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Analysis of an Automatic Sliding-Plug Door Component for Failure Prevention

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Abstract

An automatic sliding-plug door made of Aluminum Alloy 6005A-T6 has been designed for a national high-speed train project to meet lightweight structural requirements. Prior to prototyping, a Failure Mode, Effects, and Criticality Analysis (FMECA) was conducted to identify critical components. This assessment revealed that the hinges are the most critical parts during train operation. Consequently, a finite element analysis (FEA) verified the door's structural integrity. The numerical analysis applied interior pressure loads of 500 Pa and 800 Pa, a linear passenger load of 1000 N/m, and dynamic longitudinal, lateral, and vertical loads compliant with EN 14752 and EN 12663-1. The static structural analysis predicted a maximum von-Mises stress of 41.45 MPa on the door leaf, 35.53 MPa at the upper hinge, and 53.28 MPa at the lower hinge. All values remain well below the material's 230 MPa yield strength, confirming structural safety. Furthermore, fatigue analysis predicted a service life of 10^8 cycles, exceeding the standard requirement of 10^7 cycles. These numerical predictions validate the door's strength and fatigue life and justify the progression to prototype manufacturing.

Keywords: High-speed train door; FEA; structural analysis; aluminum structure

1. Introduction

A high-speed train (HST) designed for an operational speed of 250 km/h is currently being developed in Indonesia. Meeting this specification requires a lightweight carbody structure and door system to minimize overall weight and aerodynamic drag [1]. Due to their high strength-to-weight ratio, corrosion resistance and excellent extrudability [2], aluminum alloys primarily AA 6005A-T6, 6008-T6 and 6082-T6 are widely used in carbody structures. However, aluminum extrusions are relatively new to the national railway manufacturer. Currently, the operational rollingstock with an aluminum extrusion carbody in Indonesia is the Light Rail Transit (LRT) Jabodebek, which utilizes AA 6005A-T6 [3]. Investigating the structural performance of this material is therefore beneficial to support its future implementation in HST carbodies.

As a primary passenger interface, the train door is a critical component affecting both operational reliability and safety. This study focuses on the analysis of the door as an integral part of the carbody structure. Designed for continuous operation under Indonesian climatic conditions, these doors require high reliability, as any malfunction directly hinders train departure. Consequently, the HST door system must comply with both regulations and standards.

Reliability is affected by factors such as structural strength, vibration, noise, and airtightness. During high-speed cruising, aerodynamics will affect the stresses imposed on the door and disrupt interior pressure balance. Maximizing airtightness is critical to maintaining this pressure balance while minimizing noise and vibration. Furthermore, automatic operation is essential to ensure HST punctuality. Automatic train doors are categorized into three types: pocket-sliding, out-sliding, and plug-in [4].

A sliding plug-in mechanism was selected for this design because it reduces noise, improves aesthetics and creates a streamlined surface flush with the carbody, thus minimizing aerodynamic drag. This profile complements earlier optimizations of the train head design [5]. Furthermore, an automatic door system was developed to facilitate passenger boarding and alighting. The door system is powered by two electric motors, one for plugging and unplugging motion and the other for the sliding movement. It provides advantages over hydraulic systems in terms of easier maintenance, eliminates the need for pneumatic and electric interfaces, and reduces overall weight by eliminating the air tank. In addition, an electrical sys-

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tem is more effective for the anti-trap safety mechanism.

Sliding plug doors are a key component of the Electric Multiple Unit (EMU) carbody, consisting of sub-assemblies such as the door control unit, electric motor, hinges, door leaf, and door frame. The door system is driven by electric motors operating on 110 V DC [6]. The door leaf is supported at its upper and lower sections by hinges. These hinge components, which bear the structural loads of the door leaf, were identified as having a high-Risk Priority Number (RPN) in a previous FMECA study [7]. Therefore, further investigation of these components is required.

Railway door studies have been investigated across various aspects, including the analysis of operational loads acting on a metro door [8]. These include passenger loads, train acceleration, and pressure loads [8]. This parametric methodology was also applied in the simulation of door hinge stress and deflection. Another study analyzes the strain tension in a door leaf and how it impacts airtightness [9]. Although several studies have investigated sliding-plug railway doors, previous works focused on operational loads, sealing performance, or failure mechanisms of existing door systems. Limited studies have evaluated the structural integrity of a newly developed high-speed train sliding-plug door during the early design stage according to both EN 12663-1 and EN 14752 loading requirements. In addition, this study is a follow-up to a previous FMECA analysis by experts at a railway manufacturer which revealed that the highest-risk component was the hinges [7].

Accordingly, this study examines the structural integrity of the newly developed door, specifically of the door hinges, during the early development stages. This analysis will be used as an initial design verification to evaluate the door's structural performance before prototype manufacturing. This study is limited to numerical evaluation and sensitivity analysis. In future studies, a cyclic experimental test will be conducted to validate the design.

The structural assessment is conducted using finite element analysis (FEA) under the loading conditions as specified in EN 12663-1 and EN 14752. Stress distribution, deformation, and safety factors are evaluated to verify the structure of the door and its hinges during this early design stage.

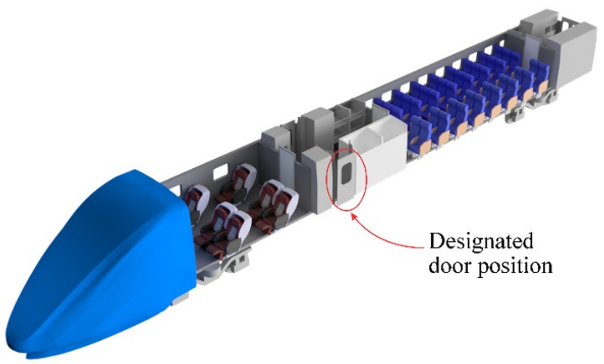
The remainder of this paper is organized as follows. Section 2 describes the door design and specifications, loading conditions, material properties, and finite element simulation. Section 3 describes the analysis results. Finally, Section 4 summarizes the main findings and recommendations for future work.

2. Theoretical method

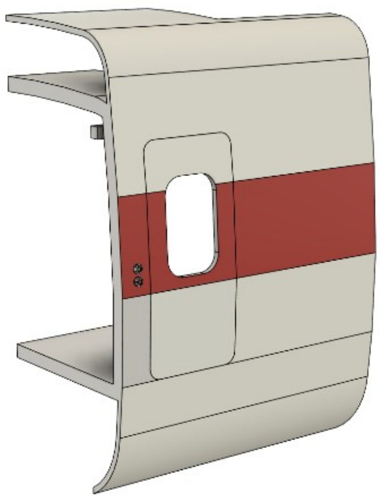
The simulation workflow begins with developing a 3D model of the door system in Autodesk Inventor based on regulatory-compliant specifications. After defining the operational loads and forces, the model is imported into ANSYS and simplified for Finite Element Analysis (FEA) to evaluate its static and fatigue strength. The simulation yields deformation, stress distribution, and safety factors for the static analysis and the number of cycles for the fatigue analysis. To ensure numerical accuracy, a mesh convergence test is conducted to determine the optimum mesh size. Additionally, the fatigue analysis evaluates component endurance, as stress amplitudes exceeding the endurance limit inevitably trigger fatigue failure [10].

2.1. Finite Element Method

Finite Element Analysis (FEA) is divided into three stages: modeling (the pre-processing step), analysis, and post-processing (evaluating the solution and results). In the pre-processing step, the model is created and dis-

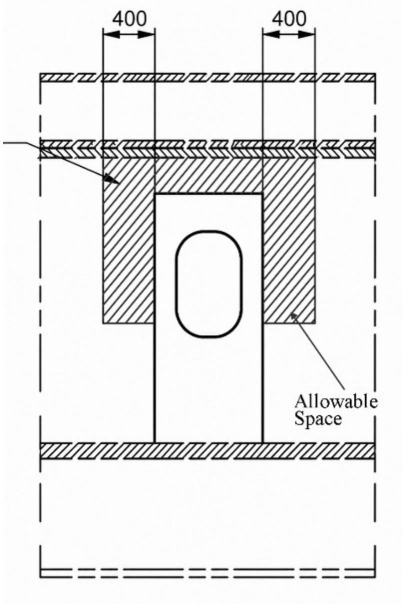


(a) Layout arrangement

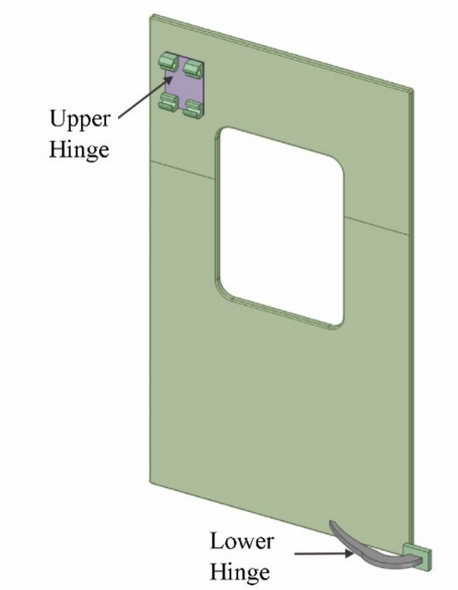


(b) (Sliding-plug door

Figure 1. (a) Interior and door arrangement of HST (b) 3D design of sliding-plug door



(a)



(b)

Figure 2. (a) Allowable area for door engine (b) hinges position of door leaf

cretized into finite elements [11], where a shape function is assumed, element equations are developed, and the elements are assembled to represent the full problem. Subsequently, boundary conditions, initial conditions, and loads are applied [12]. The computer solves a set of linear or nonlinear algebraic equations to produce nodal results. The final phase is post-processing, which will yield results such as stress distribution and displacement values.

2.2. Design and Material Assignment

A single carriage in an HST train arrangement features two door units, as seen in Figure 1. The provisions of the EN 14752:2019 standard (Bodyside entrance system for rolling stock) were used to define the dimensions of the door [8].

According to the standard, the parameters of a single door are shown in Table 1.

Table 1. Door parameters.

Parameters	Value	Unit
Minimum door height	1900	mm
Minimum door width	800	mm
Weight of the door leaf	26	kg
Modulus elasticity (E)	70	GPa

The allowable area for the door engine is described as a 400 mm distance from the door leaf in all three axes, as shown in 2. The door leaf is supported by two hinges, one upper and one lower. The upper hinge serves as a support for the side sliding movement along the carbody, while the lower hinge acts as a support for the plug and unplug mechanism. All mating interfaces between hinge components were modeled using bonded contacts because the study focuses on evaluating global structural strength rather than detailed contact stress. Although rotation can occur during operation, this study only evaluates the door under closed and locked conditions, where rotation is locked by the mechanism. Therefore, a fixed support was applied.

The components are made of aluminum alloy 6005A-T6 to support a lightweight carbody structure. This material was previously implemented in the Jabodebek LRT and will be adopted for the upcoming national HST carbody design. The material properties, sourced from the study by Syaifudin et al. (2021) [3], are shown in Table 2.

Table 2. Mechanical properties of Aluminum 6005A-T6.

Parameters	Value	Unit
Density	2700	kg/m^3
Yield strength	230	MPa
Ultimate strength	280	MPa
Modulus elasticity (E)	70	GPa
Poisson ratio (ν)	0.33	–

2.3. Load Conditions

The standard dictates that the door must be able to resist the weight of passengers leaning or falling on it without deformation. In addition, the door locking system must also be able to endure internal passenger pressure. Prior to the numerical simulation, the forces that act on the door need to be investigated to analyze its mechanical strength.

First, the forces due to its own weight and the forces due to the passenger are considered. According to EN

Table 3. Loads acting on the door and its location.

Load	Value	Location
Air Pressure	800 Pa & 500 Pa	distributed in the door area
Mass Load in Longitudinal Direction	765.18 N	
Mass Load in Lateral Direction	255.06 N	
Mass Load in Vertical Direction	382.59 N	
Passenger Load (Line Pressure)	1000 N/m	1300 mm from the floor

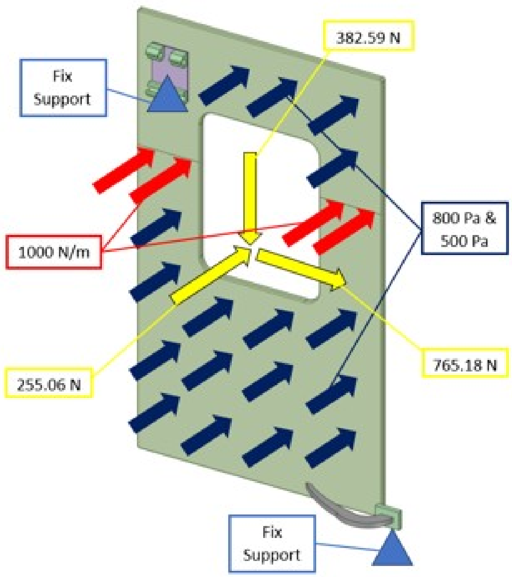


Figure 3. Free-body diagram of loads and boundary conditions

14752:2019 which specifies the bodyside entrance systems for rolling stock, at the height of 1300 mm from the bottom of the door, the door leaf must be able to withstand a linear load of 1000 N/m exerted when a passenger leans or falls on it [13, 14].

Secondly, a regulation from the Ministry of Transportation of the Republic of Indonesia, PM 69 of 2019 (Technical Specification of High-Speed Train), states that the door must be designed to maintain air pressure balance inside the passenger cabin at a maximum of 500 Pa and the maximum pressure differential of 800 Pa [14].

Thirdly, the loads from acceleration, according to the EN 12663-1 requirements for equipment attached to the carbody, have acceleration values of 3g (longitudinal direction), 1g (lateral direction), and 1.5g (vertical direction). The inertial loads were calculated using Newton's second law:

$$F = m \cdot a \tag{1}$$

Where m: mass of the door = 26 kg, a: acceleration (according to loading condition).

Fixed supports were applied as boundary conditions at the connections between the upper hinge and the lead bar,

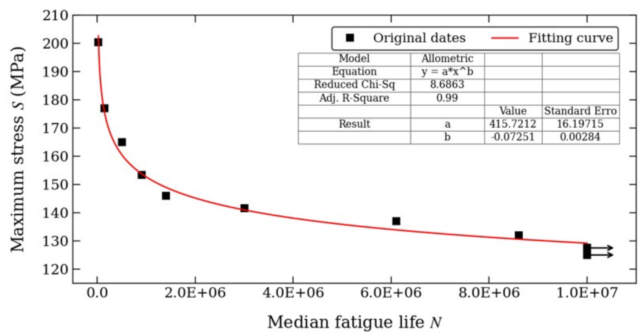


Figure 4. S-N curves of AA 6005A-T6. Adapted from [16].

and between the lower hinge and the carbody wall. The boundary conditions and applied forces are illustrated in Figure 3. Specifically, the red arrow illustrates the passenger load, which is applied as a linear load, while the dark blue arrows denote the air pressure acting on the door leaf surface. The yellow arrow represents the mass load in all three-axis directions.

Details on the static load value and its position are shown in Table 3.

According to EN 12663-1, the door construction must withstand loads induced by vehicle dynamic accelerations as well as any additional loading [15]. The boundary conditions are the same as those in the static analysis, utilizing fixed supports at the connection between the upper hinge and the lead bar, and between the lower hinge and the carbody wall.

Table 4. Load for fatigue case.

Load	Acceleration (g)	Value (N)
Longitudinal Direction	$\pm 0.15g$	$\pm$38.359 N
Lateral Direction	$\pm 0.15g$	$\pm$38.359 N
Vertical Direction	$\pm 1.15g$	$\pm$293.320 N

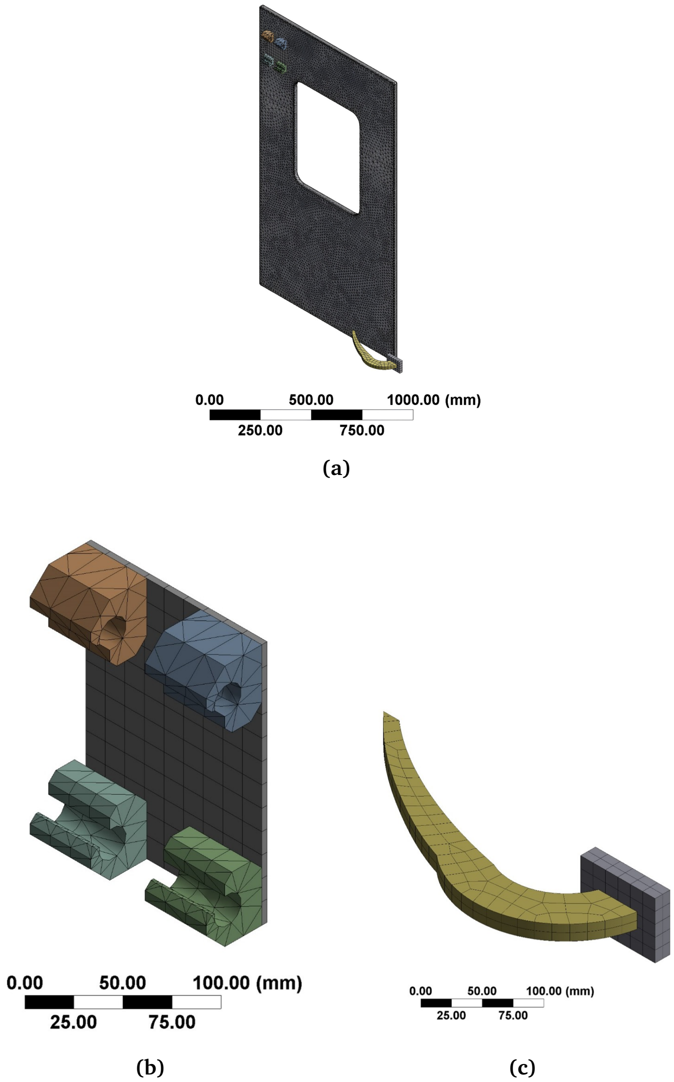


Figure 5. Meshing of a) Door leaf; b) upper hinge; c) lower hinge.

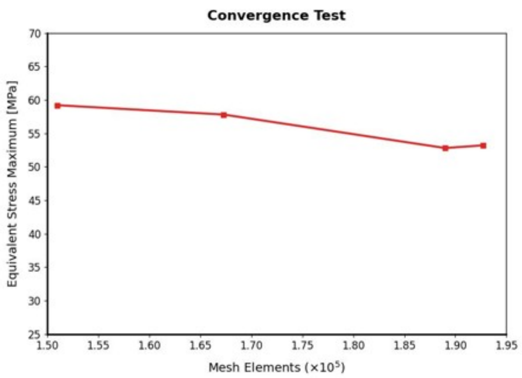


Figure 6. Mesh Convergence test in Ansys Mechanical

Although structural integrity under static loading is critical for ensuring passenger safety and regulatory compliance, its long-term durability under repeated service loading is equally important. During operation, train doors experience thousands of opening and closing cycles, as well as cyclic loads caused by vehicle vibration, aerodynamic pressure, and passenger interactions. These repeated loading conditions may initiate fatigue damage, specifically at stress concentration regions such as hinges, welded joints, and fastening locations. Since aluminum alloys do not have a distinct fatigue endurance limit, fatigue performance must be carefully evaluated during the design stage to prevent crack initiation and premature structural failure. Therefore, fatigue analysis provides a crucial complement to static strength assessment by estimating the service life of critical door components and verifying that the design satisfies the required durability throughout the intended operational lifetime.

Fatigue life prediction is commonly based on the stress-life (S–N) approach, which describes the relationship between the applied cyclic stress amplitude (S) and the number of cycles to failure (N) as seen in Figure 4. The S–N curve of aluminum alloy is obtained experimentally [16]

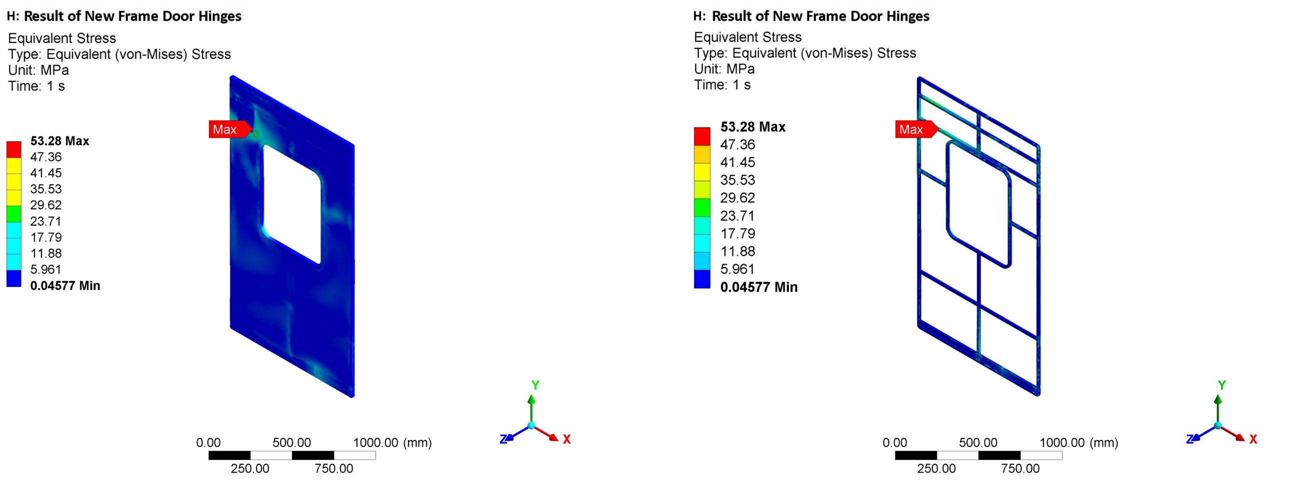


Figure 7. Stress distribution of door leaf and inner frame

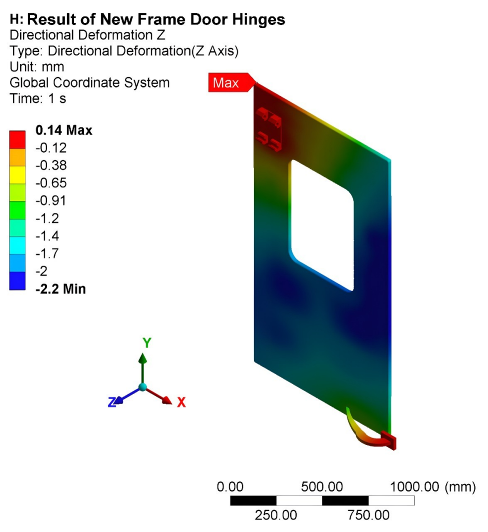


Figure 8. Mesh Convergence test in Ansys Mechanical

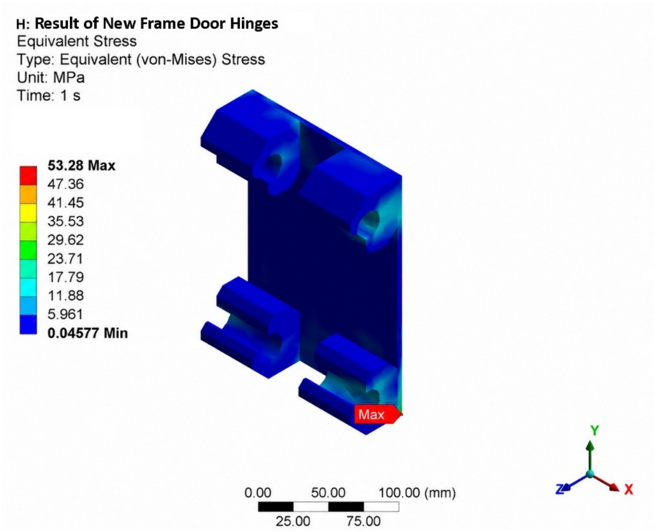


Figure 9. Von-Mises stress distribution of the upper hinge

through fatigue tests under constant-amplitude loading and provides a practical means of estimating the durability of structural components subjected to high-cycle fatigue. Here, the S–N curve exhibits a continuously decreasing trend because these materials do not possess a true fatigue endurance limit. Consequently, even relatively low stress amplitudes may eventually lead to fatigue failure after a sufficiently large number of loading cycles. In finite element-based fatigue analysis, the local alternating stress obtained from structural analysis is combined with the corresponding material S–N curve to predict the fatigue life of critical locations and identify regions susceptible to crack initiation. For fatigue loading, the number of load cycles shall be 10^7 each.

The load for fatigue case refers to EN 12663 and presented in Table 4.

2.4. Meshing Independent Test

The meshing method is a hex-dominant method, with a solid element model. Hexahedral meshes are desirable due to their greater accuracy at reduced fidelity, which correlates with a shorter turnaround time [17]. However, some complex domains still use tetrahedral meshing. The mesh quality is in the range of acceptable to good criteria, indicated by a skewness of 0.65, an orthogonal quality of 0.35, an aspect ratio of 1.3, and a Jacobian ratio of 1.35. Figure 5 shows the meshing for each component.

In a numerical simulation, grid size significantly affects the accuracy of the results. Thus, a mesh independence test was conducted to determine the appropriate mesh size and convergence [18]. In this study grid studies presented in Figure 6 indicate that at a total of 1.9×10^5 mesh elements, the results start to converge. Any further refinement beyond this size would not significantly produce different results. Therefore, the following simula-

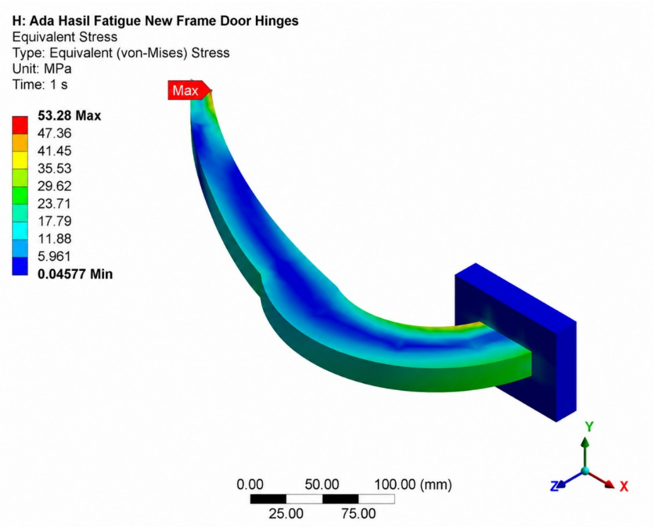


Figure 10. Von-Mises stress distribution of the lower hinge

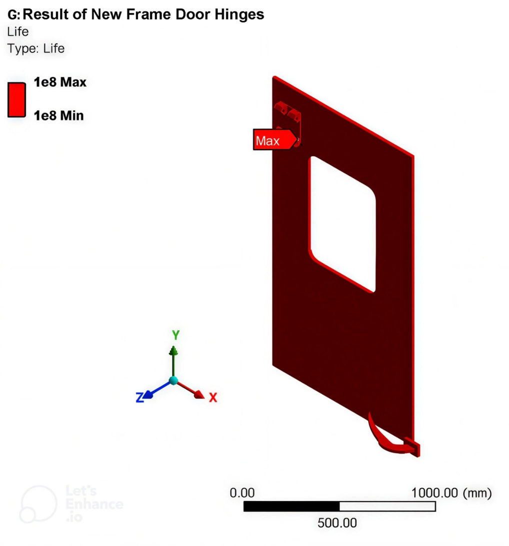


Figure 11. Result of fatigue life

tions use this mesh size.

3. Results and Discussion

There were two types of simulations run in this research: static analysis and fatigue analysis. Static loading provides insight into initial failure prediction and design verification prior to manufacturing. Furthermore, fatigue analysis is critical because the door will be subjected to cyclic operation. The outcome will be valuable for projecting the service life and planning maintenance.

3.1. Static Analysis

The door leaf, upper hinge, and lower hinge were all analyzed using static loading. Each component's stress, deformation, and safety factors were studied.

3.1.1. Door Leaf

The stress distribution of the door leaf is shown in Figure 7. Results indicate that the maximum stress in the door leaf and door frame is about 41.45 MPa. This value is still below the yield strength of the material and gives a minimum safety factor of about 5.55. However, due to the position of the upper hinge at the upper left of the door leaf, there were concentrations of stress around the corner edge of the window. Even so, this design specification is deemed sufficient due to the relatively high safety factor.

In addition, under the applied loads and pressures, deformation occurred. Figure 8 visualizes the deformation contour of the door leaf along the lateral (z-axis) direction. Deformation in this direction is carefully examined since most of the forces act along this axis. The results indicate a maximum deformation of -2.2 mm in the outward carbody direction, which is still considered safe for the design. However, these 10^8 cycles represent a numerical output from the ANSYS simulation and do not accurately reflect the actual fatigue life of the AA 6005-T6 alloy.

3.1.2. Upper hinge

The upper hinge serves as the support for the sliding movement of the door leaf; hence, a slight deformation could inhibit the smoothness of door opening and closing. This analysis helps design the optimum shape and dimensions to prevent major failure.

According to the results, the maximum stress is at the connection between the tip of the upper hinge and door leaf, with a value of about 35.53 MPa, which is still below the yield strength of the material, with a minimum safety factor of about 6.47. The stress distribution of the upper hinge is shown in Figure 9.

3.1.3. Lower hinge

The lower hinge helps with the plugging and unplugging of the door leaf. It pushes out and retracts the door leaf from the carbody.

According to the results, the maximum stress is at the connection between the tip of the lower hinge and the door leaf, with a value of about 53.28 MPa, which is still below the yield strength of the material, with a minimum safety factor of about 4.32. In the connection area between the lower hinge and the plate, stress concentration occurs because there is an additional moment load due to the lower hinge arm. The stress distribution of the lower hinge is presented in Figure 10.

3.2. Fatigue Analysis

According to the load data for the fatigue case, referencing the EN 12663 standard presented in Table 4, the loading includes the notation (+/-) for the longitudinal, lateral, and vertical directions. This indicates that the applied dynamic load oscillates symmetrically, so it is simulated as a fully reversed load. In this condition, the tensile load and compressive load have the same magnitude and occur repeatedly. However, due to the constant gravitational load from the door's mass, a mean stress is introduced, causing the peak tensile stress to exceed the compressive stress. The simulation assumes that longitudinal, lateral, and vertical loads act simultaneously. The stress can be calculated using the equivalent alternating stress. The S–N curve of Aluminum 6005A-T6 [16] illustrates the maximum stress, against the median fatigue life cycles.

Aluminum 6005A-T6 belongs to a group of nonferrous alloys that do not have a distinct fatigue endurance limit. The S–N curve for this material shows a continuously decreasing slope throughout the high-cycle fatigue (HCF) region. Consequently, the fatigue strength for Al 6005A-T6 must be defined based on a specific design life, which is typically set at 1×10^7 or 1×10^8 cycles based on standard testing guidelines. The results of the S–N curve plot show that the maximum alternating stress at the critical location still occurs below the material's S–N curve, indicating the component is within the safe limit at 10^8 cycles. Because the S–N curve of Aluminum 6005A-T6 has a continuously decreasing pattern, however, the operational stress will eventually exceed the curve and potentially cause failure.

According to the fatigue life simulation results, the door structure design meets the standard requirements; exceeding 10^8 life cycles compared to the required 10^7 cycles specified in the standard [15]. The results are shown in Figure 11. Consequently, the proposed design meets the requirements of the standard. However, these 10^8 cycles are the output of ANSYS' calculation and do not state the exact failure life of the AA 6005 T6.

4. Conclusions

This study predicts the structural strength of a newly developed sliding-plug door design using numerical simulation prior to prototype manufacturing. The FEA yields von-Mises stress, total deformation, safety factors, and fatigue life cycle estimates. The results were verified using a mesh independence test. The analysis revealed that the design is adequate for prototyping. Additionally, it helps identify the critical areas of the components, which can be used to improve the design.

The maximum stress obtained remains significantly below the material yield strength of 230 MPa required for Aluminum 6005A-T6. Furthermore, the predicted fatigue life exceeds the design requirement of 10^7 cycles specified in EN 12663-1, confirming that the proposed design satisfies the structural safety requirements.

The door leaf is considered safe within the safety limit; a slight improvement by adding a stiffener around the door window will help reduce stress concentration. The upper and lower hinges were both considered safe with safety factors 6.47 and 4.32, respectively. In addition to the static loading analysis, a fatigue analysis showed that the structural design is safe with 10^8 life cycles.

The limitations of this study are that it only provides numerical validation to justify the prototype manufacturing phase. Consequently, full-scale prototype testing and experimental validation remain essential. Specifically, dynamic cyclic testing is required to evaluate system integrity during operational opening and closing cycles.

Acknowledgments

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