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Modelling and Structural Simulation of Thin-Wall Structure

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Abstract. This paper performs a non-linear analysis of a thin-walled structure. This simulation uses the finite element method to calculate actual conditions in a matrix calculation that is visualized. In the finite element method for numerical solutions of elliptic partial differential equations, the stiffness matrix represents the system of linear equations that must be solved to ensure approximate solutions to the differential equations. A plate will be given different stiffener shapes with the same pressure value. There will be two boundary conditions applied at this thin-walled structure, displacement and fixed support will be applied at the side of the plate. The output obtained from this simulation are von mises stress, total deformation, elastic strain and strain energy. Each model of thin-walled structure will have various values of this output. And the outcome of this research will be helpful as the selected design of the best stiffener able to improve the performance of thin-walled structure for design and manufacture of marine and land transportation.

Introduction

Over time, the development of technology of transportation has increased. This has an impact on people's dependence on the use of the transportation system. People move from one point to another by vehicles for faster mobility. This is clearly seen with the number of vehicle manufactures for land, sea and air are growing rapidly. With this number of vehicles, the probability of accidents and causes of death increases. In view of this, higher demand has been advocated to ensure higher standards of safety in vehicles. The most common cause is a strong impact due to the energy not being properly absorbed by the walls of the vehicle during the collision. This has led to continuous research in designing efficient energy absorbers to dissipate energy during an accident whilst protecting the occupant in the vehicle.

This research focuses on the utilization of thin-walled tubes that are well-known to be effective in absorbing energy. These structures have good toughness and are able to withstand the forces generated during vehicle movement or impact. It is expected that this impact-resistant structure will be able to utilize energy as efficiently as possible by using the minimum mass possible. Thin-walled structures have been shown to have good energy absorption capacity while remaining lightweight. In addition, thin-walled structures using steel tubes have advantages in terms of durability and cost. Over the past decades, substantial efforts have been devoted to investigation into the crushing behaviors of the thin-walled structures through analytical and experimental methods. For example, Alexander first derived an analytical solution to calculate the axial mean crushing force for circular tubes. Wierzbicki and Abramowicz proposed the close form formulas to predict the axial crush response of aluminum thin-walled tubes. The analytical predictions were validated experimentally by Abramowicz and Jones and Langseth and Hopperstad.[1]

Thin-walled structures or tubes have been extensively used as these energy absorbers most commonly exist as either square or circular cross sections Such structures permanently deform to mitigate the crash energy and forces transmitted to the vehicle reducing the decelerations experienced by the occupants. Extensive research has been carried out in improving the energy absorption of such structures due to direct axial impact. However in the context of a vehicle collision, the vehicle's energy absorbers are commonly subjected to both axial and oblique (off-axis) loads.[2]

Many factors, including cost and weight economy, new materials and processes and the growth of powerful methods of analysis have contributed to this growth, and led to the need for a journal which concentrates specifically on structures in which problems arise due to the thinness of the walls. This field includes cold– formed sections, plate and shell structures, reinforced plastics structures and aluminium structures, and is of importance in many branches of engineering.

Research conducted by Xiaohu Dong, Xiaohong Ding, Guojie Li, and Gareth Peter Lewis entitled "Stiffener Layout Optimization of Plate and Shell Structures for Buckling Problem by Adaptive Growth Method" in 2019 revealed problems regarding the vulnerability of thin-walled plate and shell structures to collapse by buckling due to axial pressure or shear load. This research uses the Adaptive Growth Method (AGM). The design results show that AGM is effective for handling buckling problems and AGM is more efficient for achieving a clearer design result problem that includes a compact stiffener distribution compared to the traditional topology design method. To optimize this, a new method will be carried out in this research by conducting a non-linear analysis of the thin-walled structure with the finite element method.[3]

The design calculations required to estimate the strength, stability, and vibration of thin-walled structures are among the most complex problems encountered in structural design. In general, the calculations are limited to solutions of two-dimensional problems in elasticity or plasticity. Computers have been used to develop methods of calculation based on design schemes, which predict with sufficient accuracy the actual performance conditions and characteristics of the structures, for example, the yield of the supporting structure, the presence of stiffening elements, plastic deformation, variable wall thickness, and the formation of cracks.

Based on research of the study by Ali Balaei Sahzabi and Mohsen Esfahanian, it can be concluded that incorporating thin-walled structures in the design of chassis front rails in vehicles can significantly enhance crash safety and improve occupant protection. The optimized design with features such as a bumper beam and notches in the direct beam demonstrated superior performance in terms of energy absorption, plastic deformation, and crash time. This design resulted in reduced injuries to occupants and increased crash duration, making it the most suitable choice for chassis front rails. The study highlights the importance of considering thin-walled structures in vehicle design to enhance crashworthiness and ensure the safety of vehicle occupants.[4]

Thin-Walled Structure

Definition. Thin-walled structures are generally made of plates with thick materials and small walls. This structure is commonly found at ship hulls which are made up of plate, stiffener, girder and panel structures. The next research in the design of efficient energy absorbers is aimed at absorbing energy during collisions.Commonly, traditional circular and square tubes and conventional honeycomb are heavily utilized as energy absorbers due to their many advantages, such as simple structural configuration, ease of processing and low cost.[5] Internal stresses on the thin-walled structure can cause the structure to deform and displacement. Thin-walled can also perform an elastic buckling analysis of thin-walled structures subjected to longitudinal stress.

The structure being analyzed may be a folded plate system, a stiffened plate or a thin-walled structural member with uniform thickness in the longitudinal direction and simply supported at its ends. The longitudinal edges may be simply supported, clamped or free along the full length of the plate system. The analysis can be done for a number of different buckle half-wavelengths of the structure and the load factor and buckled shape are output for each length. The types of buckling modes calculated include local, distortional and flexural-torsional buckling.

Collision is classified as an accidental load and impact which can occur in various scenarios that lead to remarkable damage. Impact can be described as an applied high-magnitude load in a short-time period. Involved objects that undergo this load sus-ceptible to experiencing failure as most instruments are designed to withstand gradual energy and load. This statement explicitly clarify the negative effect of impact phenomenon which closely related with failures and casualties.[6]

In marine and ocean structures, this phenomenon is observed to evaluate safety aspects. Nonlinear behavior is expected during its occurrence, for example in ship collision.[7] The design of construction, structure and any arrangement of materials can experience failure when subjected to various loads.[8] The external dynamics of ship collisions have the role as the action in the collision process. When contact between two vessels occurs, dynamic stresses will be generated in the deformable structure because different parameters are applied in each scenario.[9] According to Newton's Third Law about force, for every action, there is an equal and opposite reaction. The statement means that in every interaction, there is a pair of forces acting on the two interacting objects. The size of the force on the first object equals the size of the force on the second object. When the external dynamic causes the action in the collision process, the reaction as the result of the action on a ships structure will be called the internal mechanics of ship collision.[10]

Many factors, including cost and weight economy, new materials and processes and the growth of powerful methods of analysis have contributed to this growth, and led to the need for a journal which concentrates specifically on structures in which problems arise due to the thinness of the walls. This field includes cold– formed sections, plate and shell structures, reinforced plastics structures and aluminium structures, and is of importance in many branches of engineering.[11]

Application on Land and Marine Based Transportation. Three dimensional structural components in which one dimension is small compared to the other two; they include shells, domes, arches, articulated plates, and membrane-type structures. Thin-walled structures have a high load-carrying capacity, despite their small thickness. They are widely used in the construction industry because of their light weight and economy, particularly for long-span floors in industrial and public buildings and for storage structures for liquids and bulk materials, such as tanks, hoppers, silos, and coal houses. Thin-walled structures are especially suitable for use in constructing exhibition pavilions, concert halls, and sports arenas because the variety of available shapes permits great architectural expression, the covering of wide areas, and flexibility in the choice of construction materials, including steel, aluminum, reinforced concrete, and laminated plastic.[12]

Thin-walled structures comprise an important and growing proportion of engineering construction with areas of application becoming increasingly diverse, ranging from aircraft, bridges, ships and oil rigs to storage vessels, industrial buildings and warehouses.[13]

A method for structural analysis under ship collision was introduced by Paik and Seo.[4] This method was considered as practical technique development for finite element modelling in observing collision and grounding phenomena. The formulation on ship collision was expanded by Liu and Amdahl.[14] Advance developments of impact engineering, especially in ship collision are not independent from the improvement of computational instrument which is considered as good calculation method in estimating structural behavior and material response under various forms of load.[7]

Structural Responses Subjected Applied Loadings

Strain Energy. Represents the internal energy stored within a material when subjected to loads within its elastic limit. It is also referred to as the work done by a material under load and is commonly known as 'resilience.' The unit of measurement for strain energy is typically expressed in Newton-meters (N-m), Newton-millimeters (N-mm), kilonewton-meters (KN-m), or kilonewton-millimeters (KN-mm).

For strain energy to exhibit its full potential, it is imperative that the material deforms only within its elastic limit. Additionally, it is important to note that the magnitude of strain energy is directly influenced by the applied load.

The Strain Energy Principle is particularly evident in springs, where the material's ability to store and release energy becomes apparent. Notably, when the applied load is removed, the material will return to its original shape, underscoring its resilience.

Loads imposed upon a material can vary in nature and may include gradually applied loads, suddenly applied loads, or impact loads resulting from objects falling from a height.

Resilience, defined as the energy stored within the elastic limit of a material, is denoted as 'u.'

$$(u) = \frac{\sigma^2}{2E} \cdot v \tag{1}$$

σ =Stress in the material ($\frac{N}{mm^2}$)
E =Young's modulus of material ($\frac{N}{mm^2}$)
v =Volume of the material (mm^3)

Equivalent Elastic Strain. Is a concept used in materials science and mechanics to quantify the amount of strain a material undergoes under an applied load. It is a scalar quantity that represents the total amount of elastic strain energy stored in the material.

Equivalent elastic strain is calculated by taking the square root of the sum of the squares of the normal and shear strains. Mathematically, it is expressed as:

$$\varepsilon eq = \sqrt{(\varepsilon n^2 + 2\varepsilon n \varepsilon s + \varepsilon s^2} \tag{2}$$

where εn is the normal or axial strain, εs is the shear strain, and εeq is the equivalent elastic strain.

The concept of equivalent elastic strain is useful in analyzing the behavior of materials under complex stress states, where the normal and shear strains may be interrelated. By combining the normal and shear strains into a single scalar quantity, the equivalent elastic strain provides a simplified measure of the total deformation energy stored in the material.

Equivalent elastic strain is also used to determine the yield strength and ultimate strength of materials. The yield strength is the stress at which the material begins to undergo plastic deformation, while the ultimate strength is the maximum stress the material can withstand before failure. By analyzing the equivalent elastic strain at different stress levels, engineers can predict the yield and ultimate strength of a material and design structures that can withstand expected loads.

Von-Mises Stress. Is a value used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal to or greater than the yield limit of the same material under simple tension then the material will yield.

Fig. 1 illustrate the curve obtained when studying the strain response of the uniaxial tension of a mild steel beam. These will help us understand why von Mises is important. The description of each emphasized point is as with full stop:

- Elastic Limit: The elastic limit defines the region where energy is not lost during the process of stressing and straining. That is, the processes that do not exceed the elastic limit are reversible. This limit is also called yield stress. Above that limit, the deformations stop being elastic and start being plastic, and the deformation includes an irreversible part. The stress value of the elastic limit is used here as Sy.
- Upper yield and lower yield: When mild steel is in the plastic range and reaches a critical point — called the upper yield limit — it will drop quickly to the lower yield limit, from which deformation happens at constant stress until it starts resisting deformation again.
- Rupture stress: Rupture, or fracture, is the separation of an object caused by stress. Therefore, at this point, a fracture of the body is expected. Materials such as mild steel — which have the property of fracturing only after large plastic deformations — are called ductile. The fracture illustrated here is called a ductile fracture. You can recognize a ductile fracture when the diagram has a curve like the one shown below. This means that as the material gets thinner, more pressure is applied until it suddenly breaks at the rupture stress point.

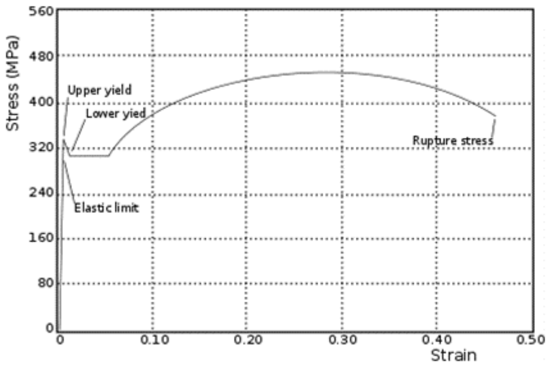

Fig. 1. Stress-strain diagram of mild steel showing critical stages when under uniaxial tension [16].

This diagram is commonly approximated for many materials, as shown in Fig. 2.

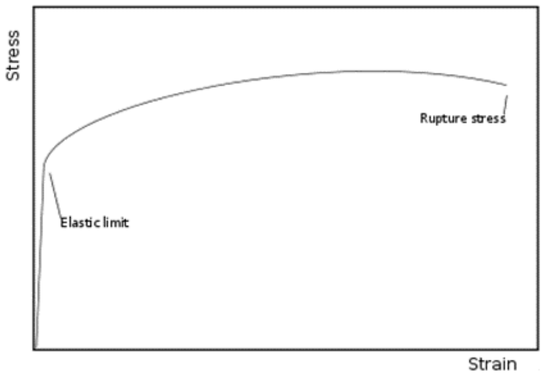

Fig. 2. Common approximation for the stress-strain plot generalized for all the materials when under unaxial tension [16].

The von Mises stress is a criterion for yielding widely used for metals and other ductile materials. It states that a body will yield if the stress components acting on it are greater than this threshold.

$$\frac{1}{6}[(T_{11}-T_{22})^2+(T_{22}-T_{33})^2+(T_{33}-T_{11})^2+6(T_{12}^2+T_{23}^2+T_{13}^2)]=K^2 \tag{3}$$

The constant k is defined through experiment, and τ is the stress tensor. Common experiments for defining k are made from uniaxial stress, where the above expression reduces to:

$$\frac{T_y^2}{3}=K^2 \tag{4}$$

If $T_y$reaches the simple tension elastic limit, S_y, then the above expression becomes:

$$\frac{S_y^2}{3}=K^2 \tag{5}$$

Which can be substituted into the first expression:

$$\frac{1}{6}[(T_{11}-T_{22})^2+(T_{22}-T_{33})^2+(T_{33}-T_{11})^2+6(T_{12}^2+T_{23}^2+T_{13}^2)]=\frac{S_y^2}{3} \tag{6}$$

Or, finally

$$\sqrt{\frac{(T_{11}-T_{22})^2+(T_{22}-T_{33})^2+(T_{33}-T_{11})^2+6(T_{12}^2+T_{23}^2+T_{13}^2)}{2}}=S_y \tag{7}$$

The von mises stress, T_v, is defined as:

$$T_v^2 = 3K^2 \tag{8}$$

Therefore, the von Mises yield criterion is also commonly rewritten as:

$$T_v \geq S_y \tag{9}$$

That is, if the von Mises stress is greater than the simple tension yield limit stress, then the material is expected to yield

Total Deformation. typically refers to the overall change in shape or displacement experienced by an object or material when subjected to an external force or load. It is commonly used in the field of mechanics, materials science, and engineering to quantify how much a material or structure has deformed under certain conditions, as shown in Fig. 3.

Total deformation can be broken down into two main components:

1. Elastic Deformation: This is the reversible deformation that occurs when a material is subjected to a load but returns to its original shape and size once the load is removed. It is often described by Hooke's Law, which states that the deformation is directly proportional to the applied force, assuming the material remains within its elastic limit.
   The elastic deformation can be calculated using Hooke's Law, which relates stress (σ) and elastic modulus (E) to strain (ε). The formula is as follows:

$$\Delta Le = (\sigma / E) * L \tag{10}$$

   ΔLe is the elastic deformation, σ is the applied stress, E is the elastic modulus (also known as Young's modulus), L is the original length of the material.

2. Plastic Deformation: This is the permanent, irreversible deformation that occurs in a material beyond its elastic limit. When a material is subjected to a load greater than its elastic limit, it will undergo plastic deformation, resulting in a change in shape that does not fully recover when the load is removed.
   To find the total deformation, you would calculate the elastic deformation using Hooke's Law and add it to the measured or known plastic deformation:

Total Deformation(ΔL) = ΔLe (from Hooke's Law) + ΔLp (measured or known plastic deformation) (11)

The total deformation of an object is the sum of both elastic and plastic deformations. It is typically measured in units such as millimeters, inches, or strain (deformation per unit length).

Total deformation is a critical factor to consider in engineering and design, as it helps engineers and scientists understand how materials and structures respond to loads and how they may change over time due to repeated loading or environmental factors. This understanding is essential for ensuring the safety and reliability of various engineering applications, from building design to the development of materials for various industries.

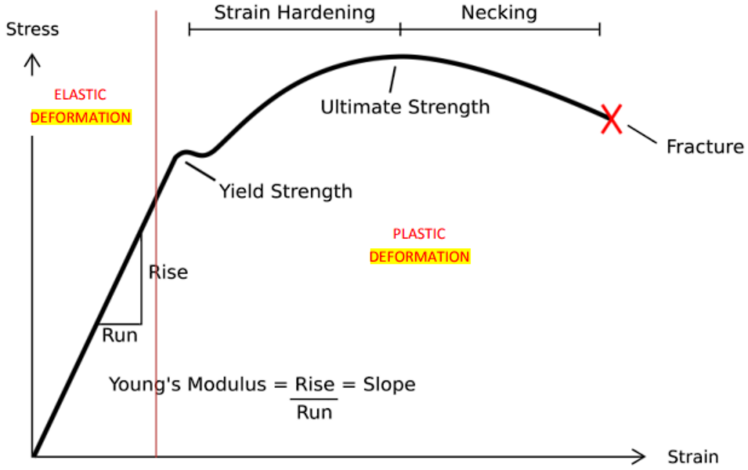

Fig. 3. Deformation Graph [6].

Research Methodology

The FEM provides a mathematical model for calculating the real system, easier and cheaper to change than a prototype. However, it remains as an approximate calculating method due to the basic assumptions of the method. Therefore, prototypes are still necessary, but in lower quantity, since the first one can be well approximated to the optimum design.

The general idea of the finite element method is to divide a continuum in a set of small elements interconnected by a range of points called nodes, as ini Fig. 4 shows the meshing process on an object.

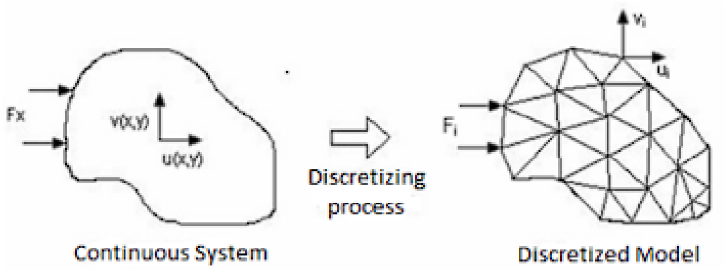

Fig. 4. Meshing Process [6].

Pre-processing, running and post processing stages in FEA simulation are the steps of the whole process. At this stage, several processes will be carried out, including geometry modelling, meshing, boundary conditions and loads, running and post-processing.

In this research, geometry modeling will be conducted with various stiffener positions, followed by the meshing process. Boundary conditions and loads will then be applied in the subsequent step. The load will be applied to the surface plate, while a fixed support will be applied to the side of the plate. After setting the boundary conditions and load, the analysis will proceed with the solving process. The outputs of this research will include strain energy, elastic strain, von-mises stress, and total deformation. These values will be plotted on graphs to compare each model.

Geometry Modeling

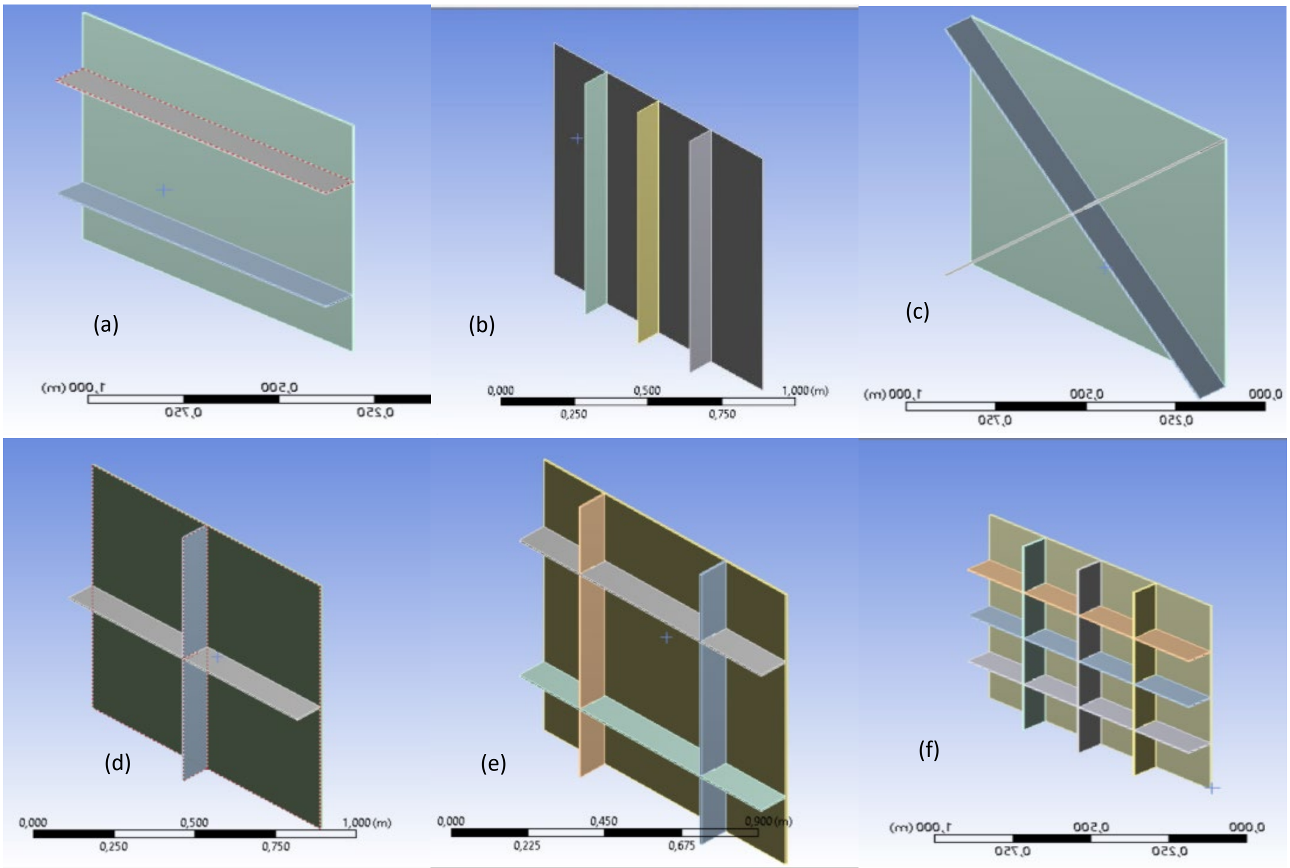

Fig. 5. Geometry modelling of (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

Table 1. Geometry model configuration.

No	Name	Number of Stiffener	Configuration
1	Model 1	2	Parallel
2	Model 2	3	Parallel
3	Model 3	2	Diagonal cross
4	Model 4	2	Cross
5	Model 5	4	Cross
6	Model 6	6	Cross

All geometry model are proceed to meshing process with 10 mm of meshing size

Material Definition

This thin-walled structure, made up from plate and stiffener. The plate is made from Structural Steel with 1000 mm x 1000 mm of area size and has 6 mm of thickness. Same as plate, the stiffener also made from Structural Steel with length adjust the plate and has 6 mm of thickness.

Table 2. Material properties.

Property	Value	Unit
Material Field Variables	Table	
Density	7,85E-06	Kg mm^-3
Isotropic Secant Coefficient of Thermal Expansion		
Isotropic Elasticity		
Derive from	Shear Modulus and Young's Modulus	
Young's Modulus	2,1E+05	MPa
Poisson's Ratio	0,36364	
Bulk Modulus	2,5567E+11	Pa
Shear Modulus	77000	MPa
Alternating Stress Mean Stress	Tabular	
Strain-Life Parameters		
Tensile Yield Strength	245	MPa
Compressive Yield Strength	245	MPa
Tensile Ultimate Strength	400	MPa
Compressive Ultimate Strength	0	Pa

Boundary Conditions and Load

Fixed Support. Fixed support applied at the side of the plate.

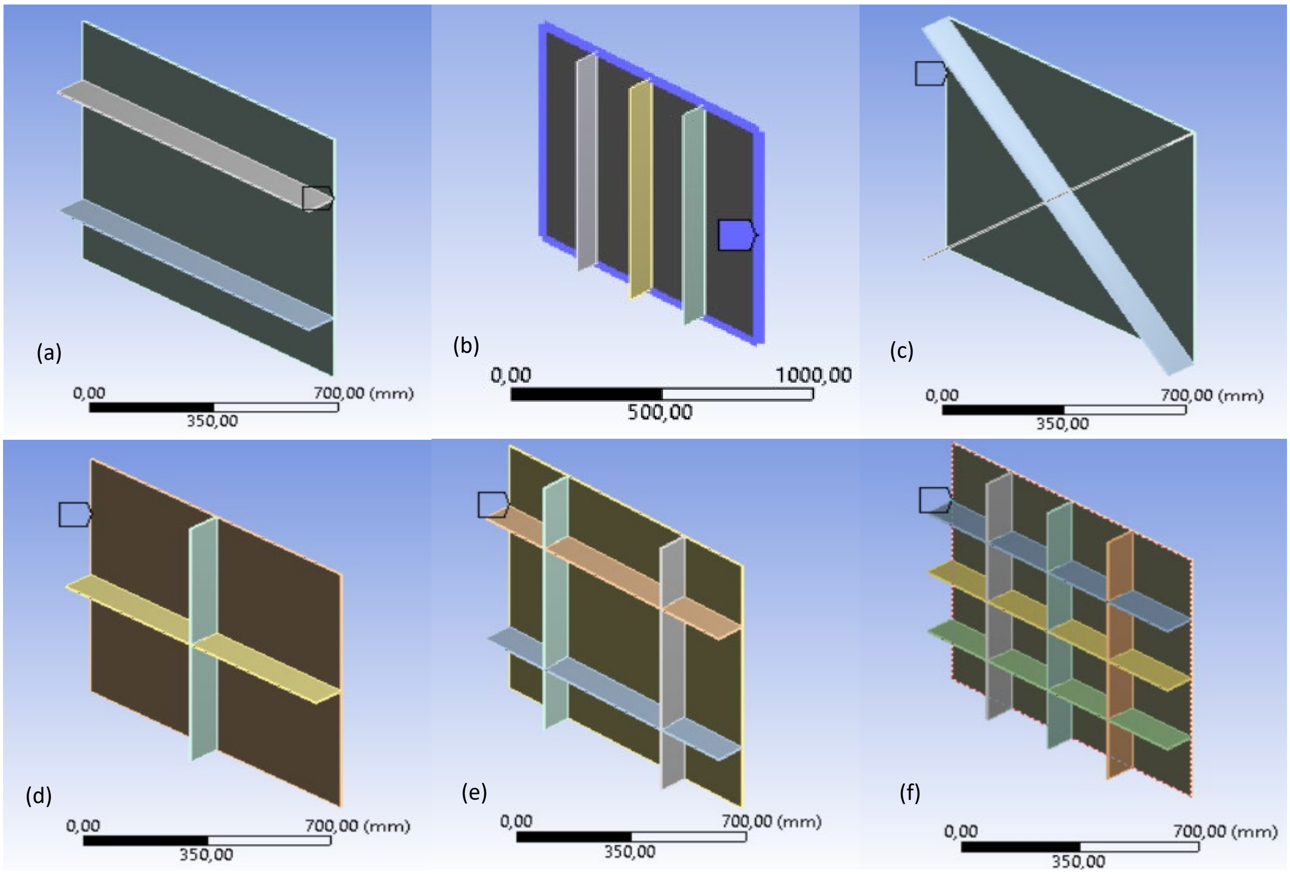

Fig. 6. Fixed support applied on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

Displacement 1. Applied at the corner of the plate

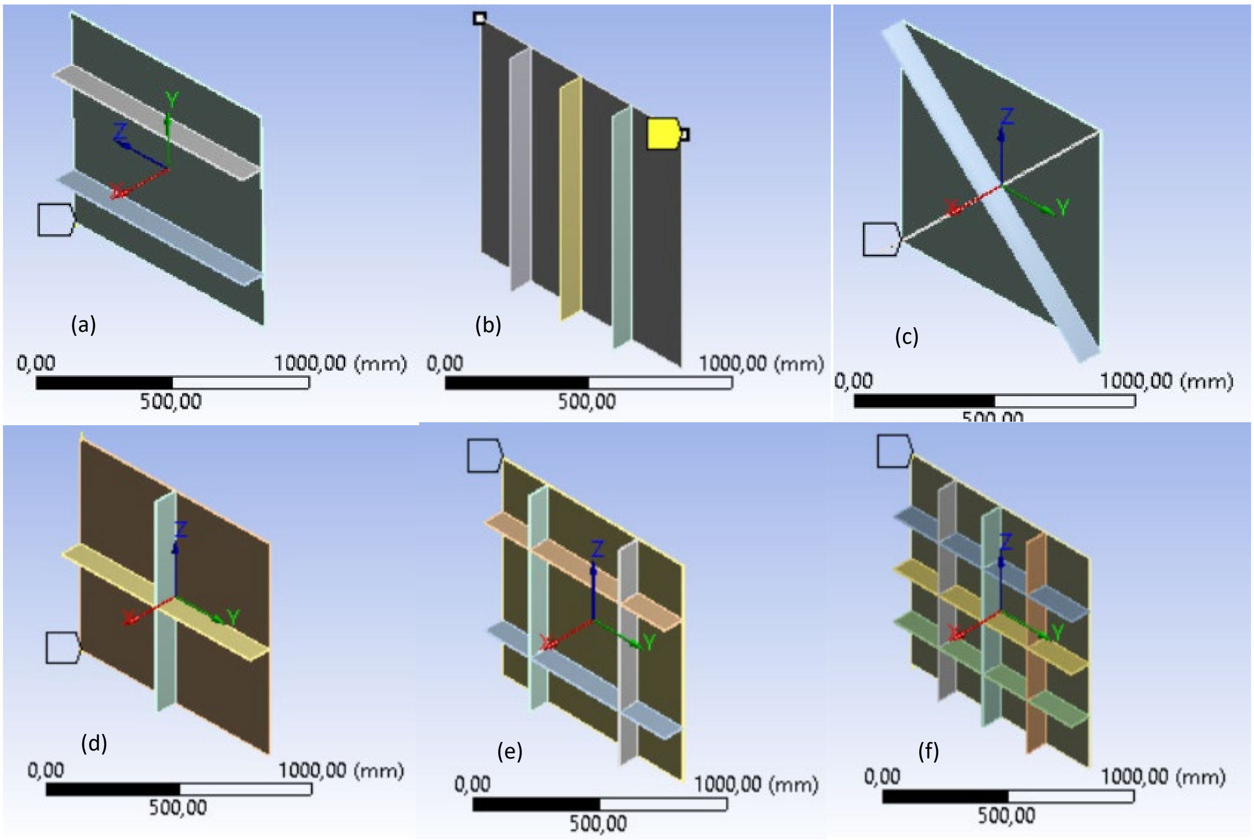

Fig. 7. First displacement applied on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

Displacement 2. Applied at the corner of the plate

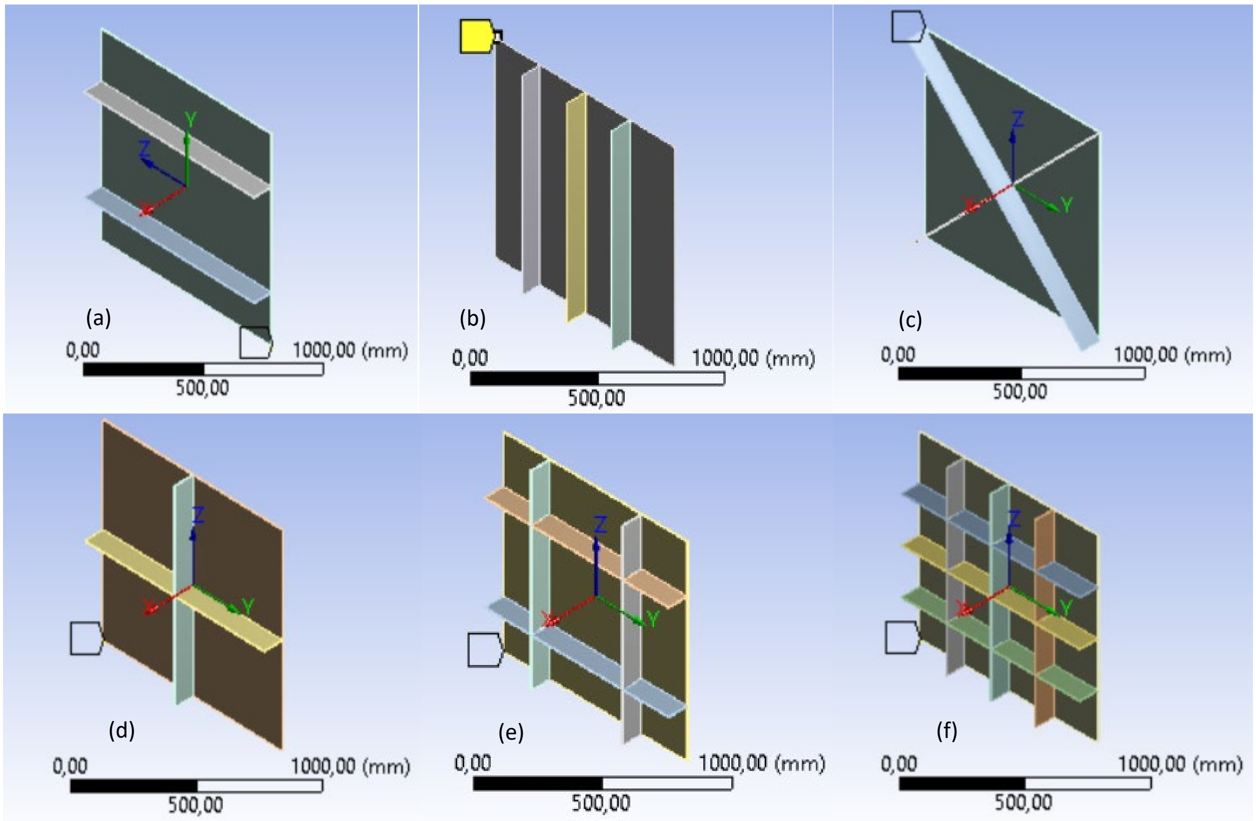

Fig. 8. Seccond displacement applied on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

Preassure Load. 20000 Pascal of pressure load applied at the surface of plate

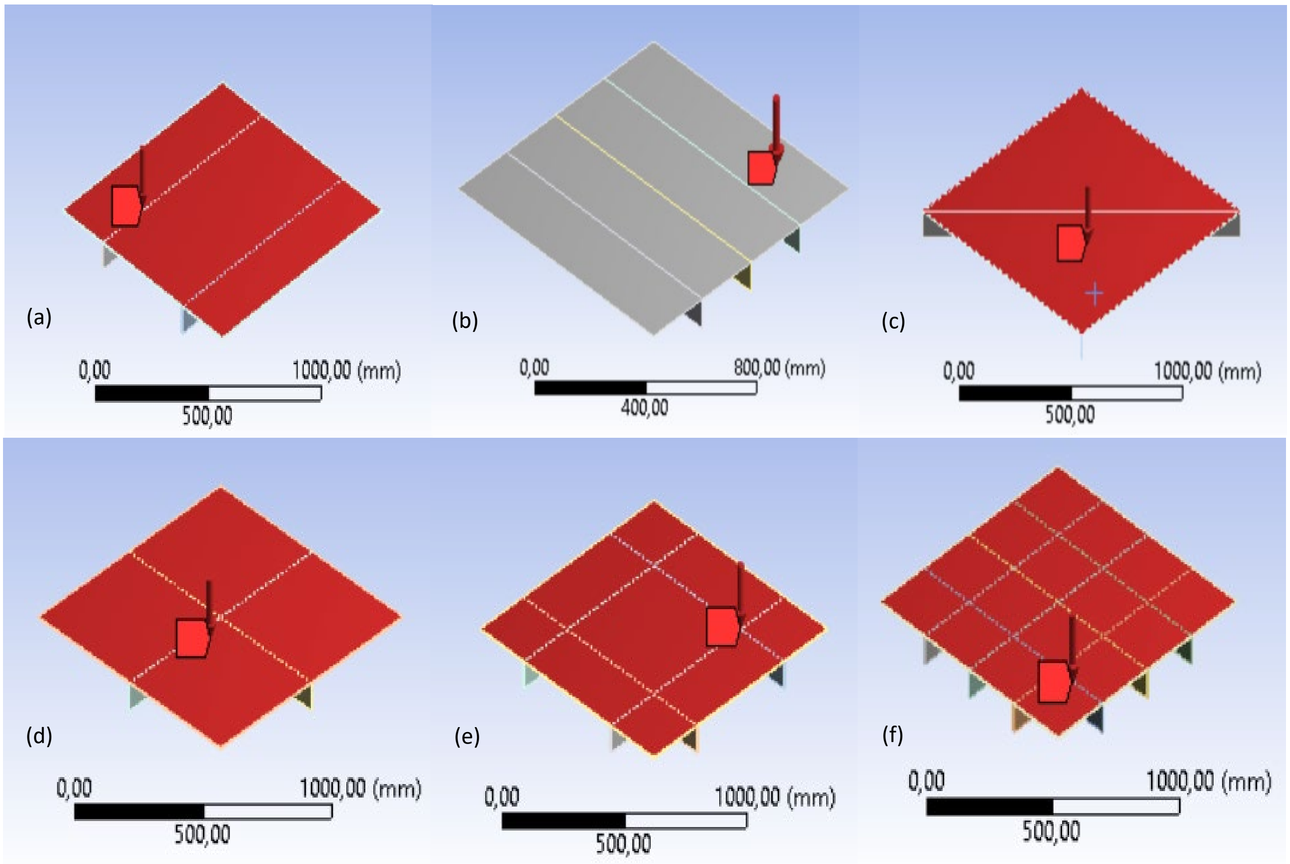

Fig. 9. 10000 Pa of pressure apllied on top side of (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6 (note: the difference in arrow placement is negligible since it represent uniform force across the surface).

Results and Discussion

The main purpose of this research is to understand and analyze stress, strain, deformation and strain energy in various stiffener models which are connected to plates that form a thin-walled structure. From these various models it will have different values from different output that can conclude which stiffener has best performance to withstand load. Boundary condition and load applied at all surfaces have the same pressure value and same boundary location. This is following results of this thin-walled structure:

Strain Energy

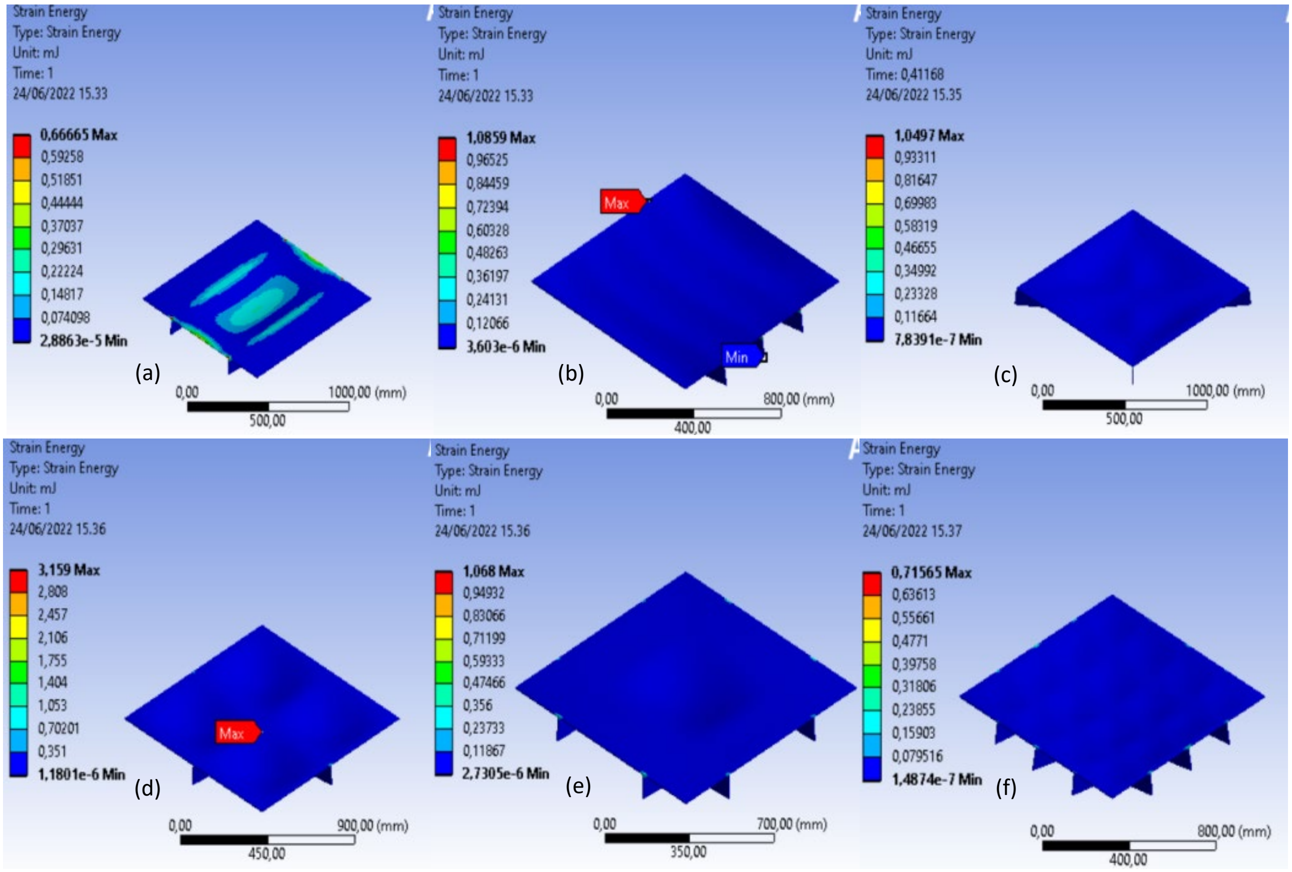

Fig. 10. Strain Energy of (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

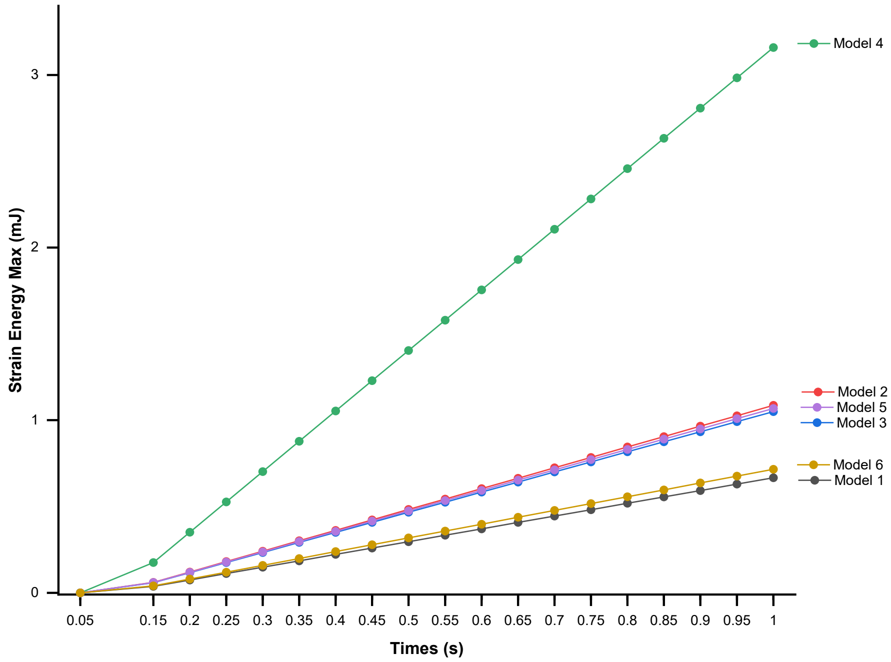

Fig. 11. Comparison of strain energy between all stiffener.

This graphic shows model 1 having better performance than 5 other models because of the strain energy occurs from simulation is at 0.6665 mJ followed by model 6 with 0.71565 mJ. This indicates that Model 1 has lower elasticity compared to the other models at a given level of applied load. In many cases, lower elasticity suggests that the material or structure is more resistant to deformation or failure when subjected to a load, which is often considered an indicator of better performance.

Equivalent Elastic Strain

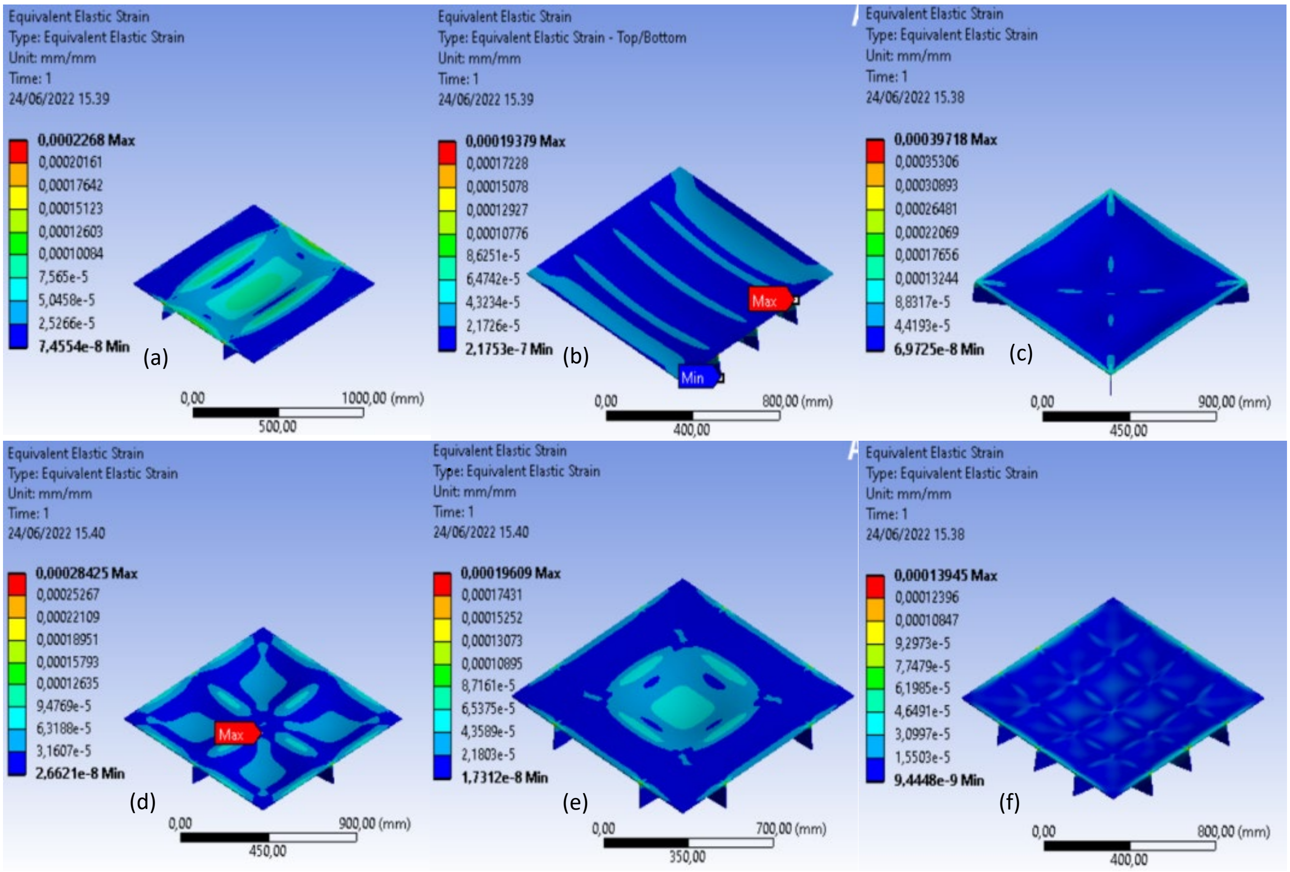

Fig. 12. Equivalent elastic strain on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

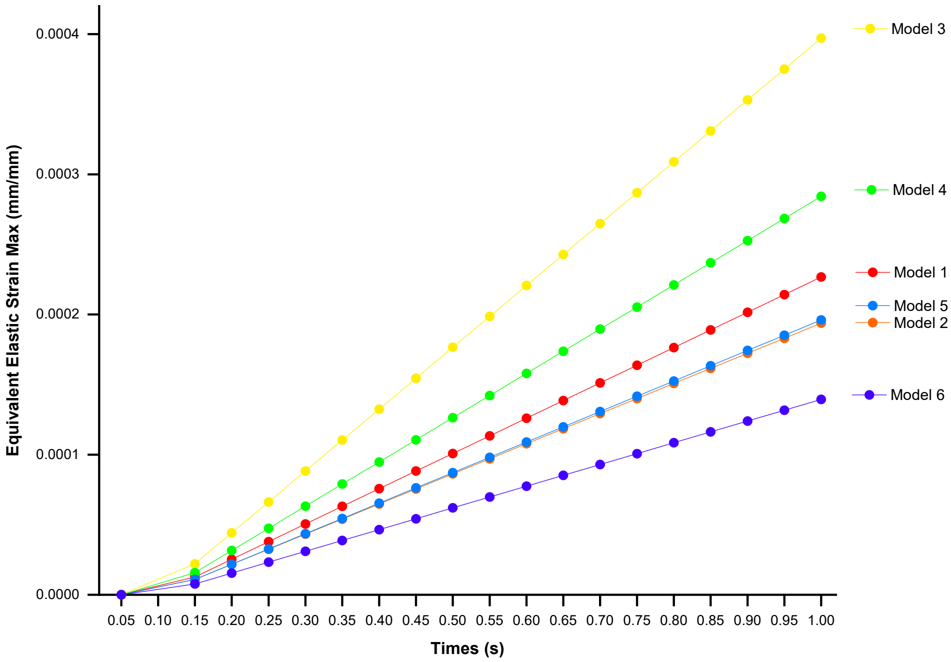

Fig. 13. Comparison of equivalent elastic strain max between all model.

This graphic also shows model 6 having better performance than 5 other models because of the lower equivalent elastic strain maximum that occurs from simulation. Lower equivalent elastic strain means the shape will have less deformation and higher energy storage capacity which on thin-walled application where the dimensional stability and stiffness is regarded as an important aspect, the model 6 performance will be more desirable. For thin-walled structures, minimizing elastic strain is a key objective for achieving optimal performance. Lower strain translates directly to superior shape retention, preventing unwanted deformations that could compromise functionality. This enhanced rigidity allows the structure to withstand greater loads without excessive deflection, maximizing its load-carrying capacity. Furthermore, in weight-sensitive applications like aerospace engineering, minimizing strain allows for thinner walls without sacrificing performance, leading to lighter and more efficient designs.

Von-Mises Stress

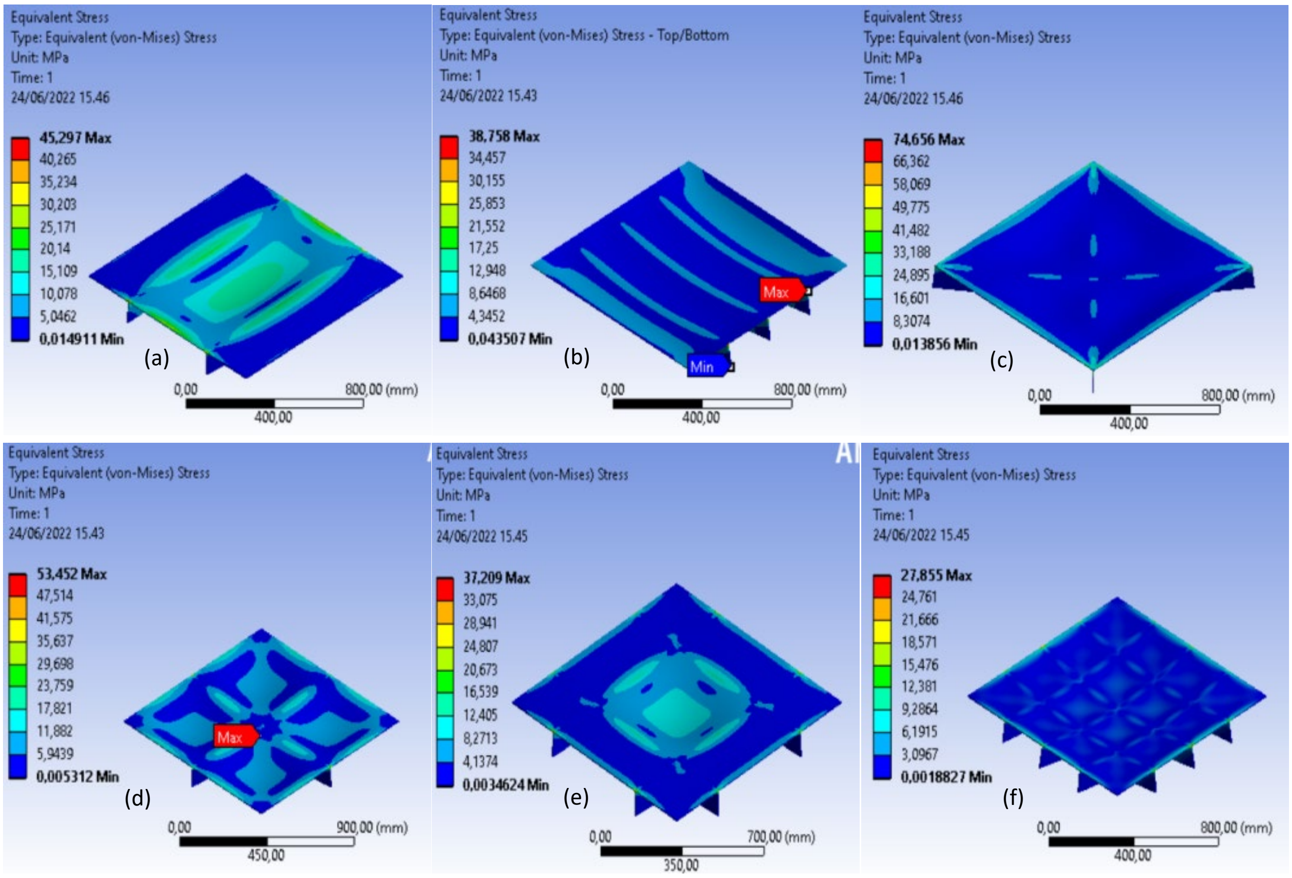

Fig. 14. Von Misses Stress on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

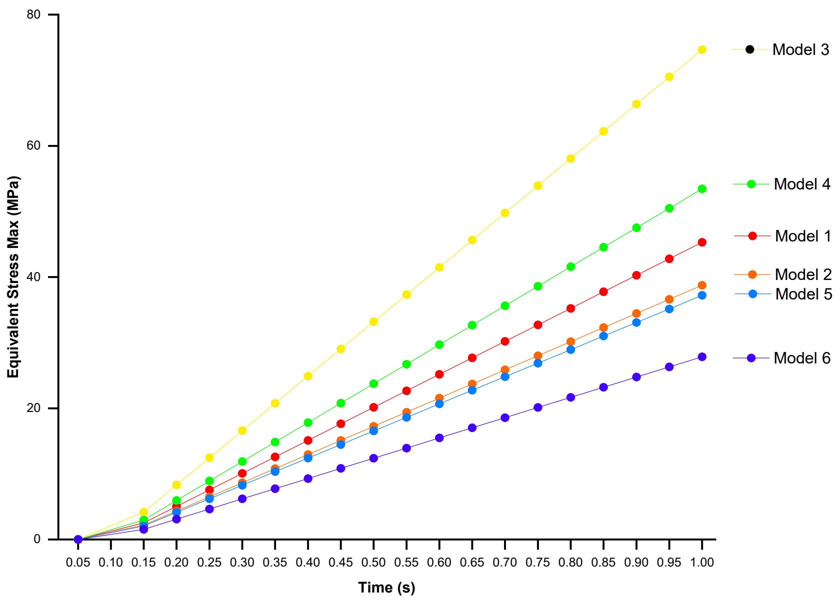

Fig. 15. Comparison of equivalent stress max between all model.

Model 6 is having better results than 5 other models because the maximum equivalent stress occurring from simulation is only 27.855 MPa compared to model 3 with 74.656 MPa which is almost 3 times the number. A lower equivalent stress value is generally desirable because it indicates the material experiences less internal pressure under load. This translates to a reduced risk of failure, increased dimensional stability, and potentially allows the material to handle higher loads before exceeding its limits. The linear function of Equivalent Stress vs time for model 6 with a very low slope is expected because of the low area of pressure due to stiffener arrangement.

Total Deformation

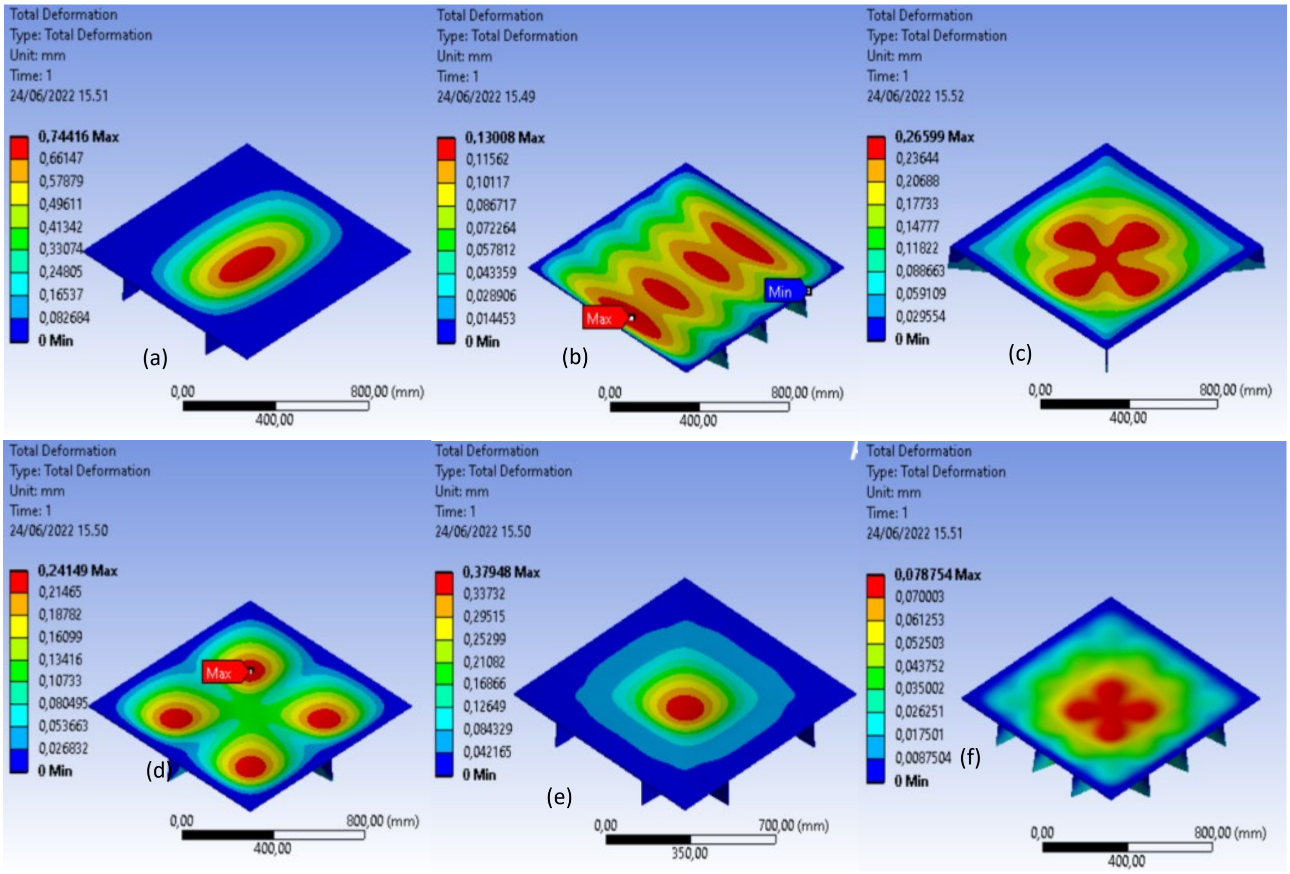

Fig. 16. Total Deformation on (a) model 1 (b) model 2 (c) model 3 (d) model 4 (e) model 5 (f) model 6.

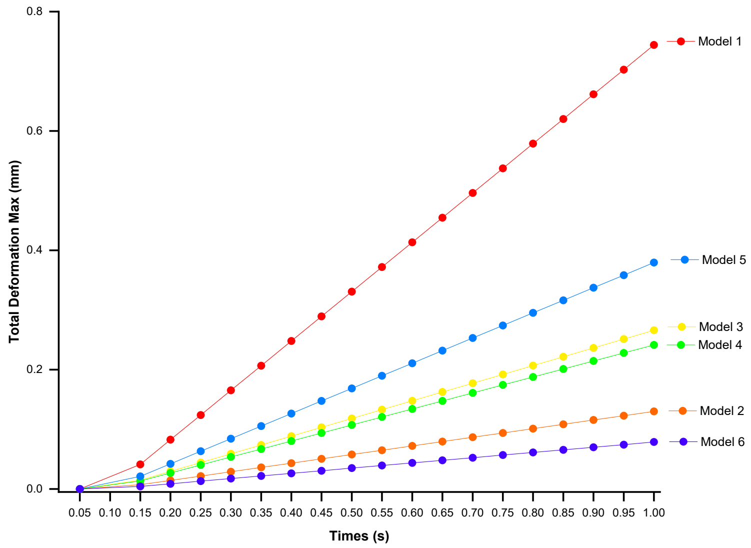

Fig. 17. Comparison of total deformation max between all model.

The results of total maximum deformation from all 6 models is showing that Model 1 having the poorest results due to limited integrity. Interesting results are shown by model 5 despite having more stiffeners but performed worse than the other. The result is due to the concentration of deformation inside the center point. Minimizing total maximum deformation is generally considered a sign of strong performance in engineering applications. When a structure or material exhibits lower overall deformation under stress, it translates to several benefits. Firstly, it retains its original shape more effectively, crucial for components that need to maintain precise dimensions. Secondly, this minimal deflection improves dimensional accuracy in the final product. Furthermore, a design with lower total deformation often boasts a higher load capacity. The structure can handle greater forces without excessive bending or warping, leading to improved overall stability.

In thin-walled structures, the pursuit of the smallest strain energy, lower elastic strain, lower equivalent stress value, and lower total maximum deformation stems from various performance objectives. Firstly, by minimizing strain energy and elastic strain, these structures optimize material usage, ensuring that the material is utilized efficiently while maintaining structural integrity. This efficiency is crucial for applications where weight reduction is paramount, such as in aerospace and automotive industries, as it allows for lightweight yet robust designs. Additionally, lower elastic strain and equivalent stress values enhance stability, reducing the risk of buckling or deformation under load, which is vital for safety in dynamic or high-stress environments. Moreover, minimizing total maximum deformation improves durability by reducing the strain on the material, thus extending the fatigue life of the structure, particularly in cyclic loading conditions. Lastly, achieving low deformation and strain energy contributes to better dimensional stability and precision, crucial for applications requiring tight tolerances or high accuracy. In essence, optimizing thin-walled structures for these parameters leads to enhanced performance in terms of efficiency, weight reduction, stability, durability, and precision, meeting the demands of industries requiring lightweight, high-performance structures.

Previous research publications in the journal "Computational Modeling and Constructal Design Theory Applied to the Geometric Optimization of Thin Steel Plates with Stiffeners Subjected to Uniform Transverse Load" have shown that despite keeping the same steel volume, dimensions (except thickness), load, and support conditions, all proposed stiffened plates generally have lower central deflection when compared to non-stiffened reference plates. The results that were obtained demonstrate the effectiveness of the proposed method in predicting physical effects accurately. It was also observed that for a fixed amount of weight, stiffened plates are more efficient. Therefore, adequate stiffening is necessary, and welding techniques are also required.[15]

The stiffness and deflections of plates are greatly influenced by the number of transverse stiffeners (N_{ts}), number of longitudinal stiffeners (N_{ls}), and ratio between height and thickness of stiffeners (h_s/t_s). It is important to note that an increase in the number of stiffeners does not necessarily result in a reduction in the central deflection of stiffened plates fabricated with the same amount of steel volume. Therefore, it is crucial to conduct geometric evaluations to efficiently use the material when designing and constructing such structures.

Conclusions

This paper discusses the strengthening effects of thin-walled structure with various stiffeners applied on the top side of the plate with the same pressure and boundary condition. Through the results, following conclusions can be made :

- Stiffener number 6 has a better performance between 5 other stiffeners on 3 out of 4 output aspects.
- The use of stiffeners in the structural plates can effectively protect the plates from cyclic and impact loading, therefore extend the plate's service time and reduce its maintenance cost
- For regular stiffened plates, stiffeners with more number of stiffener provide better performance than the other stiffeners with less arrangement
- The optimum number of stiffeners on one configuration in an interesting topic to be further discussed

The listed conclusions will enhance the capability of predicting the structural plates' buckling performance, therefore have wide applicability in any industry that involves design and analysis of constructional plates. The interesting finding that the strengthening effects of an oblique stiffener can be approximated as those of two regular stiffeners aligned along X and Y-direction can be applied in analytical analysis of the stiffened plate.

Future Work

This research can be extended in a number of ways, including

- Investigating the performance of thin-walled structures with different stiffener materials
- Optimizing the design of stiffeners for different loading conditions
- Developing experimental methods to validate the FEA results

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