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STRENGTH AND DEFORMATION ANALYSIS ON CAR DOOR DESIGN FOR ENERGY SAVING CONTEST

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Abstract
The car door is a vital component of an automobile, playing a key role in passenger safety during accidents. For an energy-saving competition, the strength of a car prototype's door was thoroughly examined using Finite Element Analysis (FEA). This study involved three testing methods: pole side impact, side impact, and door slam tests. Simulations were conducted using the Finite Element Method (FEM) with aluminum alloy 6061-T4, type-E fiberglass, and type-S fiberglass as materials. These materials were selected based on their stress properties, mass, and cost. The simulation indicated that the side impact test produced the highest stress levels, especially in the fiberglass materials. While the aluminum alloy exhibited higher von Mises stress than its tensile strength in one case, both types of fiberglass maintained safety as their tensile strengths exceeded the maximum von Mises stress. The pole side impact test showed aluminum's highest stress and deformation, whereas fiberglass materials showed higher stress and deformation in the side impact test. The door slam test demonstrated minimal stress and deformation across all materials. Among the three, type-E fiberglass demonstrated the most favorable and safest performance. Consequently, type-E fiberglass is highly recommended as the ideal material for the car prototype's door.

1. Introduction

With the depletion of the earth's fuel reserves, it has become imperative to devise a strategy that addresses the global fuel demand by either reducing fuel consumption or identifying alternative sources of renewable energy. In light of advancements in technology, the global automotive industry has begun manufacturing vehicles with significantly lower fuel consumption rates [1]. To equip students in Indonesia to effectively confront the energy crisis, the Ministry of Education and Culture of the Indonesian Government (Kemendikbud RI) has organized a competition titled "Kontes Mobil Hemat Energy (KMHE)" focused on energy-efficient vehicles. The objective is for students to design and construct vehicles that exhibit low fuel consumption, high safety standards, and environmental friendliness. All vehicle designs submitted must adhere to the standards and regulations set forth by the organizers, which include specifications for the car doors. The car door design must meet certain parameters, such as a minimum size of 50×80 cm, ensuring driver and passenger safety, and secure installation to the vehicle's body while allowing for easy ingress and egress within 10 seconds [2]. To ensure compliance with all the established standards, a thorough strength analysis of the designs is mandated.

The testing of car door strength has been conducted several times by researchers using different methods. Shikkerimath et al. analyzed the car door design of the TATA Indica V2 using a pole side impact mechanism at velocities of 30 m/s and 90 m/s [3]. Long et al. tested the strength of the Toyota Yaris 2010 door using the FMVSS 214 standard [4]. This was achieved by pushing the door perpendicularly at a velocity of 8 m/s in 92 ms into a steel bar with a diameter of 254 mm. Setiawan et al. analyzed the door strength of an electric city car prototype using the Euro NCAP standard [5]. This involved pushing the door at a 75-degree angle on a horizontal plane at a velocity of 20 mph (8.94 m/s) in 80 ms into a steel bar with a diameter of 254 mm. Prem Kumar et al. analyzed

the strength of a car door design specifically made to withstand a side impact of 8000 N, following the FMVSS 214 standard [6]. The results were obtained without considering the price of the materials used, and S-Glass Fiber was found to be the most applicable in terms of weight and strength compared to aluminum alloy and E-Glass Fiber. Ezkelia et al. analyzed the strength of a car door using the door slam method [7]. This involved slamming the door onto a stiff surface with an acceleration of 350 m/s² in 0.1 seconds. Patil et al. also employed the door slam method but with different parameters, utilizing an angle of 20 degrees, a velocity of 1 m/s, in 0.35 seconds [8].

In this research, a design for a car door will be created and tested using three simulation methods to assess its strength. These methods include pole side impact, side impact, and door slam tests. The simulations will be conducted using ANSYS 2019 R3 software, employing materials such as aluminum alloy 6061 T4, Type-E Fiberglass, and Type-S Fiberglass. The objective of this research is to identify a contest car door design that is safe, lightweight, and economically viable for use in an energy-saving vehicle competition.

2. Methodology

Figure 1 showed the car door design that was tested in this paper. The size of the door was set at 77 cm × 87 cm with a thickness of 2.9 mm as advised by the rules of the competition.
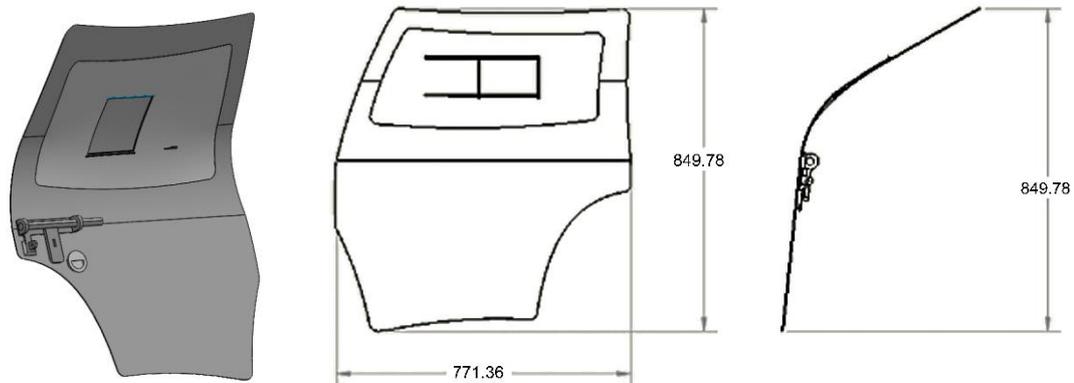

Figure 1. Car door design (unit in mm).

In this research, simulation was performed using three types of materials which were aluminum alloy, type-E fiberglass, and type-S fiberglass. Aluminum alloy 6000 series was the commonly used type as a body panel. The 6000 series aluminum alloys were known for their good formability, moderate strength, and corrosion resistance [9]. These alloys were heat treatable and alloyed with magnesium and silicon if required, which could lead to the precipitation of secondary phases such as Al3Sc, Al3Zr, and Mg2Si, resulting in improved mechanical strength and comparable properties to the 5000 and 7000 series aluminum alloys [10]. Additionally, the 6000 series aluminum alloys had been extensively studied due to their better strength, weldability, corrosion resistance, and cost compared to other aluminum alloys [11]. However, it was important to note that these alloys could develop susceptibility to intergranular corrosion because of improper heat treatments or alloying [9].

The other types of materials, type-E fiberglass and type-S fiberglass were also tested. The mechanical and thermal properties of fiberglass-reinforced composites were influenced by the type of fiberglass used and the orientation of the fibers within the composite material [12,13]. Additionally, the amount of fiberglass incorporated into the composite material played a critical role in balancing mechanical strength and thermal conductivity [14]. Furthermore, the fabrication process and the adjustment of fiberglass contents could significantly impact the compressive strength and thermal insulation properties of porous ceramics [15]. Type-E fiberglass was known for its effective tensile properties and adhesive strength, making it suitable for reinforcing polymer composites [16,17]. On the other hand, type-S fiberglass was recognized for its superior mechanical properties, including high strength and modulus values, which made it ideal for applications requiring exceptional mechanical performance [17]. Each material's properties comparison was shown in Table 1.

This research was done using Solidworks 2020 SP4 software for the modeling of the car door design. The strength analysis was simulated using ANSYS 2024 R1 (Research License) software using the mechanical function of Finite Element Method (FEM) analysis. Three simulations were conducted to analyze the structural integrity of

the car door. The prescribed simulation tests employed were delineated as follows. Firstly, the Pole Side Impact Test was executed by exerting a perpendicular force on the door at a velocity of 8 m/s within a time frame of 92 ms. This force was applied onto a steel bar possessing a diameter of 254 mm. Secondly, the Side Impact Test was performed by subjecting the door to a uniform force of 8000 N. Lastly, the Door Slam Test was conducted by imparting an acceleration of 350 m/s² to the door within a time span of 0.1 seconds.

Table 1. Mechanical properties of the door material.

Materials	Density (kg/m^3)	Young Modulus (GPa)	Poisson's Ratio	Tensile Strength (MPa)	Yield Strength (MPa)
Aluminium alloy, wrought, 6061, T4 [18]	2713	68.9	0.33	241	145
Composite, PA12/E-glass fiber, woven fabric, biaxial [19]	1749	19.54	0.1049	4700	-
Composite, Epoxy/S-glass fiber, UD prepreg, QI [19]	1904	19.97	0.3065	1950	-

Other than the Finite Element Method simulation results, price estimation of the material used also became a deciding factor when comparing the end results. Price estimation calculation was performed using Equation 1. Where P_{T-Al} was the total price of aluminum alloy in IDR, P_{Al} was the aluminum alloy price per kg in IDR/kg, and w_{Al} was the weight of the aluminum alloy used in kg.

$$P_{T-Al} = P_{Al} \times w_{Al} \tag{1}$$

For type-E Fiberglass and type-S Fiberglass, both materials consisted of two base elements which were fiber and matrix (binder). The percentages of fiber determined the load-bearing capacity of the composite and load transformation capabilities depending on the contents of the matrix. A type-E fiber mat as reinforcement and the polyester resin with 65% fiber composite provided maximum impact strength of 12.6 Joule and 51.46 MPa stress concentration with 1.4 mm deformation [20]. Based on that, the ratio of the fiber and matrix elements in this study was decided to be 63.20%: 36.80%. The matrix element also consisted of two other elements which were resin and catalyst with the ratio of 90%: 10%. To estimate the cost of fiber, the weight of fiber was multiplied by the price of fiber per kg shown in Equation 2. Where P_{T-fg} was the total cost of fiber in IDR, P_{fg} was the price of fiberglass per kg in IDR/kg, $\%_{fg}$ was the percentage of fiberglass, and w_{fg} was the weight of fiberglass in kg.

$$P_{T-fg} = P_{fg} \times \left(\%_{fg} \times w_{fg} \right) \tag{2}$$

Equations 3 and 4 were used to calculate the total cost of the matrix. Where P_{Mat} was the total cost of the matrix in IDR, P_R was the resin price per kg in IDR/kg, P_C was the catalyst price per kg in IDR/kg, $\%_R$ was the percentage of resin, $\%_C$ was the percentage of catalyst, $\%_M$ was the total percentage of the matrix, and W_M was the total weight of the matrix used in kg.

$$P_{Mat} = [P_R \times (\%_R \times W_M)] + [P_C \times (\%_C \times W_M)] \tag{3}$$

$$W_M = \%_M \times w_{fg} \tag{4}$$

3. Result and Discussion

Firstly, the determination of the material cost is carried out by taking into consideration the mass of the car door. The mass of each individual material employed in the construction process is depicted in Table 2, utilizing the Solidworks 2020 SP4 software. In addition, Table 3 presents the current market availability and corresponding costs of the materials and resins at the time of the production of this study. Based on the computation employing equations (1)–(4), the aggregate cost necessary for each substance is exhibited in Fig. 2. Concerning the fiberglass calculation, the proportion of fiberglass and matrix element stands at 63.20%: 36.80%, whereas the proportion of catalyst and resin in the matrix element is 10%: 90%. After the computation, it is ascertained that the substances are ordered from the most expensive to the least expensive as follows: aluminum 6001-T4 (Rp 179,102.55), type-S Fiberglass (Rp 135,397.50), and type-E Fiberglass (Rp 127,182.99).

Table 2. Car door mass based on materials.

Material	Car door mass (kg)

Aluminum Alloy 6061-T4	3.743
Type – E Fiberglass	2.516
Type – S Fiberglass	2.716

Table 3. Cost of materials.

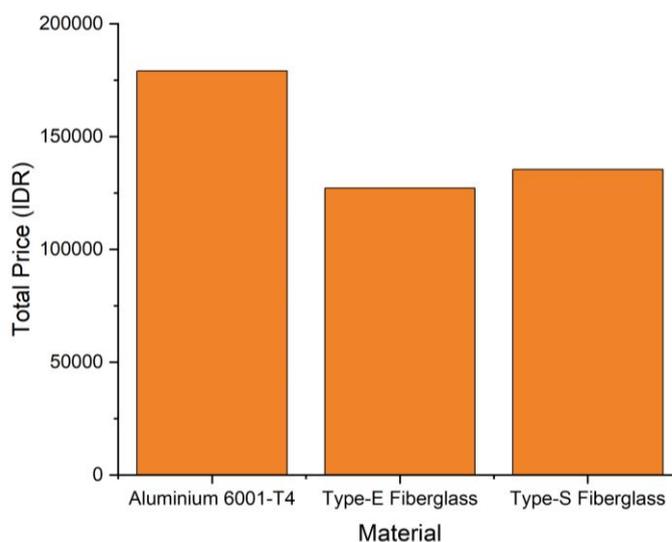| Material	Cost of Materials
Aluminum Alloy 6061-T4	US$ 3.3 / kg (IDR 47,850 / kg*)
Type – E Fiberglass [21]	US$ 1.5 / kg (IDR 21,750 / kg*)
Type – S Fiberglass [22]	US$ 1.0 / kg (IDR 14,500 / kg*)
Material	Cost of Materials
Resin [23]	IDR 55,100 / kg
Catalyst [24]	IDR 105,000 / kg

(*Exchange rate $1= Rp 14,500)

Figure 2. Total cost of materials.

Secondly, the evaluation of the outcomes obtained from the simulations of deformation and stress is thoroughly deliberated. This evaluation encompasses an in-depth analysis of the results derived from the pole side impact test, side impact test, and door slam test.
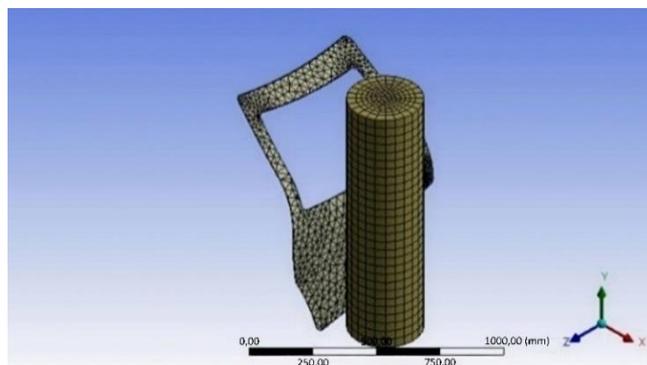

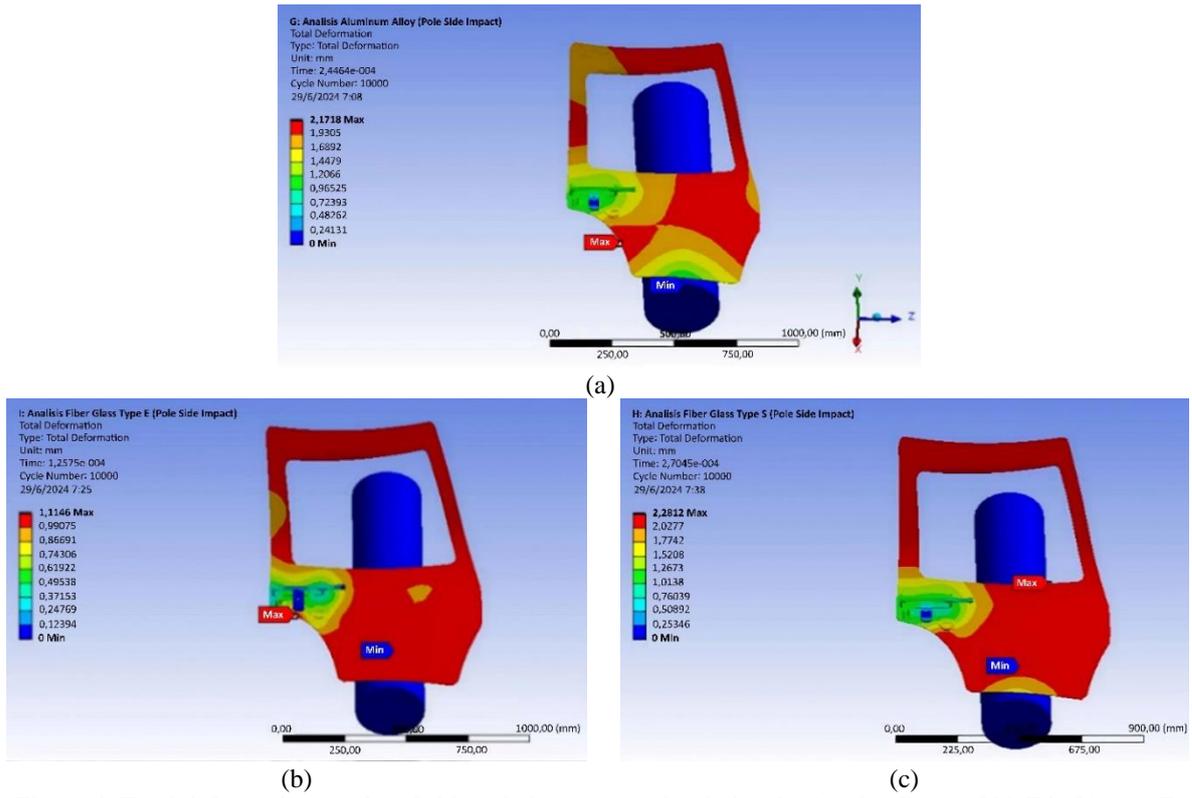Figure 3. Meshing results for pole side impact test simulation.

(a)

(b)   (c)

Figure 4. Total deformation results of side pole impact test simulation for (a) aluminum 6001-T4, (b) type E-fiberglass, and (c) type-S fiberglass.

(a)

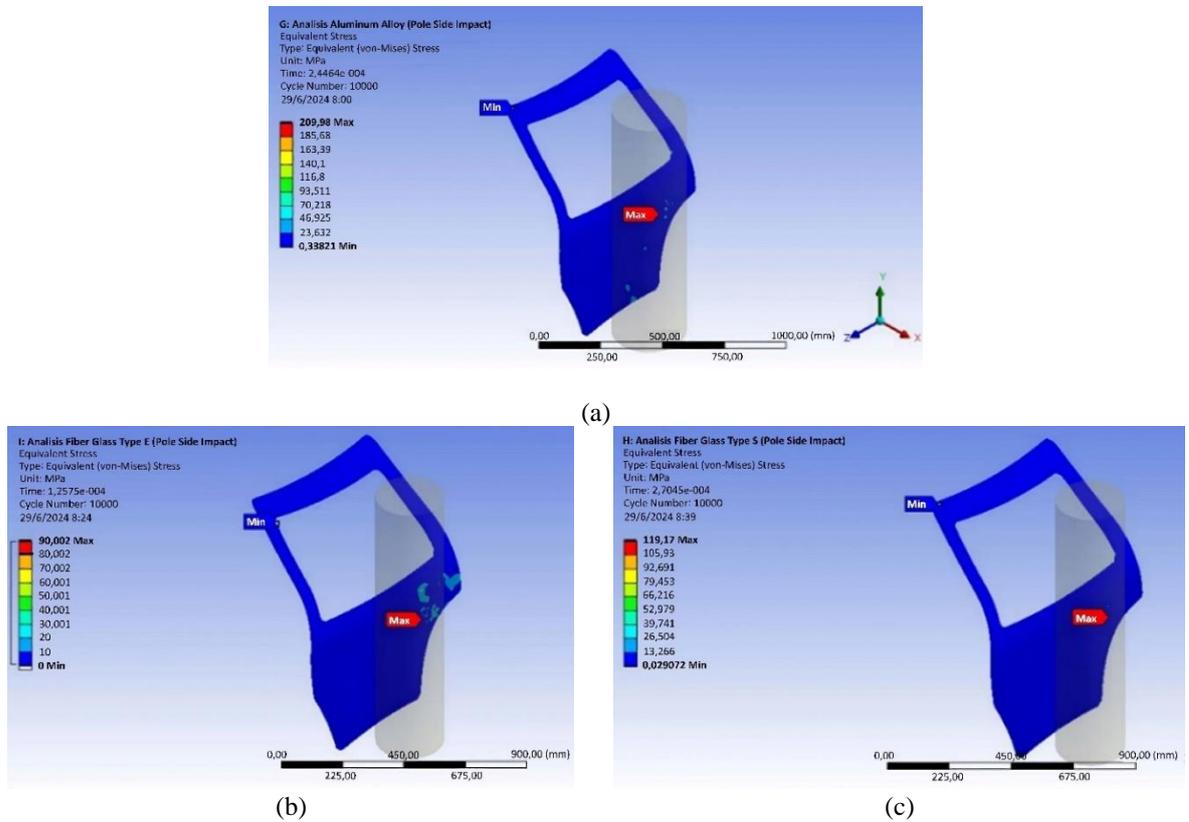(b)   (c)

Figure 5. Von Mises stress results of side pole impact test simulation for (a) aluminum 6001-T4, (b) type-E fiberglass, and (c) type-S fiberglass.

Figure 3 depicts the meshing of the pole side impact simulation. The mesh used for the door comprises 18,269 elements with 43,453 nodes. The results of the simulation unveil the total deformation and von Mises stress values, as presented in Figs. 4 and 5, respectively. Notably, the aluminum 6001-T4 records a maximum total deformation of 2.1718 mm, while type-E fiberglass and type-S fiberglass register total deformations of 1.1146 mm and 2.2812 mm, respectively. Evidently, the fiberglass materials exhibit a broader extent of deformation compared to the aluminum 6001-T4 because fiberglass has a lower modulus of elasticity while having higher tensile strength. Thus, aluminum is stiffer than fiberglass. The type-S fiberglass material achieves the highest total deformation, whereas the type-E fiberglass material records the lowest.

When assessing the von Mises stress, the maximum values for each material are 209.98 MPa, 90.002 MPa, and 119.17 MPa for aluminum 6001-T4, type-E fiberglass, and type-S fiberglass, respectively, as illustrated in Figure 5. As indicated by the simulation results, each door exhibits a single point of maximum value. Consequently, the door materials display a relatively low average von Mises stress. Comparatively, aluminum 6001-T4 exhibits the highest von Mises stress among the materials, while type-E fiberglass exhibits the lowest stress.
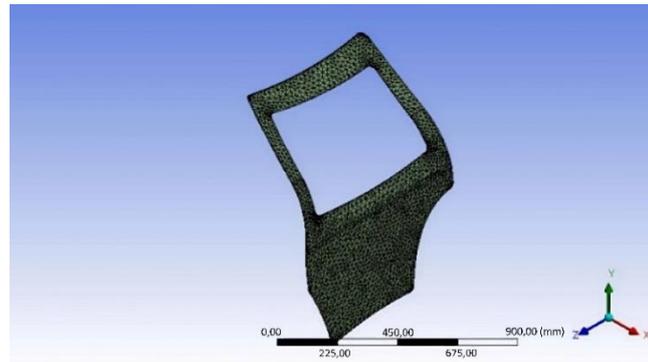

Figure 6. Meshing results for side impact test simulation.
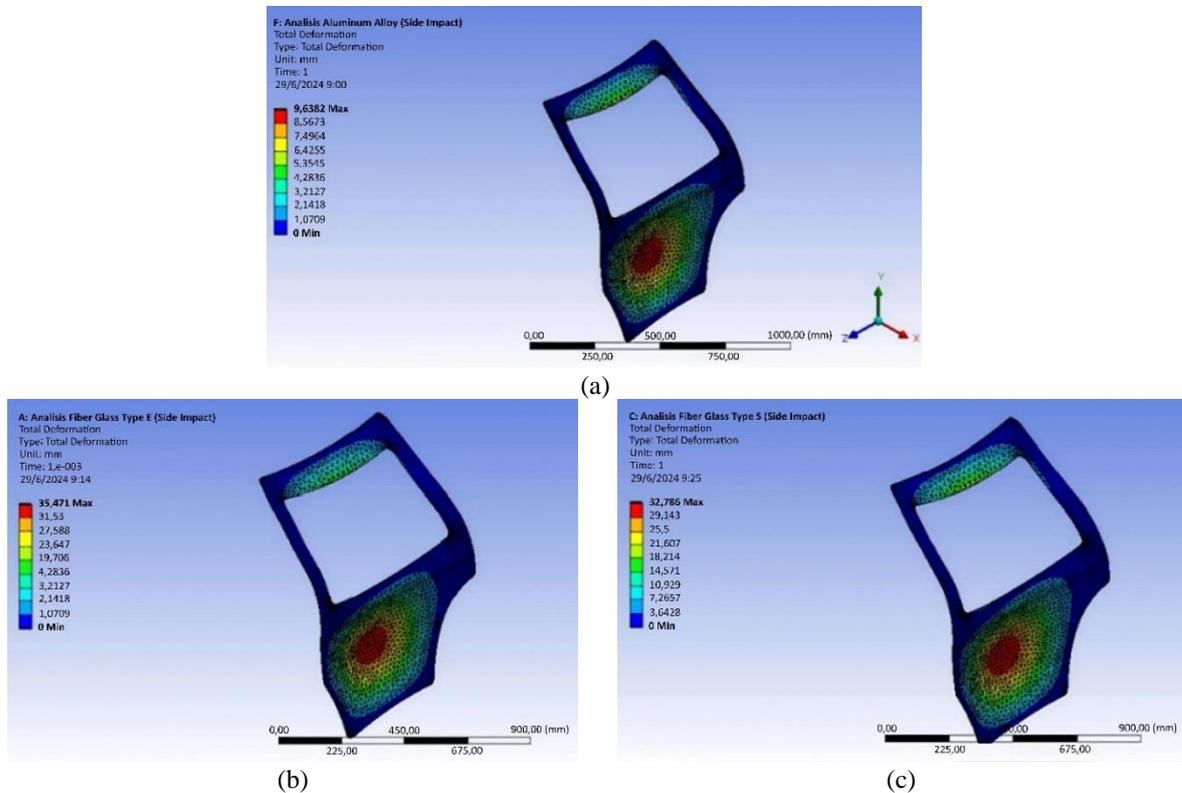

(a)

(b)

(c)

Figure 7. Total deformation results of side impact test simulation for (a) aluminum 6001-T4, (b) type E-fiberglass, and (c) type-S fiberglass.

The illustration in Fig. 6 depicts the meshing utilized for the simulation of the side impact test. In Fig. 7, the utmost degree of deformation is observed for each material, with values of 15.658 mm, 56.753 mm, and 52.457 mm, corresponding to aluminum 6001-T4, type-E fiberglass, and type-S fiberglass, respectively. It should be noted that all materials exhibit their highest deformation in the lower middle portion of the door. Interestingly, the type-E fiberglass attains the highest deformation value, whereas the aluminum 6001-T4 achieves a comparatively lower deformation value.

For the von Mises stress, the values of 266.41 MPa, 590.06 MPa, and 595.49 MPa are observed for aluminum 6001-T4, type-E fiberglass, and type-S fiberglass respectively, as depicted in Fig. 8. It is noteworthy that fiberglass exhibits twice the von Mises value compared to aluminum 6001-T4. The stress area distribution reveals that most of the area is colored light green and blue, implying that all materials experienced a moderate level of stress. The maximum von Mises stress was only observed in a small portion of the door. Notably, type-S fiberglass exhibited the highest von Mises stress value among the various materials, whereas the aluminum 6001-T4 achieved the lowest value.
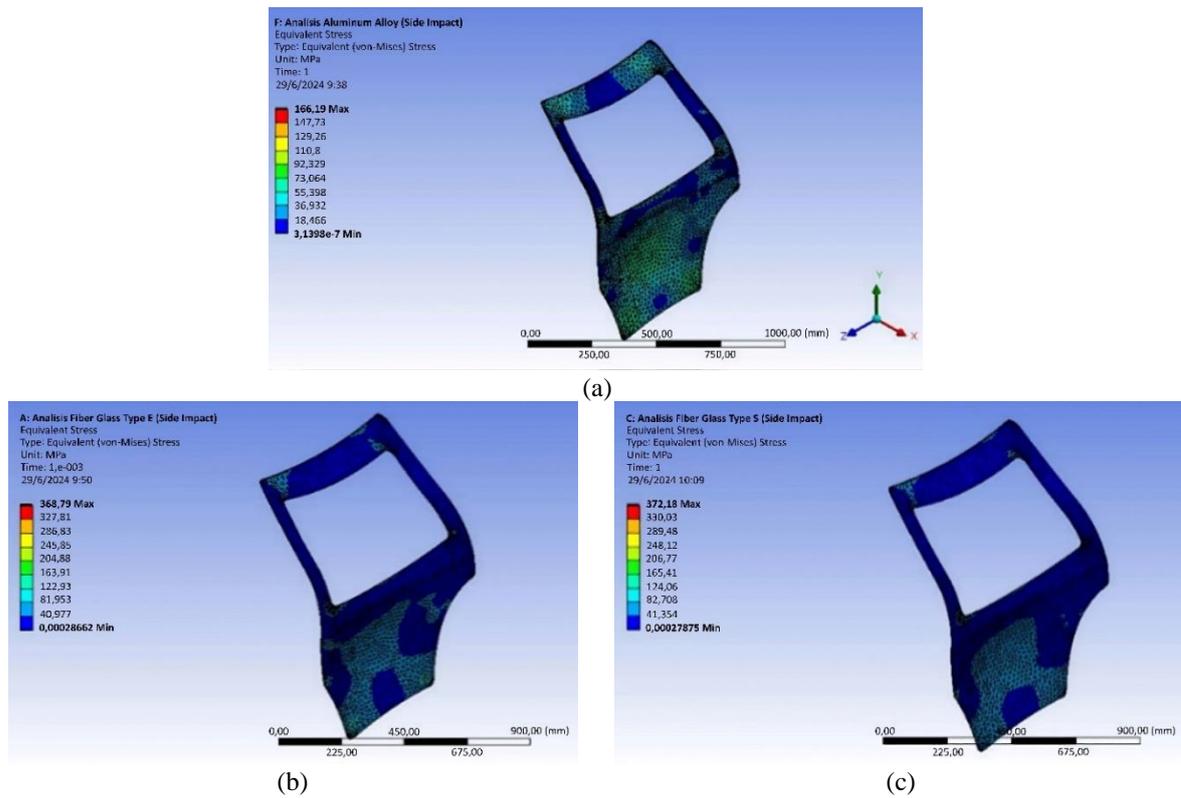
(a)

(b)

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Figure 8. Von Mises stress results of side impact test simulation for (a) aluminum 6001-T4, (b) type-E fiberglass, and (c) type-S fiberglass.
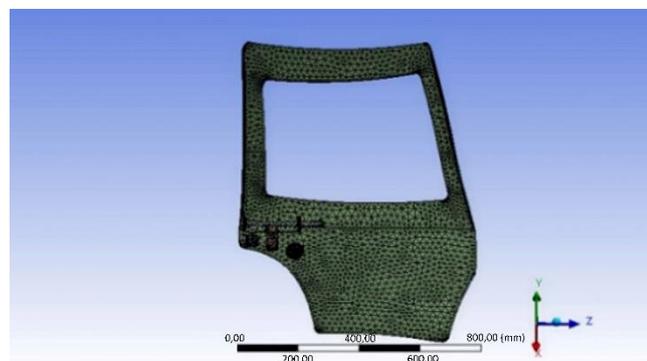
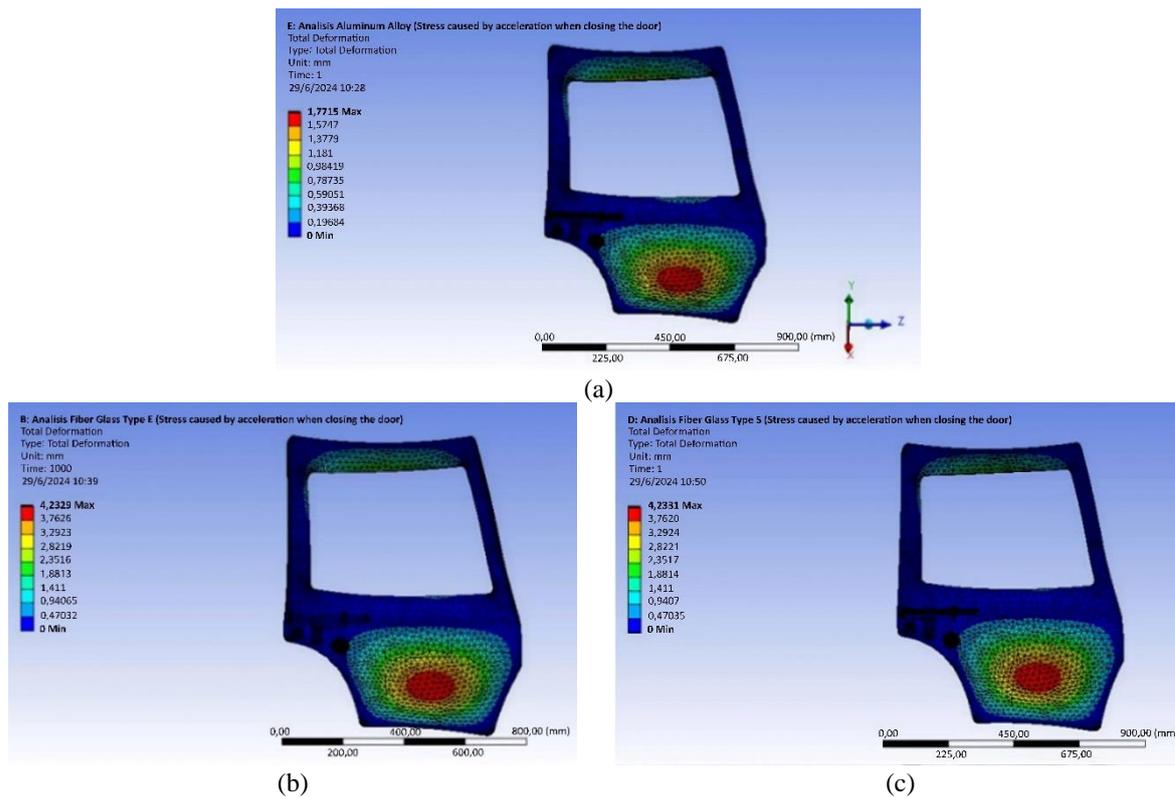Figure 9. Meshing results for door slam test simulation.

51

(a)

(b)

(c)

Figure 10. Total deformation results for door slam test simulation for (a) aluminum 6001-T4, (b) type E-fiberglass, and (c) type-S fiberglassv.
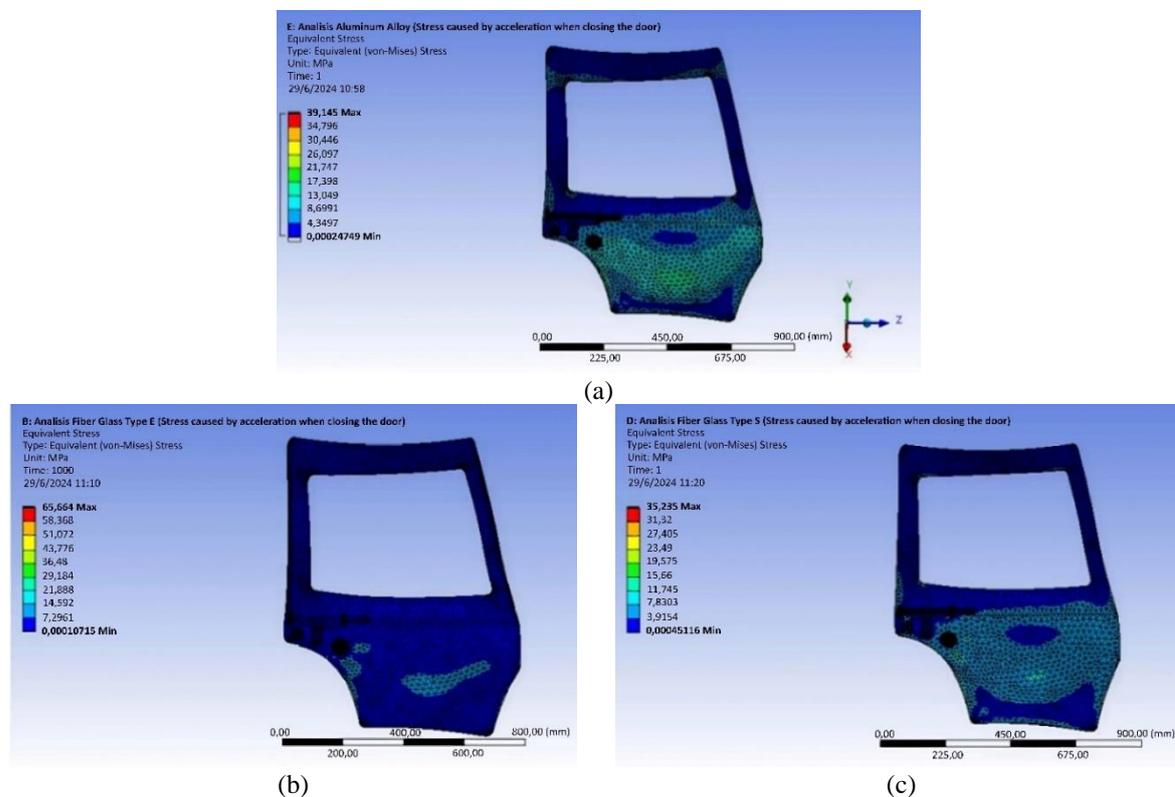

(a)

(b)

(c)

Figure 11. Von Mises stress results for door slam test simulation for (a) aluminum 6001-T4, (b) type-E fiberglass, and (c) type-S fiberglass.

Figure 9 depicts the meshing utilized in the simulation for the door slam test. The maximum value of total deformation observed for aluminum 6001-T4 is 1.7715 mm, while for type-E fiberglass it is 4.2329 mm, and for type-S fiberglass it is 4.2331 mm. It can be observed that the fiberglass materials exhibit a broader region of deformation when compared to aluminum 6001-T4. In Fig. 10, it is illustrated that the most significant deformation occurs in the bottom middle section of the door, which corresponds to the findings of the side impact test. In this observation, the fiberglass materials attain the highest maximum value for total deformation.

The von Mises stress, as portrayed in Fig. 11, reaches its peak values of 39.145 MPa, 65.664 MPa, and 35.235 MPa for aluminum 6001-T4, type-E fiberglass, and type-S fiberglass, respectively. This stress is induced by the acceleration experienced during the door closing process. Notably, among all the materials, type-E fiberglass exhibits the highest von Mises stress, while type-S fiberglass registers the lowest value. In this study, von Mises stress is preferred over engineering stress because the car door experiences multiaxial stress states or plastic deformation. It provides a more accurate representation of the stress state and can help in predicting material failure under complex loading conditions, which are common in many engineering applications.

Figures 12 and 13 display the maximum values of deformation and strength comparison obtained from all test materials and all three methods. The side impact test yields the highest deformation and stress, whereas the pole side impact results in the lowest deformation. However, the door slam test exhibits the lowest von Mises stress compared to the other methods. Despite these variations, all three materials can withstand the stress from the side impact test as the stress value remains below the tensile strength of each material.
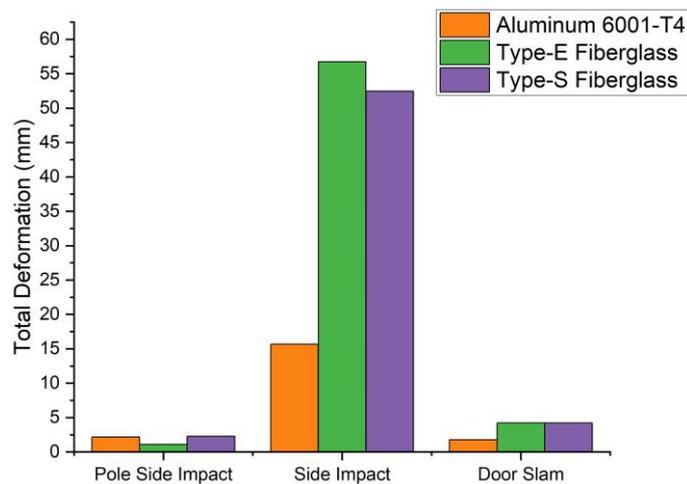

Figure 12. Comparison of maximum deformation values for three types of door materials in three testing methods.
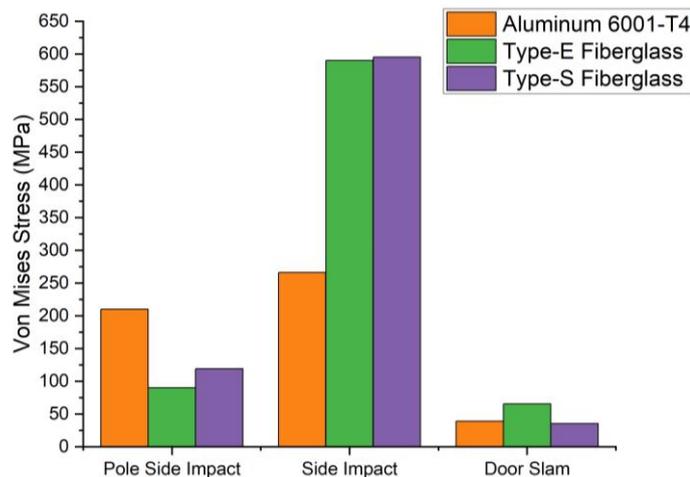

Figure 13. Comparison of maximum von Mises stress values for three types of materials in three testing methods

During the Pole Side Impact test, aluminum's higher stiffness, represented by its greater Young's modulus, along with its ability to deform locally, leads to higher von Mises stress. On the other hand, fiberglass composites, which have a lower modulus of elasticity and better energy distribution properties due to their Poisson's ratio and material structure, experience lower stress. In the Side Impact test, aluminum's higher modulus of elasticity enables it to distribute uniform loads more effectively, resulting in lower von Mises stress compared to fiberglass composites. The latter, with their lower modulus and less uniform load distribution capabilities, exhibit higher stress under the same loading conditions.

To establish a ranking for each material, it is imperative to establish specific criteria. These criteria comprise the strength of the door in the pole side impact, which accounts for 25% of the evaluation, the strength of the door in the side impact, also accounting for 25% of the evaluation, the cost of the material, which contributes 25% to the evaluation, and the mass of the material, which also contributes 25% to the evaluation. It is worth noting that the strength results obtained from the door slam test will not be considered in the evaluation criteria. This decision is based on the simulation results, which indicate that the door strength is minimally affected by the test and therefore holds little value. The results of the evaluation of the three different materials are presented in Table 4. The data show that type-E fiberglass yields the highest value of 2.75.

Table 4. Total material weight values according to simulation results.

Material/Parameter	Pole Side (25%)	Side Impact (25%)	Mass (25%)	Cost (25%)	Rank Value	Safety Factor
Aluminum	1	1	1	1	1	0.54
Type-E Fiberglass	3	2	3	3	2.75	7.97
Type-S Fiberglass	2	3	2	2	2.25	3.28

Safety factor calculation in Table 4 is defined as the yield strength (for aluminum alloy) or tensile strength (for fiberglass) of the material divided by the maximum von Mises stress in the side impact test since it produces the largest stress in the test. Type-E Fiberglass and Type-S Fiberglass achieved a safety factor above 1, which is within the general range of mechanical design safety factors of 1.5 – 2 [25]. Type-E fiberglass has the highest safety factor. Consequently, it can be concluded that type-E fiberglass is the most suitable material for utilization as the car door in the energy-saving car prototype.

4. Conclusion

The car door design has undergone comprehensive strength testing utilizing three different methods—pole side impact, side impact, and door slam tests—employing three distinct materials: aluminum 6001-T4, type-E fiberglass, and type-S fiberglass. The results of these tests have provided critical insights into the performance and suitability of each material for use in energy-efficient vehicle prototypes.

The pole side impact test revealed that aluminum 6001-T4 experienced the highest levels of stress and deformation among the tested materials. This outcome is attributed to aluminum's higher stiffness and localized deformation characteristics, which result in elevated von Mises stress values under concentrated impact conditions.

In the side impact test, both type-E and type-S fiberglass materials exhibited significantly higher stress and deformation compared to aluminum 6001-T4. The lower modulus of elasticity in fiberglass materials, coupled with their less effective load distribution capability, accounts for the increased von Mises stress observed in these tests.

The door slam test indicated minimal deformation and stress across all three materials. However, type-E fiberglass recorded the highest levels of stress and deformation, although these values remained relatively low overall. This test further highlighted the robustness of aluminum 6001-T4 in withstanding dynamic loads during door closure scenarios.

A comprehensive evaluation considering the generated stress, overall mass, and material cost was conducted to determine the most suitable material for the car door prototype. Type-E fiberglass emerged as the optimal choice due to its superior balance of cost-effectiveness, lightweight properties, and adequate strength. Its higher safety factor and satisfactory performance in all conducted tests affirm its suitability for use in energy-efficient vehicle designs.

In conclusion, while aluminum 6001-T4 demonstrated excellent stiffness and strength under certain impact conditions, type-E fiberglass offers a more balanced combination of properties, making it the most appropriate material for the car door in the context of energy-saving vehicles.

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