

Finite Element Analysis for Estimating Strength and Fatigue of the APM Structure

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Abstract. APM stands for autonomous people mover, which is a mass transit system widely used in many airports to transport passengers between terminals. This article focuses on APM structure newly designed comprising five components namely, chassis, floor, body, roof, and support. The objective of this article is to estimate the strength and fatigue of each component to assess safety. The finite element analysis is implemented to figure out the key results in both static and fatigue load analysis as follows: maximum displacements, maximum stresses and minimum factors of safety in static load, and minimum fatigue life cycles. The grid independence test, which is a significant process in numerical method, is carried out. The results show that the maximum displacements of the chassis, floor, body, roof, and support provide 13.3, 1.13, 0.21, 2.0, and 0.06 millimeters, respectively. The maximum stresses are about 155, 138, 35.9, 167, and 58.2 MPa, respectively, which do not exceed yield strength of material. The minimum factors of safety are about 1.6, 1.8, 7.0, 1.5, and 4.3, respectively, which are in accordance with APM standards. The minimum fatigue life cycles are obtained 1.4, 1.25, 4.81, 1.03, and 2.96 million cycles, respectively, which are not less than the infinite life cycle. Thus, it is obvious that all five components of APM structure are adequate strength and safe to function.

1 Introduction

Automated people mover (APM) is a public transit system operated on fixed guideways by driverless. They are normally in the range of 30-100 passengers. APM have a variety designs. They can be rubber tired, steel wheeled, or drawn by cables. APM are smaller, lighter, and more maneuverable than light or heavy rail transit vehicles [1]. These systems are utilized in relatively small areas such as airports, theme parks, etc. These systems have gone through a series of developments and transformations which resulted in the present APM. They use technologies such as monorail, duorail, automated guideway transit [2]. APM systems have proved themselves and become important components in the development of new airside-landside terminal passenger concept. Due to the project in the design and manufacturing of the APM prototype of King Mongkut's University of Technology North Bangkok (KMUTNB), this study focuses on the estimation in strength and safety of a new design of APM structure. Methodology to use is the finite element analysis (FEA) sometimes called finite element method (FEM).

There have been several researchers who performed this method to estimate the results in static and dynamic behavior. Rogerio Lopes et. Al (2021) conducted finite element method to investigate the dynamic behavior of a multi-body passenger bus articulated by a damping joint. They found that the vibrations generated by the

movement of the bus can cause motion amplification. If the frequencies from external factors coincided with natural frequencies, it would endanger to the bus body [3]. Ekkarin Phongphinitana et. al (2023) used finite element analysis to predict the rolling contact fatigue of steels used for APM guide wheel. The result showed that they obtained the optimized models for wheel and rail from FEM calculation [4]. Fang Ren et. Al (2024) developed finite element procedure to simulate wheel-rail cyclic contact and ratcheting by adding the non-linear kinematic hardening steel material model. The result showed that the simulated plastic deformation was found to alter the contact geometry and thus, contact stress affect further accumulation of plastic deformation and subsequent ratcheting strains [5].

The purpose of this study is to estimate the strength and fatigue of KMUTNB APM structure on static and fatigue load. The FEA is conducted for estimating that. For this study, The APM structure will be divided into five major components comprising (i) chassis, (ii) floor, (iii) body, (iv) roof, and (v) support.

2 Methodology

This section presents the finite element analysis procedure to assess the strength and safety of the KMUTNB APM structure when the external forces acting on. For the static load analysis, the term "strength" means the ability to withstand stress

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occurred. The term “safety” means that the strength of APM structure is greater than the maximum stress (factor of safety, F.S.) by 1.5 times according to the APM standards published by the American society of civil engineers [6]. The theory of elasticity of solids is executed in the form of finite element theory to predict the stresses and displacements occurring in the structure. The failure theory uses the distortion energy to assess the factor of safety (F.S.) for static load analysis and uses Soderberg to estimate the factor of safety in fatigue life (n).

2.1 APM structure model and materials

The KMUTNB APM structure is divided into five major components consisting of (i) chassis, (ii) floor, (iii) body, (iv) roof, and (v) support. All components are fabricated by the square pipe made of a SS400 steel. All components will be modelled in 3D parts by means of a computer-aided design (CAD) via SolidWorks software. The chassis assembly has two pieces of a truss which is a square pipe of 75x75x6 mm. There are 14 pieces of rubber placed in the middle to help absorb the shock load. The overall size of chassis assembly is 775x6200x165 mm as presented in Figure1. The mechanical properties of the SS400 steel and rubber are shown in Table1

Table1. Mechanical properties [7]

Properties	steel	Rubber
Density (kg/m ³)	7,850	1,200
Elastic modulus (MPa)	200,000	6.47
Yield stress (MPa)	250	n/a
Poisson ratio	0.3	0.49

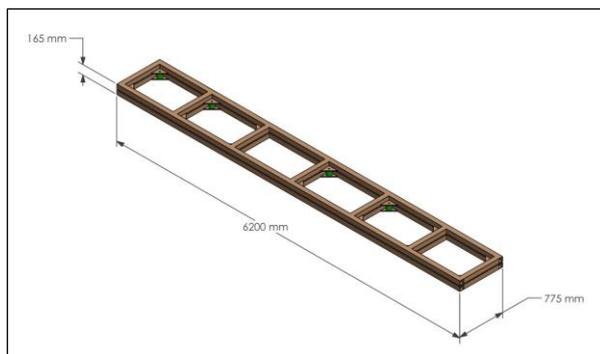


Fig. 1. Chassis

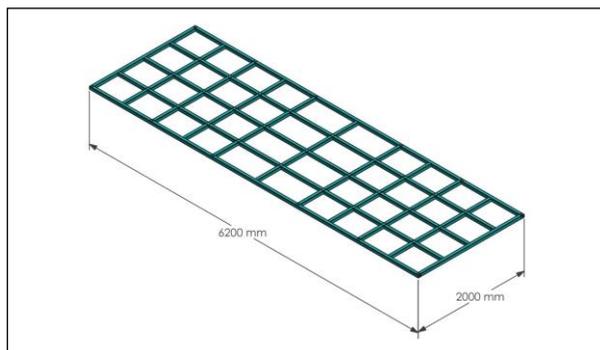


Fig. 2. Floor

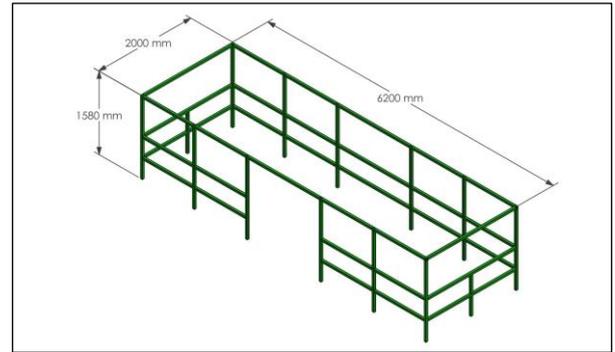


Fig. 3. Body

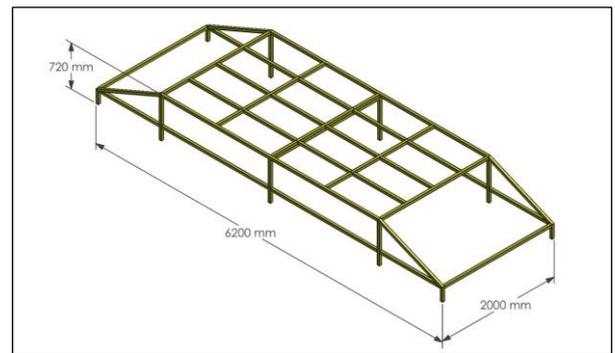


Fig. 4. Roof

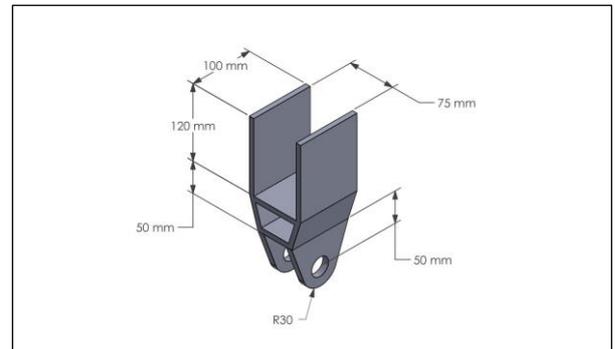


Fig. 5. Support

The floor of the APM is constructed by a square pipe of 50x50x3.2 mm. The overall size is about 2000x6200x50 mm as shown in Figure2. In addition, the body of the APM is also built from a square pipe of 40x40x3.2 mm. The overall size of the APM body is 2000x6200x1580 mm as presented in Figure3. Furthermore, the roof of the APM is fabricated by a square pipe of 40x40x3.2 mm. The overall size is 2000x6200x720 mm as presented in Figure4. Finally, the support is built by SS400 steel plates of 8-mm thickness as illustrated in Figure 5. The support is installed onto the chassis in eight positions to use in fastening the leaf spring and wheel assembly. These five major components (No.1-5) could be assembled according to the exploded view as shown in Figure 6. Then, the complete structure of the KMUTNB APM could be presented in Figure 7.

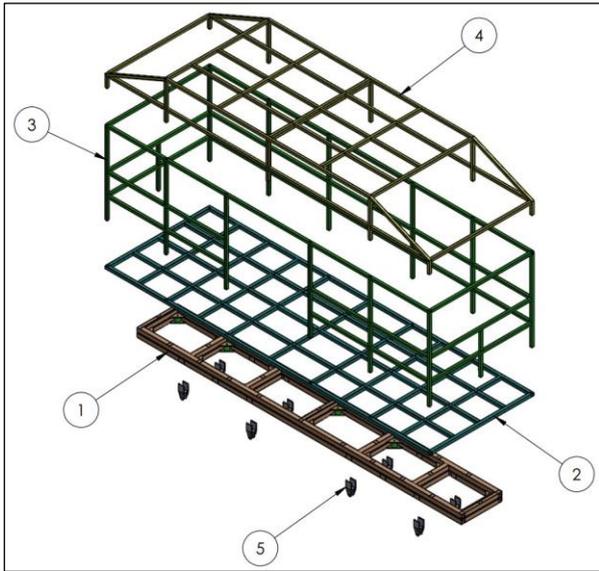


Fig. 6. Exploded view of the APM structure

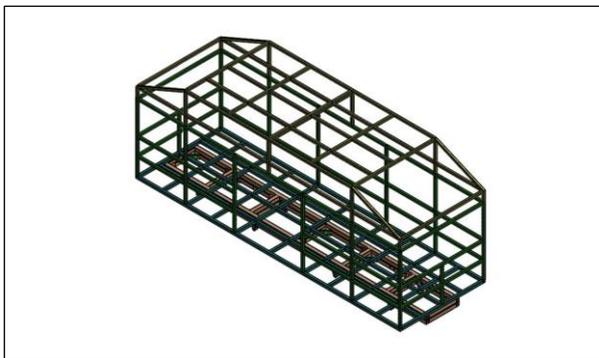


Fig. 7. APM structure assembly

2.2 Theory

2.2.1 Finite Element Analysis

The finite element equation could be derived by various method such as direct method, variational method, and weight residual method. However, the equation from whatever method could be written in the short form of matrix as presented in equation (1).

$$[K]\{\delta\} = \{F\} \quad (1)$$

where $[K]$ is element stiffness matrix, $\{\delta\}$ is vector of nodal displacements, and $\{F\}$ is vector of nodal forces. The strain occurred in material could be calculated according to equation (2).

$$\{\varepsilon\} = [B]\{\delta\} \quad (2)$$

where $[B]$ is derivation of shape function. The stress could be presented in equation (3)

$$\{\sigma\} = [C][B]\{\delta\} \quad (3)$$

where $[C]$ is stiffness material matrix [8]

2.2.2 Distortion energy theory

The maximum distortion energy or von-Mises criterion is a well-known failure theory to predict the failure of the objects that is a kind of ductile materials such as SS400 steel, which is used tremendously for APM structure design in this study. The concept of this theory is assumed that yielding will begin when the shear strain energy component equals to uniaxial yield strength [9] as shown in equation (4).

$$\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] = S_y^2 \quad (4)$$

where

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where $\sigma_1, \sigma_2, \sigma_3$ are principal stresses, σ_v is equivalent von-Mises stress, and S_y is yield stress. The factor of safety (F.S.) is the ratio of yield stress to equivalent von-Mises stress expressing in equation (5).

$$F.S. = S_y / \sigma_v \quad (5)$$

According to APM standards [6], the factor of safety (F.S.) must be greater than 1.5 to be considered safe.

2.2.3 Fatigue failure criteria

This study uses the stress-life method in fatigue analysis that the common failure criteria are such as Gerber, Modified Goodman, ASME-elliptic, and Soderberg as shown in Figure8. Soderberg is used for this study because of a very conservative single check of both fatigue and yielding. The factor of safety in fatigue life (n) of Soderberg is shown in equation (6).

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y} = \frac{1}{n} \quad (6)$$

where σ_a is alternating stress or stress amplitude, σ_m is midrange stress or mean stress, S_e is endurance limit, S_y is yield stress, and n is the factor of safety in the fatigue life.

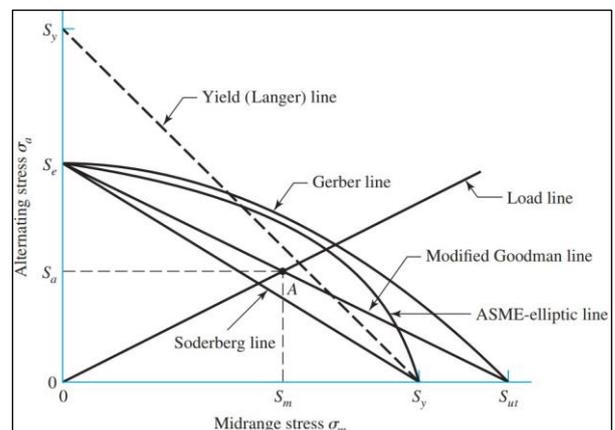


Fig. 8. Various criteria of fatigue failure [10]

2.3 Boundary conditions

The estimating strength and fatigue of APM structure are conducted in component-by-component by FEA simulation as mentioned before. Each component has different boundary conditions (BC) such as the amount of load as well as the number and type of support.

Static load

Each of five major components of the APM structure is subject to the external forces and its own gravity according to Table 2. The external forces and gravity setting could be prescribed by using Ansys mechanical software. The BC setting results for all components are illustrated in Figure 9-13.

Fatigue load

All components would be estimated the fatigue life after the static analysis accomplishes. The constant amplitude load in zero-based type of cyclic load (repeated load) in compression is applied for this study. The simulation of fatigue behavior is proceeded in the aspect of stress life and used Soderberg theory to predict the factor of safety in fatigue life (n).

Table 2. The external forces and gravity acting on each component of the APM structure

No.	Components	Loaded by	Mass (kg)
1	Chassis	- Air condition systems	200
		- Roof	143
		- Body	154.2
		- Floor	231.1
		- Payload	5,000
		- Chassis	243.6
2	Floor	- Air condition systems	200
		- Roof	143
		- Body	154.2
		- Floor	231.1
		- Payload	5,000
3	Body	- Air condition systems	200
		- Roof	143
		- Body	154.2
4	Roof	- Air condition systems	200
		- Roof	143
5	Support	- Total mass of structure per unit support	746.5

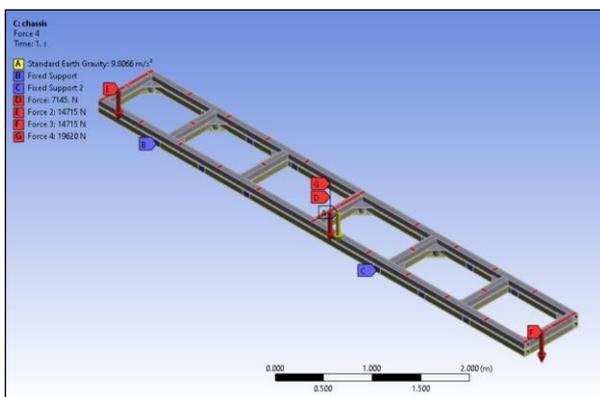


Fig. 9. External forces and gravity on the chassis

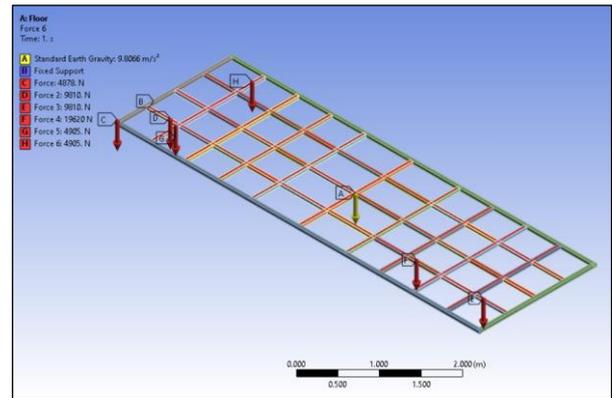


Fig. 10. External forces and gravity on the floor

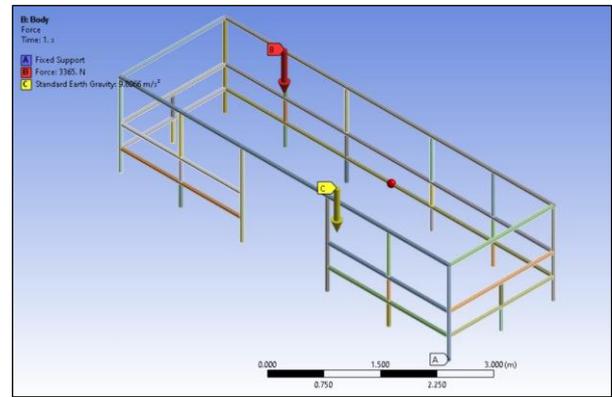


Fig. 11. External forces and gravity on the body

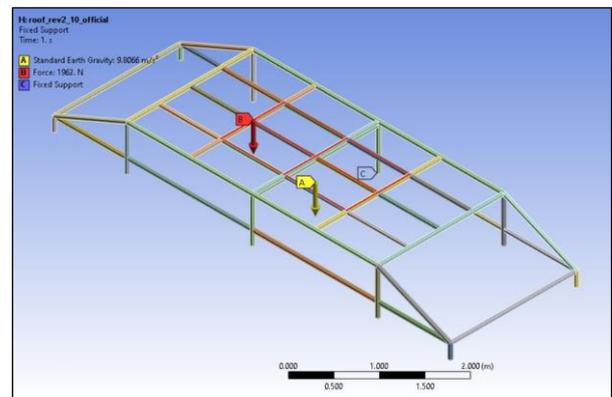


Fig. 12. External forces and gravity on the roof

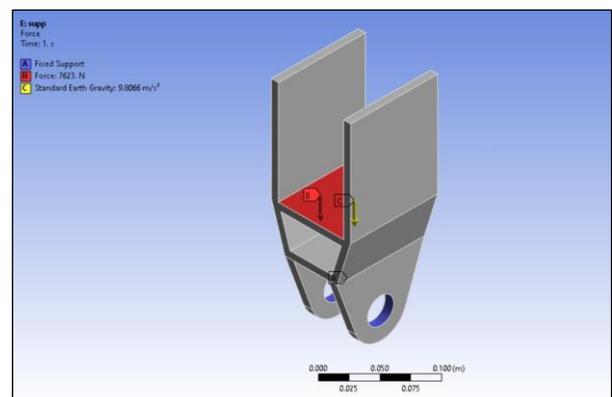


Fig. 13. External forces and gravity on the support

3 Results

The results of this study are accomplished by finite element analysis (FEA) and presented in two sections comprising (i) the results of finite element analysis estimation for the strength and safety of the KMUTNB APM structure and (ii) the results of grid independence test for the finite element analysis simulation. As mentioned in section 2, the term “strength” means the ability to withstand stress occurred. Therefore, the results of stress distribution occurring in the APM structure would be presented to appraise the strength of the structure. Additionally, the term “safety” means that the factor of safety (F.S.) is greater than 1.5. Thus, the results would also show the minimum factors of safety (F.S) occurring. Finally, the factors of safety in fatigue life (n) would be investigated as well.

3.1 Finite element analysis estimation

This study focuses on the key results as follows: (i) maximum displacements, (ii) maximum stresses (von-Mises stresses) and minimum factors of safety in static load (F.S.), and (iv) minimum factors of safety in fatigue life (n) for all components of APM structure. The finite element analysis results are calculated by using Ansys Mechanical software.

For the chassis results (Figure 14-16), the maximum displacement is 13.3 mm. It is quite high because the chassis assembly is designed to be able to move slightly and elastically to help absorb the shock load. The maximum stress is 155 MPa that means the minimum F.S. equals to 1.6 being at the bottom side and near the area for equipping support. The minimum factor of safety in fatigue life (n) is 1.4 (the fatigue life cycle equals to 1.4×10^6 cycles).

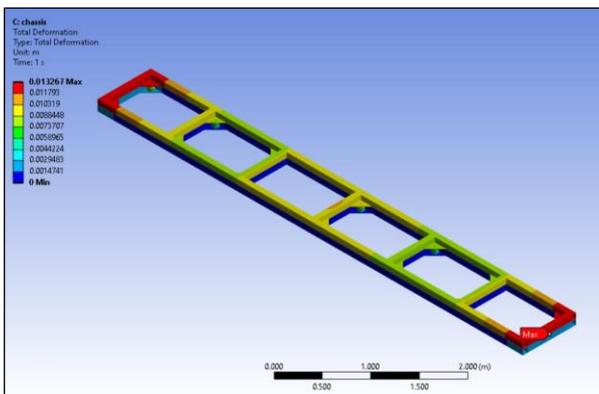


Fig. 14. Displacements in chassis

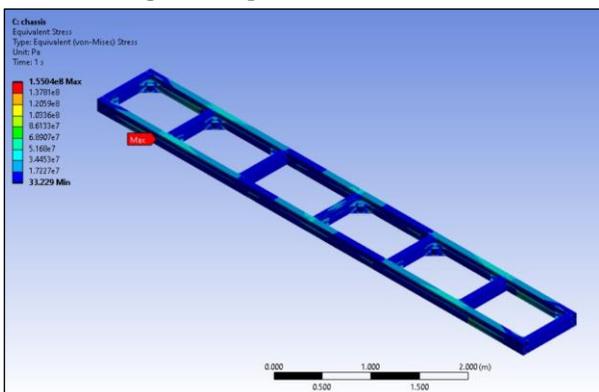


Fig. 15. von-Mises stresses in chassis

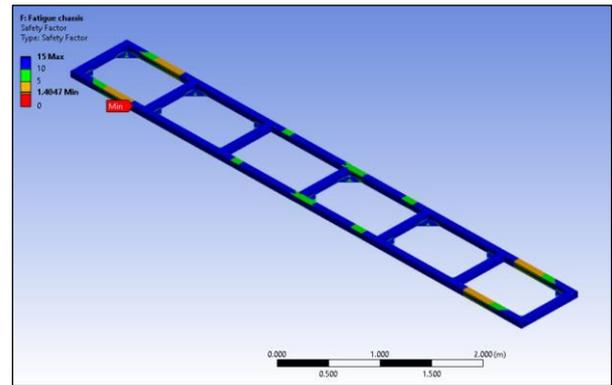


Fig. 16. Factors of safety in fatigue life (n) in chassis

For the floor results (Figure 17-19), the maximum displacement is about 1.13 mm occurring on the left and right side of the floor. The maximum stress is 138 MPa that means the minimum F.S. equals to 1.8 being at the junction with the chassis. The minimum factor of safety in fatigue life (n) is 1.25 (the fatigue life cycle equals to 1.25×10^6 cycles).

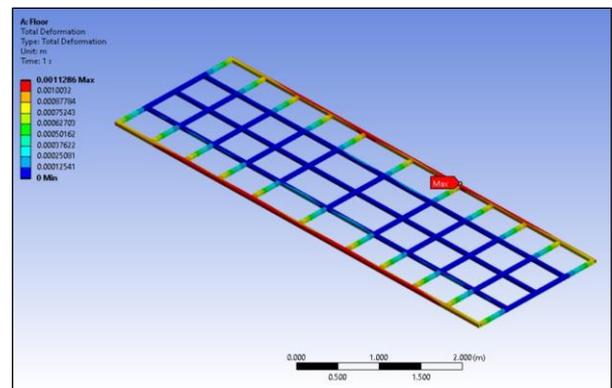


Fig. 17. Displacements in floor

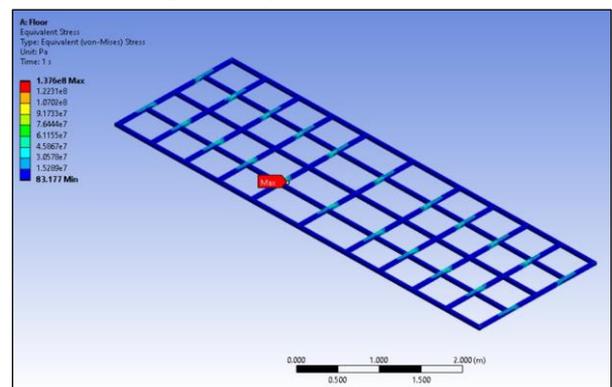


Fig. 18. von-Mises stresses in floor

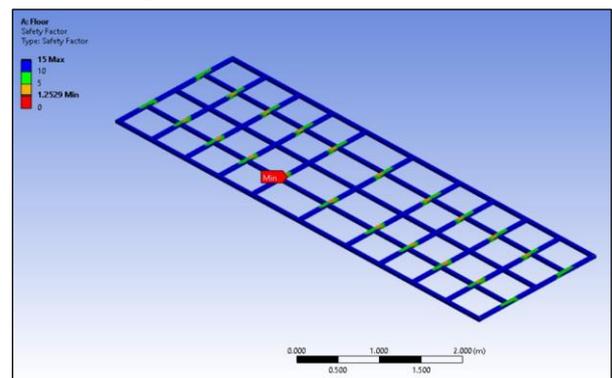


Fig. 19. Factors of safety in fatigue life (n) in floor

For the body results (Figure20-22), the maximum displacement is about 0.21 mm. The maximum stress is 35.9 MPa that means the minimum F.S. is about 7.0 as shown in Figure21. The minimum factor of safety in fatigue life (n) is 4.81 (the fatigue life cycle equals to 4.81×10^6 cycles).

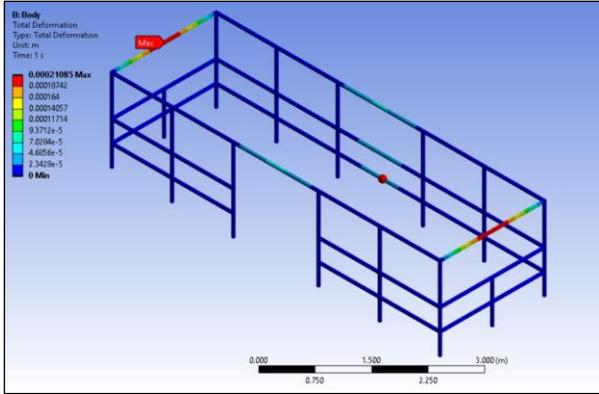


Fig. 20. Displacements in body

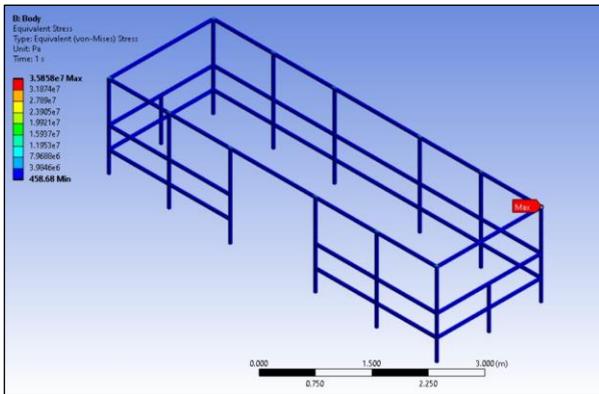


Fig. 21. von-Mises stresses in body

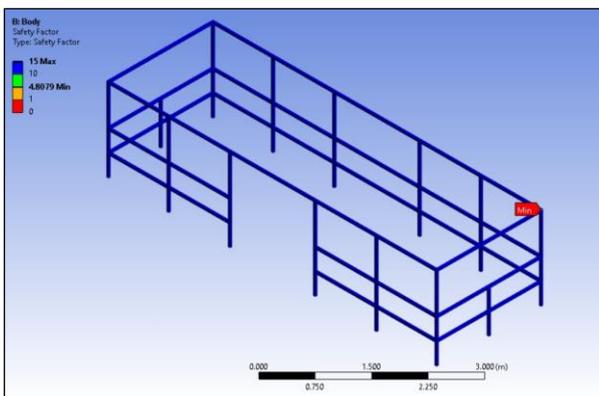


Fig. 22. Factors of safety in fatigue life (n) in body

For the roof results (Figure23-25), the maximum displacement is about 2.0 mm occurring near the middle of the roof. The maximum stress is about 167 MPa that means the minimum F.S. equals to 1.5 appearing on the junction of beam and column of the roof according to Figure24. The minimum factor of safety in fatigue life (n) is 1.03 (the fatigue life cycle equals to 1.03×10^6 cycles).

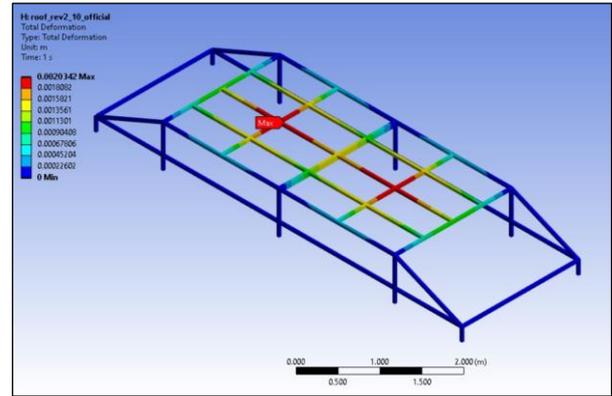


Fig. 23. Displacements in roof

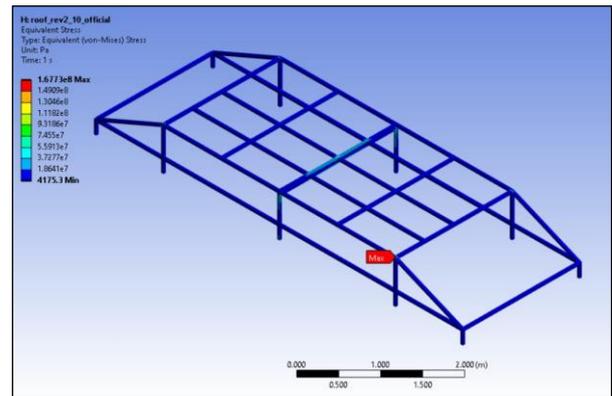


Fig. 24. von-Mises stresses in roof

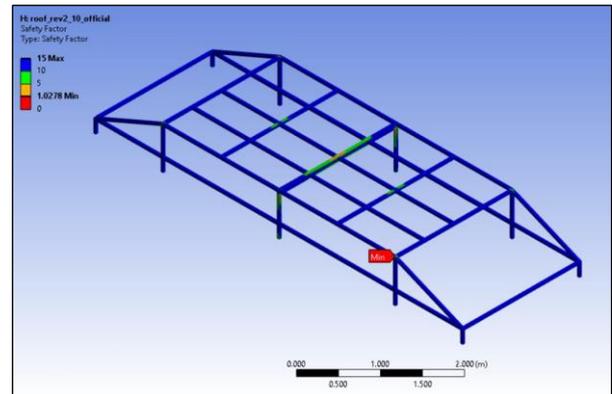


Fig. 25. Factors of safety in fatigue life (n) in roof

For the support results (Figure26-28), the maximum displacement is about 0.06 mm. The maximum stress is about 58.2 MPa, therefore the minimum F.S. equals to 4.3 appearing on the angle of the plate as shown Figure18. The minimum factor of safety in fatigue life (n) is 2.96 (the fatigue life cycle is 2.96×10^6 cycles).

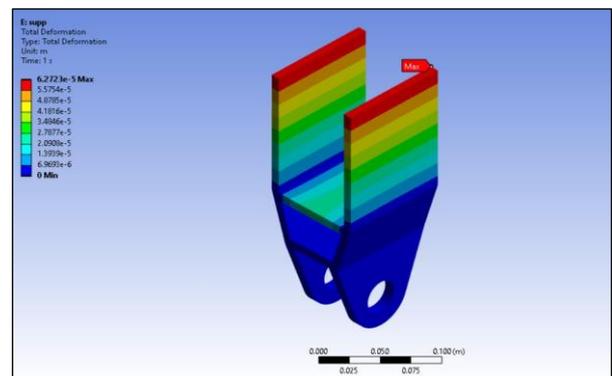


Fig. 26. Displacements in support

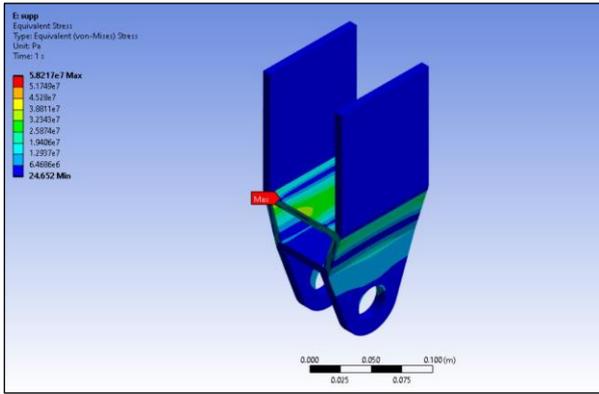


Fig. 27. von-Mises stresses in support

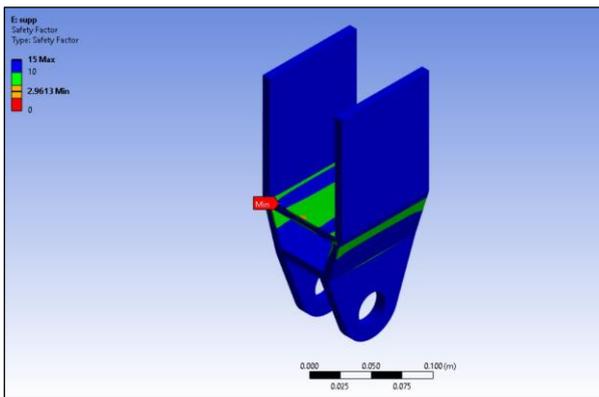


Fig. 28. Factors of safety in fatigue life (n) in support

It is obvious that all components obtain the F.S. in static load analysis higher than 1.5 which is safe enough according to the APM standards [6]. Furthermore, the fatigue life cycles of all components are more than the infinite life cycle (10^6 cycles) as shown in Figure16, 19, 22, 25, and 28. This indicates that the new design of KMUTNB APM structure is adequate strength and safety to function.

3.2 Grid independence test

The finite element analysis is a kind of numerical method to solve any physical problems which always requires the process of grid independence test to ensure that the number of elements to use does not affect the results. Thus, all five components of the APM structure will be tested by creating the different number of grids (elements) in the 3D models and calculate results by using Ansys mechanical software.

For the grid independence test results, it is apparent that the number of elements affects enormously the results of the maximum displacements and maximum stresses of the components especially when the number of elements is relatively small, which means the element size is coarser. On the other hand, the results are steadier when the number of elements increases, which means the element size is smaller as shown in Figure29-38. In conclusion, the chassis, floor, body, roof, and support use approximately the number of elements to solve the system of equations according to finite element method as follows: 6.56, 3.82, 2.69, 2.96, and 4.0 million elements, respectively. This is because it is the first point providing quite stable results of each component.

Maximum displacements

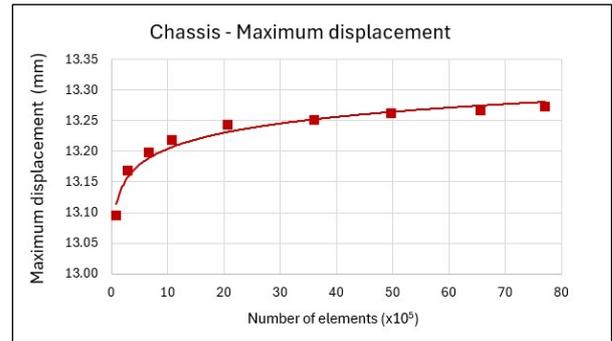


Fig. 29. Maximum displacements of chassis

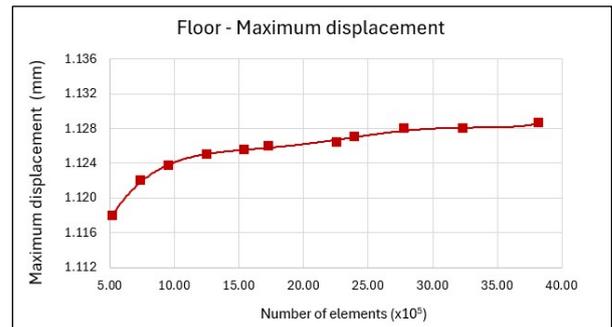


Fig. 30. Maximum displacements of floor

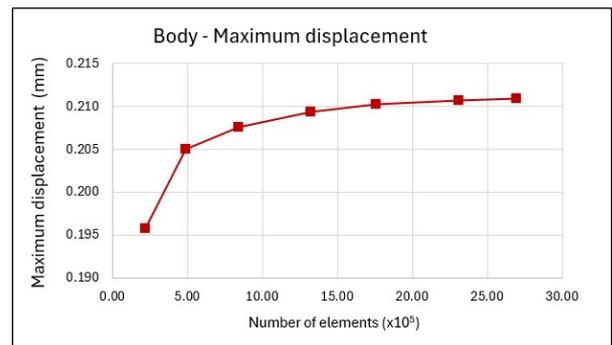


Fig. 31. Maximum displacements of body

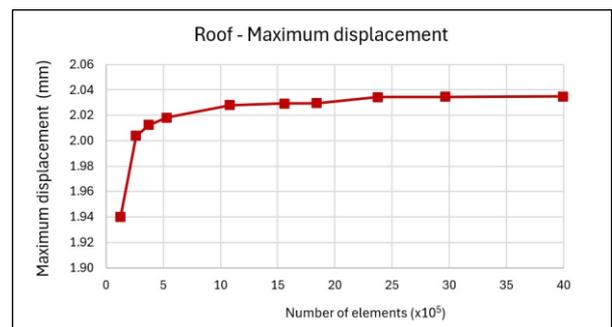


Fig. 32. Maximum displacements of roof

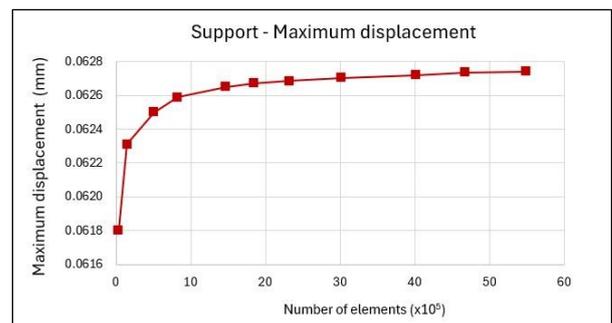


Fig. 33. Maximum displacements of support

Maximum stresses

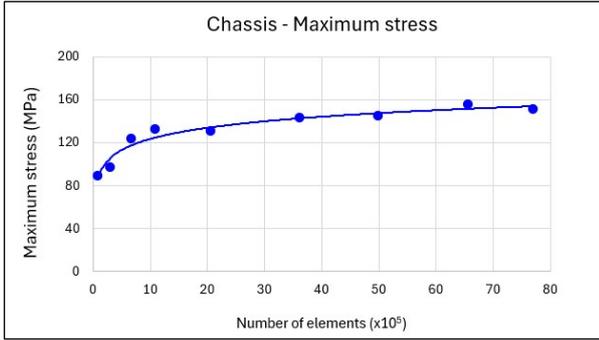


Fig. 34. Maximum stresses of chassis

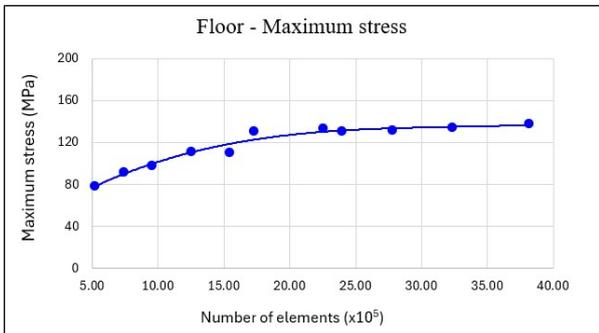


Fig. 35. Maximum stresses of floor

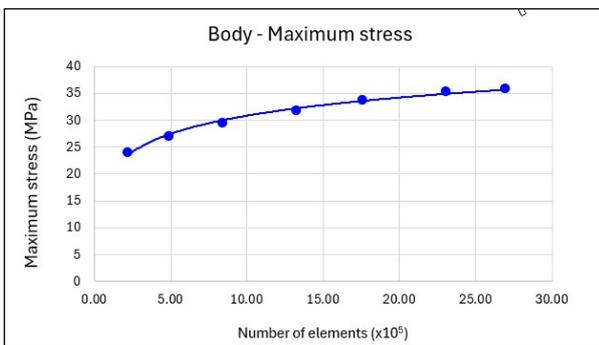


Fig. 36. Maximum stresses of body

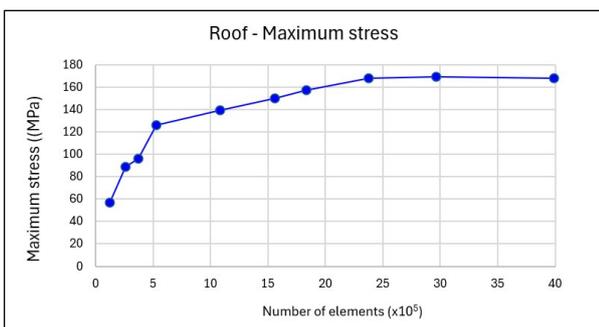


Fig. 37. Maximum stresses of roof

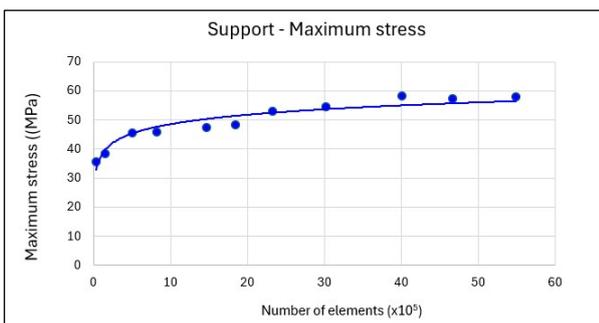


Fig. 38. Maximum stresses of support

4 Conclusions

The two components obtained the lowest maximum stresses are the body and support whereby their factors of safety (F.S) provide 7.0 and 4.3, respectively. On the other hand, the two components appeared the highest maximum stresses are the roof and chassis whereby their factors of safety (F.S.) provide 1.5 and 1.6, respectively. For the fatigue load behavior analysis, it is found that all five components can tolerate more than infinite life cycle (1.0 million cycles). Therefore, the new design of the KMUTNB APM structure is considered adequately strength and safe to function.

Acknowledgement

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