminates were adopted for the beam construction. Then, the ANSYS program FE-based analysis is employed to evaluate the load capacity of the analyzed structure. Tsai-Wu and Hoffman's maximum stress criteria were adopted as the failure criteria. It is concluded that the most considerable convergence of both results was obtained on the maximum stress reduced to fiber direction criteria. The composite beams have shown high stiffness degradation after exceeding the compressive and tensile strength.

Banat [34] analyzed the multilayer rectangular composite beam under a three-point bending test using finite element simulation. The carbon fibre-reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) with different laminate stacking were modeled. Hashin and Puck, Tsai-Hill, Hoffman, Tsai Wu were performed as the failure criteria. The results show that the nonlinear analysis can approximate the equilibrium path for the variation of beam type with laminate layer configuration. Seifoori et al. [35] investigated the flexural characteristic of GFRP and CFRP of the composite beam. The beam with various geometry was investigated. The bending test measurement was also conducted with a digital image processing (DIP) method equipped with a displacement sensor. The DIP method was used for continuous measurement of the material yielding phase through the two-dimensional specimen displacement. The experimental result shows that the DIP method accurately estimated deflection, stress, and bending slope in real-time during the bending test. The simulation model was developed for the bending test. The DIP method measurement has shown a discrepancy of less than 5% compared to the experiment and simulation results.

Based on the review of the above articles, this study intends to develop the tensile test modeling GFRP composite structure using the finite element method. The configuration of GFRP composite material was defined with the variation of the angle of orientation of unidirectional glass fiber. The material properties and the large displacement due to the tension load were determined and estimated using transversely isotropic assumption. The comparison of the experimental measurement and the finite element method estimation would be presented as the verification and validation of the proposed modeling method.

MATERIALS AND METHOD

Experimental Study

In this study, the GFRP composite material was made following the lamination procedures used by the traditional boatyard. However, the reinforcing fiber adopted a unidirectional fiber orientation. The assumption was made to present the influence of the orientation angle of reinforcing fiber on the laminate strength. The variations of the fiber orientation angle were determined as 0°, 30°, 45°, 60°, and 90°. The hand lay-up method was adopted for the lamination process. The mechanical properties of polyester and E-glass are shown in Table 1. The roving E-glass which is used as the reinforced fiber was manufactured by Asahi Fiber Glass Corp. The designated polyester resin was Yukalac 157 BQTN-EX. The Yukalac resin is a quick-drying, thixotropic, pre-accelerated, and non-waxed type of general orthophthalic resin. This kind of resin is very suitable for hand-layup and spray-up molding FRP product applications. The GFRP composite material was made with the fiber-resin weight fraction ratio of 20 wt%.

Table 1. The material properties of the E-glass and polyester resin.

Mechanical properties	E-Glass	Polyester resin
Tensile strength	1928 MPa	5.5 MPa
Tensile strain	0.018	0.016
Modulus of elasticity	78 GPa	309 MPa
Density	2428 Kg/m ³	1120 Kg/m ³

The tensile test specimens are made according to ASTM D3039 standards. The specimen has a rectangular shape with a length of 200 mm, a width of 25 mm, and thicknesses of 3 to 4.5 mm. The grip length of 50 mm is located on each side. Then the test length is 90 mm. The geometrical shape of the test specimen can be seen in Figure 2.

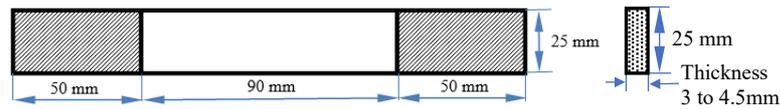


Figure 2. The tensile test specimen dimension according to ASTM D3039.

The specimens were made using unidirectional fiberglass with various orientation angles of 0° , 30° , 45° , 60° , and 90° . Each laminate with the defined orientation angle, the three specimens were made for the tensile strength measurement by a universal testing machine. Therefore, the total number of specimens was 15 specimens. The tensile test was carried out using a universal testing machine with a displacement rate from 0.5 mm/s to 1 mm/s. The tensile load increases linearly until the maximum tensile load is reached when the specimen is in failure.

Simulation Model

The simulation analysis used the finite element method to estimate the mechanical response of the tensile test specimen, such as displacement, maximum stress, and material failure. The material model adopts a transversely isotropic assumption because the specimens have unidirectional reinforcing fiber with similar mechanical characteristics in each principal axes (X and Y axes). The experimental data determine the mechanical properties of the material model as the results of tensile test measurement. The tension loads have been defined as a displacement in the axial direction. Therefore, the actual force can be found as the reaction force on the constraint node of the model. The magnitude of the force load is according to the elongation of the model. The displacement amplitude increased linearly until the maximum displacement was achieved. The boundary condition applied a symmetry/encastre/fix support, which is $U_1=U_2=U_3=R_1=R_2=R_3=0$. The definition of displacement loads and the boundary condition can be seen in Figure 3.

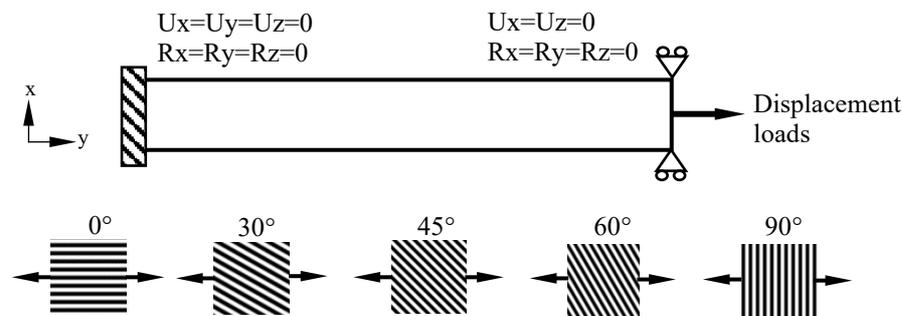


Figure 3. Boundary condition, fiber orientation angle and load condition of specimen model.

RESULTS AND DISCUSSION

Experimental Tensile Test Results

Based on the experimental results, it can be seen that the orientation of the reinforcing fiber influenced the maximum tensile strength. The laminate showed the highest tensile strength with an angular orientation of 0° . The greater the orientation angle presented, the smaller the tensile strength. The significant decrement of 51.5% in tensile strength can be found in the orientation changes from the straight fiber (0°) to the inclined fiber (30°). It indicates that the orientation angle significantly influenced the tensile strength of the GFRP material. The comparison of the tensile strength values for each configuration of the fiber orientation angle can be seen in Figure 4(a).

The effect of the reinforcing fiber orientation angle on the strain value can be seen in Figure 4(b). The measurement results show that the magnitude of the material strain is affected by the variations of the orientation angle. The larger orientation angle can reduce the strain value of the GFRP material. The strain value decrement of the straight orientation angle (0°) to inclined angle (30°) was obtained of 32%. Meanwhile, the strain value difference of the straight fiber direction with the perpendicular (90°) was 96%.

The changes in the modulus of elasticity due to the variation of the reinforcing fiber orientation angle can be seen in Figure 4(c). The experiment results show that the inclined fiber has a larger modulus of elasticity than the straight fiber. This measurement results have a different tendency with the other study results [36]. Regarding to the study, the young modulus should be declined with the inclined fiber reinforced. This phenomenon can be occurred because of the poor quality of the tensile specimen. The lack of layering process with the hand lay-up method and the other imperfection in the production process might influence the tensile properties of GFRP composite. Although the experiment data present the poor quality of the specimen, the measurement result still can be used for conducting the numerical analysis as a representation of the real composite material mechanical properties. Otherwise, it is also indicated that the composite structural response analysis should be supported by the actual measurement of the material's mechanical properties to develop the material model for the numerical simulation.

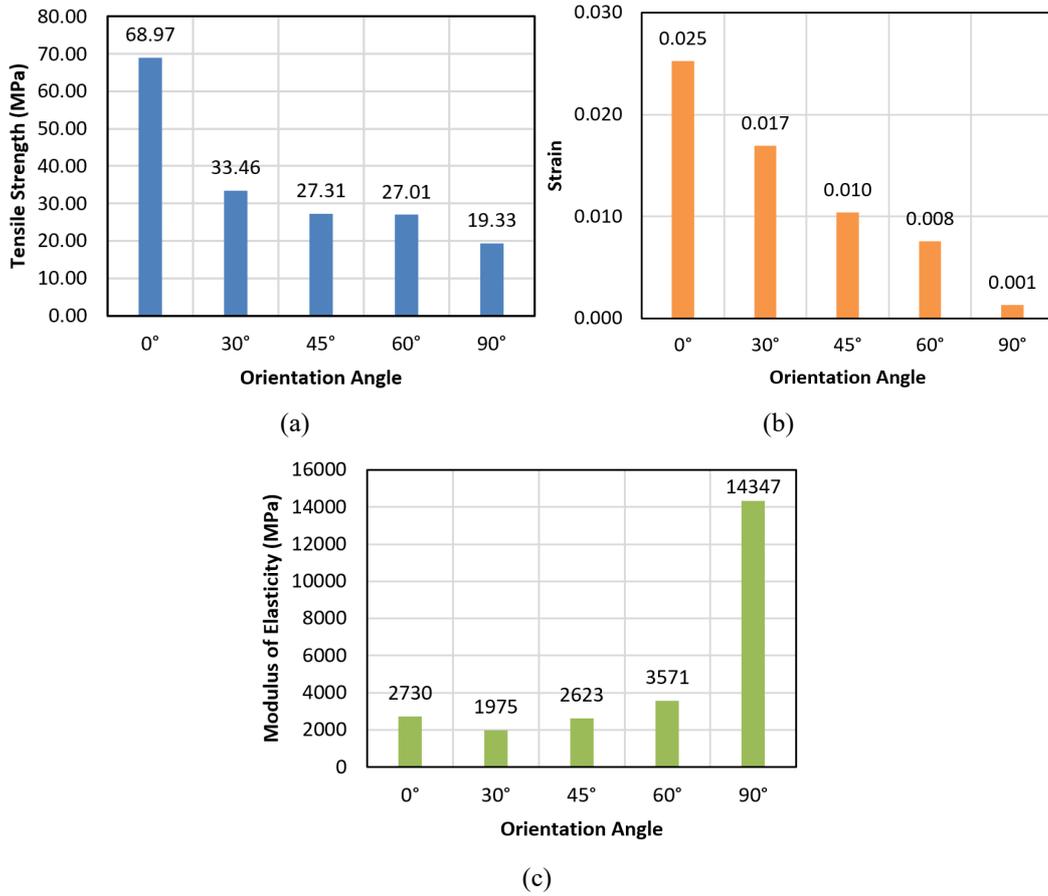


Figure 4. (a) Tensile strength, (b) maximum strain and (c) modulus elasticity on the variation of reinforcing fiber angle orientation.

Based on the characteristics of tensile strength, strain, and modulus of elasticity, it can be seen that the variations of the orientation angle have influenced the strength and stiffness of the unidirectional GFRP composite material. The representation of the mechanical characteristics of the tensile test can be seen in the stress-strain diagram, Figure 5.

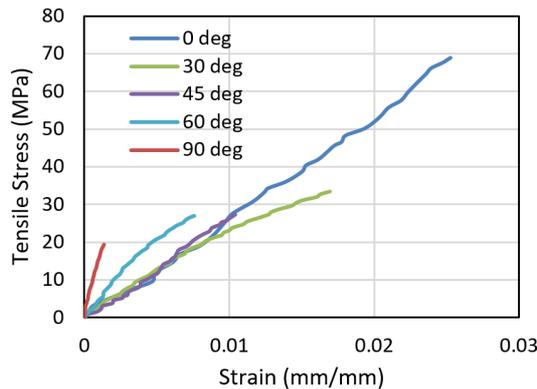


Figure 5. Stress-strain relations of the unidirectional GFRP with the variation of orientation angle.

Stress Distribution on the Unidirectional GFRP Tensile Test Model

The simulations were conducted with the material properties which are obtained in the experimental study. Since the experimental results have shown that the stress-strain relation of the unidirectional GFRP is nearly linear, the linear material model was selected. Moreover, the brittle characteristics also were identified as the plastic zone is not apparently recognized in the curve. The plasticity was defined with the yield stress equal to the maximum tensile stress. Otherwise, the plastic strain was assumed as zero value because of the material's brittleness. Figure 6(a) to 6(e) depict the ultimate effective stress (Von mises stress) that constitutes the estimation of the tensile strength characteristics of the modeled material. Regarding the results, all of the models have shown similar maximum tensile stress with the experiment measurement. It can be explained that the maximum tensile stress of the model cannot exceed the defined yield stress properties with the zero-plastic strain. According to this definition, the model tensile properties turn into the elastoplastic material behavior. Therefore, the tensile stress did not increase when the maximum stress was achieved. The maximum

stress remained constant until the maximum strain was achieved. The model failed when the strain magnitude was exceeded the defined fracture strain. These phenomena also can be seen in the color contour of the stress distribution. The red color representing the highest stress almost appeared on all body parts of the tensile specimen model. It is indicated that the model did not fail directly, although one of its elements has reached maximum stress. Therefore, the elements turned red until the fracture strain was reached, and the model failed.

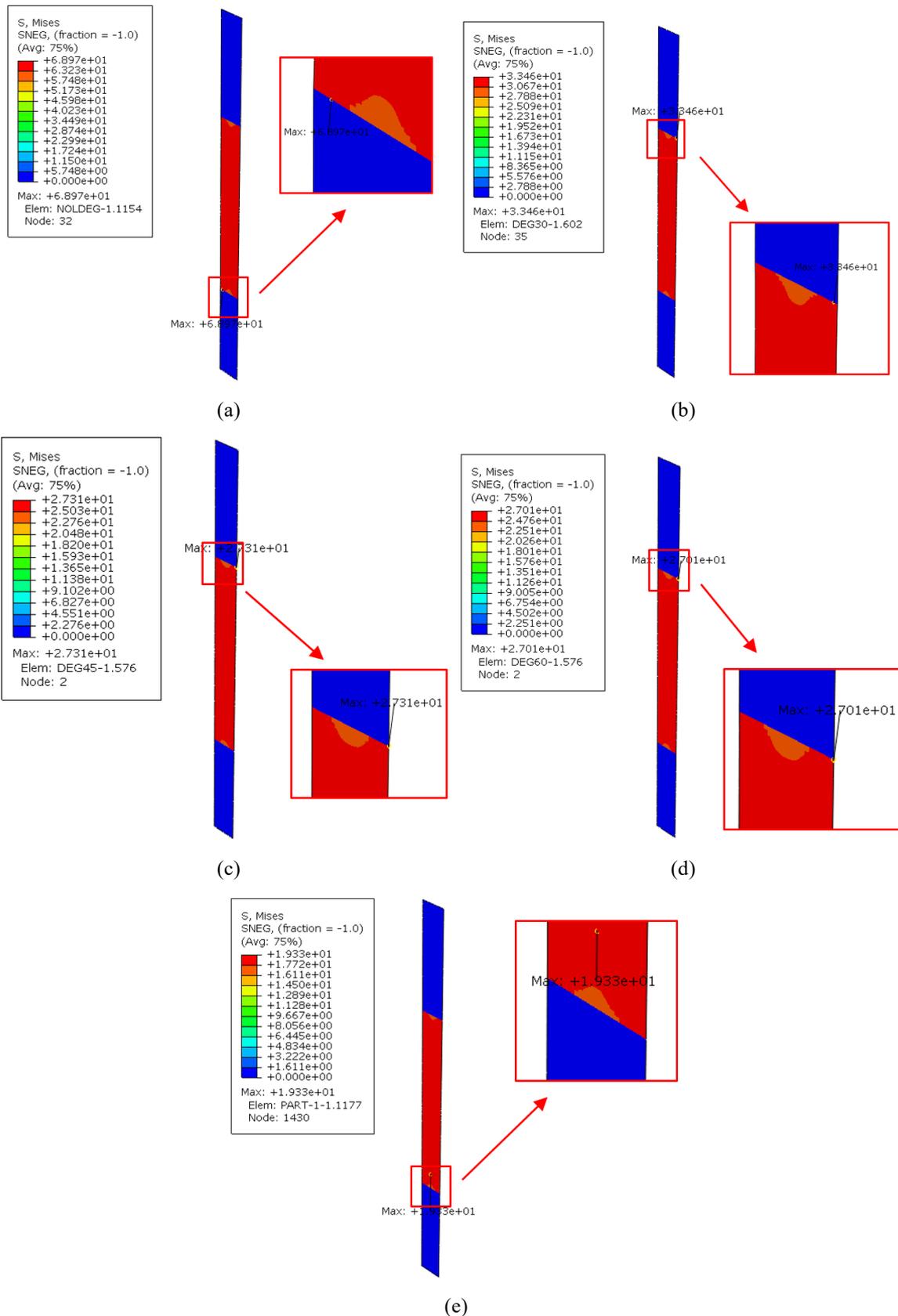


Figure 6. Ultimate effective stress of GFRP with (a) 0°, (b) 30°, (c) 45°, (d) 60°, and (e) 90° orientation angle.

According to the above characteristics, the simulation models have a limitation on identifying the initial point of fracture. Since the model was defined as the homogeneous material and ideal mechanical properties, the elements presented a similar response due to the tensile load. Otherwise, material flaws such as a notch, porosity, and imperfect layering are also neglected. Therefore, the location of the maximum stress was not representing the initial point of fracture. It can be seen that all of the models have shown the maximum stress on the region which is adjacent to the defined load point.

The Comparison of the Numerical and the Experimental of the Unidirectional GFRP Stress-Strain Diagram

Figure 7(a) to 7(e) depicts diagrams of the stress-strain relations generated from the experimental measurement and the numerical calculation. The experiment curves (blue color) were determined following the relation of the generated tensile force and the vertical displacement due to the tensile test measurement. The results have shown a good agreement between the numerical and experiment measurement results. The numerical estimations presented the linear behavior on the stress-strain relation. The accuracy of the defined simulation models was diminishing while the material GFRP had nonlinear behavior.

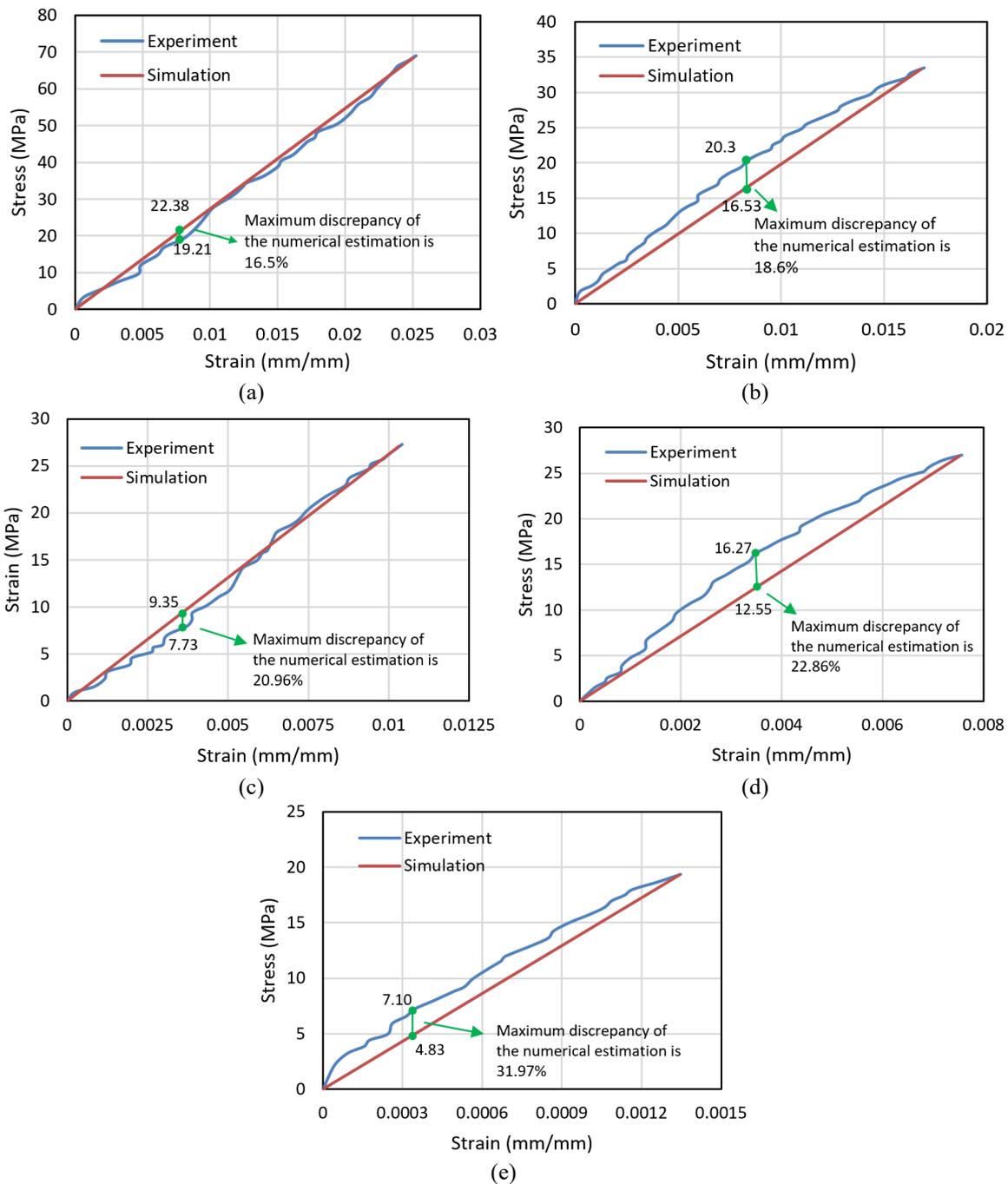


Figure 7. Stress-strain diagram of GFRP with (a) 0°, (b) 30°, (c) 45°, (d) 60°, and (e) 90° orientation angle.

Figure 7(a) and 7(c) show that the numerical estimation has excellent accuracy. The GFRP showed linear behavior with an angular orientation of 0° and 45°. Therefore, the experimental data measurement is suitable for the character of

the defined model. However, in Figure 7(b), 7(d), and 7(e), the GFRP with the angle orientation of 30°, 60°, and 90° have shown nonlinear behavior. Since the stress-strain relation has nonlinear characteristics, the discrepancy of the numerical estimation is increased. The maximum discrepancy was shown on the GFRP with a 90° angle of orientation. The simulation also presented underrated tensile stress compared to the experimental result.

Regarding the presented stress-strain diagram, Figure 7(d), the GFRP with 60° angle of orientation gives an impression that discrepancy appears very high. However, the maximum discrepancy was obtained on the 90° orientation. Furthermore, it also can be seen that the discrepancies have an incremental tendency while the angle of orientation was turned on from 0° to 90°. These phenomena might have occurred because the larger angle has reduced the reinforcing fiber role to strengthen the GFRP composites. Therefore, the specimen response is dominantly influenced by the polyester mechanical behavior. These conditions are also explained by the increase of the nonlinearity characteristics of the GFRP composites material.

The Comparison of the Numerical and the Experimental of the Unidirectional GFRP Tensile Properties

The FE simulation model can also estimate the ultimate tensile strength, maximum displacement, and fracture load representing the GFRP tensile properties. As shown in Table 2, for the experimental and the numerical ultimate strength, maximum displacement and fracture load decreased with the orientation angle. There seems the composite tensile strength was reduced due to the diminishing of the fiberglass reinforcement. Therefore, the ultimate strength and fracture load have declined.

Table 2. The ultimate strength, maximum displacement and fracture load of the unidirectional GFRP composites.

No	Orientation angle	Ultimate strength (MPa)			Maximum displacement (mm)			Fracture load (N)		
		Exp.	FE	Error (%)	Exp.	FE	Error (%)	Exp.	FE	Error (%)
1	0°	69.97	68.45	2.17	2.273	2.256	0.75	2724.28	2703.59	0.76
2	30°	33.46	33.25	0.63	1.524	1.513	0.72	1498.86	1489.59	0.62
3	45°	27.31	27.11	0.73	0.937	0.929	0.85	1291.58	1282.38	0.71
4	60°	27.01	26.83	0.67	0.681	0.676	0.73	1177.84	1171.36	0.55
5	90°	19.33	19.29	0.21	0.121	0.118	2.48	736.58	735.26	0.18

According to the results, the FE simulation with the linear transversely isotropic material model has estimated respectable tensile properties for the unidirectional GFRP with the variation of fiber orientation angle. The brittleness behavior of the GFRP tensile properties is suitable with the adopted linear approach. The FE simulation analysis was suggested to detect the bending and flexural properties, the nonlinearity behavior, and multilayer laminates for future research.

CONCLUSION

Tensile characteristics of the unidirectional GFRP with the variation of fiber orientation angle were investigated by finite element analysis. The results of the numerical analysis are also being compared with the experimental test. Regarding the conducted comparison outcome, it was found that the linear transversely isotropic model is capable of detecting the specimen response at any point along the specimen length during the tensile test.

The maximum discrepancy of the estimated stress-strain diagram is about 16.5% to 32%. It is indicated that the nonlinearity characteristics generated the discrepancy value due to the domination of polymer mechanical behavior on the large orientation angle. Therefore, it is recommended to adopt the nonlinear material model for the GFRP composite with the large reinforcing fiber orientation angle. Otherwise, the linear model is suitable for the brittle material.

Although the estimated stress-strain diagrams have shown moderate discrepancy, the linear transversely isotropic model still can be adequately accepted for the estimation method of the structural response of the GFRP composite construction. It was found that the simulation model is capable of estimating the ultimate strength, maximum displacement and fracture load accurately.

CONFLICTS OF INTEREST

The authors declare that no conflict of interest could have appeared to influence the reported result in this paper

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