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Structure Analysis of Warren Truss Bridge using 3D CAD Software

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ABSTRACT

The Warren truss consists of longitudinal members joined only by angled cross-members, forming alternately inverted equilateral triangle-shaped spaces along its length, ensuring that no individual strut, beam, or tie subjected to bending or torsion straining forces, but only to tension or compression. Tension and compression resulting from the reaction force from the load received. Every bridge has a load limit that can be received. These limits can be seen from the bridge safety factor. The purpose of the analysis of safety factor that occurs on a Warren truss bridge, i.e. to know the load limit that can be received for a bridge structure design, Warren truss types. On the bridge with a length of 57.38 m, 9.25 m wide bridge, with a thickness of 27.5 m of concrete, and asphalt thickness of 4.5 m, will be given a load containing 28 Toyota Avanza 4 adults with 75 kg per person, which to determine load limits and safety factors of this bridge design. Before the static analysis, safety of factor and stress calculations performed with the determination of area of road A = 530.765 m2, the determination of the height of asphalt t = 0.045 m, and the determination of the height of concrete t = 0.275 m, this calculation aims to facilitate the determination of volume of asphalt and volume of concrete, and the results of maximum load obtained from the determination of volume, and the determination of gravitation to gain maximum load. From maximum load, it can be determined of reaction force that to be used for analysis. Stress analysis and safety factors analysis were performed using SolidWorks software.)

I. Introduction

A bridge is a structure built to span physical obstacles such as a body of water, valley, or road, for the purpose of providing passage over the obstacle. The first bridges were made by nature itself as simple as a log fallen across a stream or stones in the river. A truss bridge is a bridge whose load-bearing superstructure is composed of a truss. This truss is a structure of connected elements forming triangular units. The Warren truss was patented in 1848 by its designers James Warren and Willoughby Theobald Monzani, and consists of longitudinal members joined only by angled cross-members, forming alternately inverted equilateral triangle-shaped spaces along its length, ensuring that no individual strut, beam, or tie is subject to bending or torsion straining forces, but only to tension or compression.

Recent studies have explored various aspects of truss bridge design and analysis. A 2025 study conducted a comprehensive analysis of truss bridge behavior, highlighting the importance of considering dynamic loads and environmental factors in design processes [1]. Another investigation focused on the structural behavior of modular steel truss bridges during incremental launching, providing insights into their performance during construction phases [2]. Additionally, research has been conducted on damage detection methods for Warren truss bridges, utilizing frequency change

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correlation to estimate structural damage effectively [3]. These studies underscore the ongoing efforts to enhance the safety and reliability of truss bridge structures through advanced analytical and monitoring techniques.

The bridge strength becomes a critical issue as there were some bridges collapsed, for example *Yangmingtan* Bridge over the Songhua River collapses because overloading, and the cause of collapse is suspected the usage of unsuitable building material. The other example is, *Gongguan* Bridge and Baihe Bridge in Huairou district because of the weight of an overloaded truck, and *Kutai Kartanegara* bridge because of design defect.

There are many reasons why a bridge collapsed, from natural disaster such as an earthquake and flood, overload, design defect, manufacturing defect, and odd occurrences. Therefore, observing the strength that occurs in the bridge design towards the stress of the structure caused by external load is necessary.

The objectives of this research are as follows:

- To determine safety factor of a bridge
- To investigate the effect of material changed from material ASTM A26 to material S355N that reduces maximum stress and maximum load.
- To calculate maximum load and external load of the bridge under critical condition or safety factor is 1.

II. Method

In designing and analyzing the factor of safety and stress load, the required amount of data must be complete, accurate, and reliable, based on a comprehensive literature study. Recent studies have emphasized the importance of integrating advanced monitoring techniques and analytical methods to assess the structural integrity of steel truss bridges. For instance, a study conducted a modal analysis of a steel truss bridge under varying environmental conditions, highlighting the significance of environmental factors on bridge dynamics [4]. Similarly, explored failure propagation in steel truss bridges, providing insights into the mechanisms leading to structural failures [5]. Additionally, a damage detection method based on Gaussian Bayesian networks, demonstrating its effectiveness in identifying and localizing damage in steel truss bridges [6]. The theory and material from various references regarding the issues of stress, strain, and displacement of steel bridge structures were collected, focusing on the Warren truss bridge located at Jl. Lapangan, Wisma Asri, Bekasi.

Designing a steel bridge structure involves creating detailed installation images to be analyzed and explaining the procedures of research and analysis to be performed. Structural analysis was carried out on the steel bridge structure while being subjected to vehicular loads. The results of the analysis were obtained from data collection and calculations. Data retrieval involved several stages, including creating figures of the bridge structure, the drawing process, and area measurements. For the calculations, stages included determining the maximum load, clamp load calculation, and calculation of reaction forces.

Photographs of the bridge were taken for early modeling of the bridge structure. The purpose of photographing the truss was to determine the shape, location of bolt positions, the connector plate shape, and the overall structure of the bridge. The captured photos were used to sketch the bridge structure and the location of bolt joints. After sketching, measurements of truss length, truss width, bolt and nut diameters, and the distance between bolts and plates were conducted. This process facilitated accurate modeling of the steel bridge to precisely locate bolt joint positions. Accurate dimensions are required for the design process. The design images were analyzed using SolidWorks 2010 software, with millimeters (mm) as the unit of measurement. To analyze the stress, strain, and displacement of the steel bridge structure, design drawings with dimensions corresponding to the Warren truss steel bridge structure were necessary.

The area of the steel bridge was used to calculate the maximum load through measurements, beginning with the measurement of road length, road width, and road thickness. The method used involved summing the truss length with the distance between trusses, then multiplying by the number of trusses from the beginning to the end of the road. To measure the road thickness, distinctions were made between different types of asphalt and concrete, as their thicknesses vary; thus, measurements were carried out separately. The next step was to predict the load serviced by vehicles. The assumed load received by the steel bridge was based on a street filled with vehicles such as Toyota Avanza cars. The method of counting the number of vehicles involved reducing the overall length of the bridge by the length of a vehicle, then multiplying by two because the road was a two-way street. Using the Method of Joint for Truss Analysis, equilibrium forces were calculated. The Method of Joint is a procedure for determining the forces in each truss by analyzing the equilibrium forces acting on each connection point.

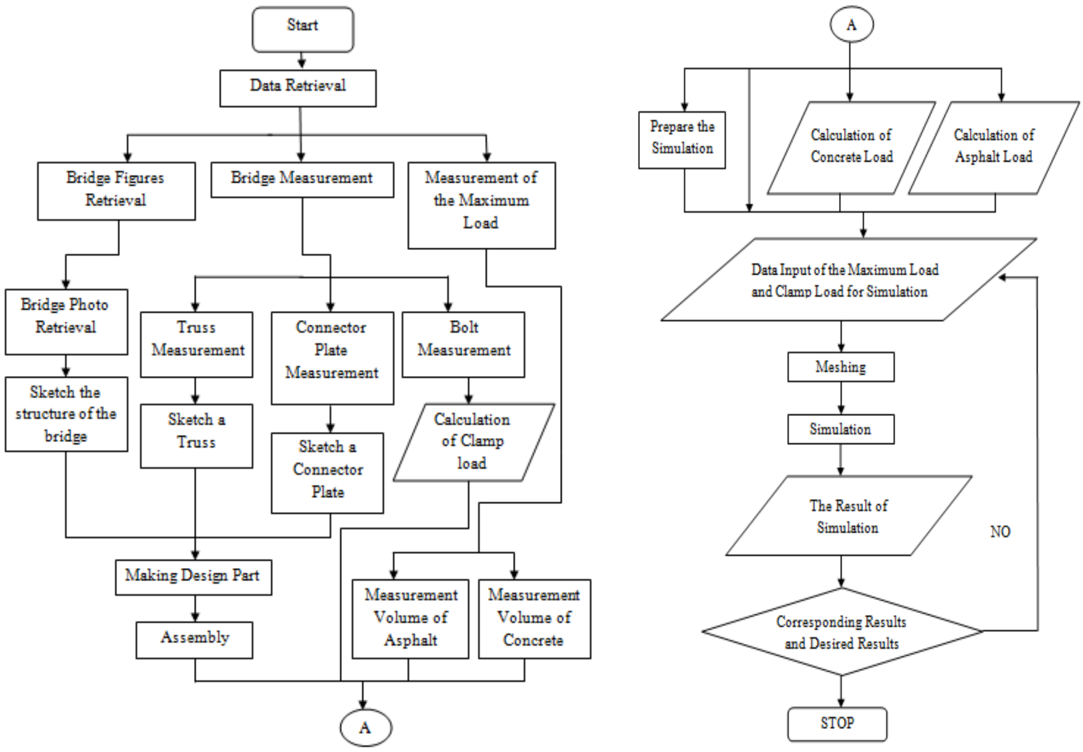

Fig. 1. Flow process method.

The simulation process begins with the creation of 2D sketch parts from the bridge, which serve as the foundation for further simulation. After developing the 2D sketches, the next stage is the construction of 3D parts. Once all required 3D parts are modeled, the subsequent phase is assembly—combining all parts into a complete model to be simulated. These sketches form the foundation of the 3D model. The initial step in creating a sketch is selecting a reference plane (e.g., Front Plane, Top Plane, or Right Plane), or defining a custom plane depending on the geometry [7].

Features in this context refer to the geometric entities that make up the parts; these can include protrusions, cuts, holes, and other shapes that, when combined, complete the part model. Features can also be added to assemblies to build more complex systems that may consist of parts or subassemblies. This multimode part capability is essential in modeling interconnected structures, such as bridges with trusses, beams, and joints [8].

The meshing process is critical in preparing the model for simulation. It defines how the model is subdivided into smaller elements for numerical analysis. A mesh represents the geometry using finite elements, which are used in computational analyses such as Finite Element Method (FEM). Automatic meshing tools in modern CAD/CAE software generate meshes based on global element sizes, tolerances, and any user-defined mesh control specifications [9].

Upon generating the mesh, linear static analysis follows a three-step sequence:

- The program formulates and solves a system of finite element equilibrium equations to determine nodal displacement components.
- Using the computed displacements, the software calculates strain components across the model.

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- Based on stress-strain relationships, it then derives the stress distribution within the structure [10].

III. Results and Discussion

A. Specification

Specification was aimed to determine the maximum load, the reaction force, and Cremona diagram. Specification was taken from bridge as seen as figures 2.

Fig. 2. Photo of Warren Truss Bridge.

Table 1. Dimension of Bridge and Material Specification

Dimension Bridge	
Bridge type	Warren truss
Length	57.38 m
Width	9.25 m
Height of asphalt	0.045 m
Height of concrete	0.275 m
Truss Dimension	
Truss type	I Beam Truss
Length	6.000 mm
Width	380 mm
Height	300 mm
Thickness	10 mm
Type of Material	ASTM A36
Ultimate Tensile Strength	400 MPa
Yield Strength	250 MPa
Plate Joint Dimension	
Length	980 mm
Width	870 mm
Thickness	15 mm
Type of Material	ASTM A36
Ultimate Tensile Strength	400 MPa
Yield Strength	250 MPa
Dimension of Bolt and Nut	
Diameter of Head Bolt	45 mm
Diameter of Pitch	2.5 mm
Diameter of Nut	45 mm
Diameter of Nut Hole	20 mm
Diameter of Rod Bolt	20 mm
Type of Material	AISI 1045 Steel, Cold Drawn
Type of Material	625 MPa
Yield Strength	530 Mpa
Material for Simulation 1	
Material	ASTM A36 Steel
Elastic Modulus	200000 N/mm^2
Poisson's Ration	0.26
Shear Modulus	79300 N/mm^2
Mass Density	7850 kg/m^3
Tensile Strength	400 N/mm^2
Yield Strength	250 N/mm^2
Material for Simulation 2	
Material	S355N
Elastic Modulus	210000 N/mm^2

Material for Simulation 2	
Poisson's Ration	0.28
Shear Modulus	79300 N/mm^2
Mass Density	7800 kg/m^3
Tensile Strength	475 N/mm^2
Yield Strength	275 N/mm^2

B. Load Calculation

The load of asphalt, and concrete load could be calculated after the volume of asphalt, and concrete volume found. The load of asphalt and load of concrete can be found as well if asphalt density and concrete density was known. Road's area, asphalt volume, and the volume of concrete can be calculated as follows:

$$A = 57.38\ m \times 9.25\ m = 530.765\ m^2$$
$$V_{asphalt} = 530.765\ m^2 \times 0.045\ m = 23.884\ m^3$$
$$V_{concrete} = 530.765\ m^2 \times 0.275\ m = 145.96\ m^3$$

To calculate the load, the densities of asphalt and concrete are required. Recent studies indicate that the standard density of asphalt is approximately 2,322 kg/m³ [11], and the density of normal concrete is around 2,400 kg/m³ [12]. Using these values, the mass (m) and load force (F) can be calculated with the following equations:

$$\rho = \frac{m}{V}$$
$$m = \rho \ x\ V$$
$$F = m\ x\ g$$
$$F = \rho\ x\ V\ x\ g$$

Where:

ρ = Mass of Density (kg/m^3)
F = Load Force (N)
m = Mass (kg)
g = Gravitation (9,81 m/s^2)
V = Volume (m^3)

Applying these formulas:

$$F_{asphalt} = \rho_{asphalt}\ x\ V_{asphalt}\ x\ g$$
$$= 2000\ kg/m^3\ x\ 23{,}884\ m^3\ x\ 9{,}814\ m/s^2$$
$$= 468.604{,}08\ N$$
$$F_{concrete} = \rho_{concrete}\ x\ V_{concrete\ x}\ g$$
$$= 2400\ kg/m^3\ x\ 145,\ 96\ m^3\ x\ 9{,}814\ m/s^2$$
$$= 3{,}436{,}382.24\ N$$

The maximum load was determined using the equation as follows:

$$F_{max} = F_{asphalt} + F_{concrete} + (m_{vehicle}\ x\ g)$$
$$= 468{,}604.08\ N + 3{,}436{,}382.24\ N + (37{,}660\ kg\ x\ 9{,}814\ m/s^2)$$
$$= 4{,}274{,}681.74\ N$$

The result of maximum load weight and vehicles weight at road is 4,274,681.74 N (kgm/s2) or 4,274.68 kN. Because there are two structures, the maximum load will be divided by 2 each structure. These calculations are essential for assessing the structural load and ensuring the safety and integrity of the bridge design.

C. Force Equilbrium Distribution

The method used to determine force equilibrium in truss structures is the Method of Joints, which involves analyzing each joint individually to solve for unknown member forces. This method is particularly effective when a joint has no more than two unknowns, as is the case with Joint A in the current analysis as in figures 3. By applying the equilibrium equations ∑Fx = 0 and ∑Fy = 0 at Joint A, the two unknown forces can be determined [13].

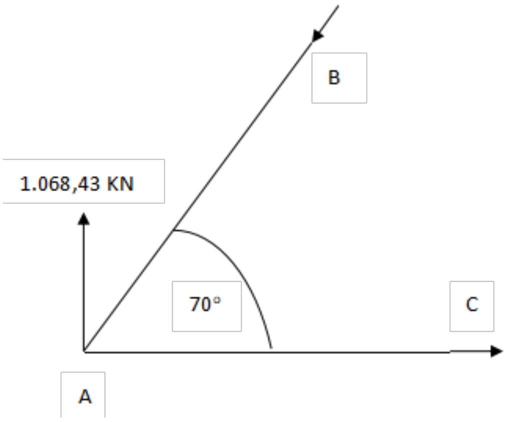

Fig. 3. Joint A

$$\sum Fy = 0$$

$$F - \sin 70\ Fab = 0$$

$$1068{,}43 - \sin 70\ Fab = 0$$

$$1068{,}43 = \sin 70\ Fab$$

$$\frac{1068{,}43}{\sin 70} = Fab$$

F_{ab} = 1137,225 (Compression)

$$\sum Fx = 0$$

$$Fac - \cos 70 Fab = 0$$

$$Fac - \cos 70 (1137{,}225) = 0$$

$$Fac = \cos 70\ (1137{,}225)$$

F_{ab} = 338,96 (Tension)

The calculated reaction forces for varying external loads—specifically, external load multiplied by 1, 2, and 3—are summarized in Table 2. These values provide insight into the structural response under different loading scenarios.

Table 2. Reaction Force Result Table

Beam	Force of beam (kN)					
	External load 1x		External load 2x		External load 3x	
	Compressive	Tension	compressive	Tension	compressive	Tension
AB	1,137.255	-	1235.58	-	1333.91	-
AC	-	388.96	-	422,59	-	456.225
BC	-	1137.25	-	1235.58	-	1333.91
BD	777.92	-	845.18	-	912.45	-
CD	1137.255	-	1235.585	-	1333.91	-
CE	-	1166.88	-	1267.77	-	1368.675
DE	-	1137.25	-	1235,58	-	1333,91
DF	1555.84	-	1690.36	-	1824,9	-
EF	1137.25	-	1235.58	-	1333.91	-
EG	-	1944,8	-	2112.95	-	2281.12
FG	-	1137.25	-	1235.58	-	1333.91
FH	2333.76	-	2535.54	-	2737.35	-
GH	1137.25	-	1235.58	-	1333.91	-
GI	-	2722.72	-	2958.13	-	3193.575
HI	-	1137.25	-	1235.58	-	1333.91
HJ	3111.68	-	3380.72	-	3649.8	-

Beam	Force of beam (kN) External load 1x		External load 2x		External load 3x	
	Compressive	**Tension**	**compressive**	**Tension**	**compressive**	**Tension**
IJ	1137.25	-	1235.58	-	1333.91	-
IK	-	3500.64	-	3803.31	-	4106.025
JK	-	1137.25	-	1235.58	-	1333.91
JL	3889.6	-	4225.9	-	4562.25	-
KL	-	-	-	-	-	-
KM	3889.6	-	4225.9	-	4562.25	-
LM	-	-	-	-	-	-
LN	-	3889.6	-	4225.9	-	4562.25
MN	-	1137.25	-	1235.58	-	1333.91
MO	-	3500.64	-	3803.31	-	4106.02
NO	1137.25	-	1235.58	-	1333.91	-
NP	3111.68		3380.72		3649.8	
OP	-	1137.25	-	1235.58	-	1333.91
OQ	-	2722.72	-	2958.13	-	3193.57
PQ	1137.25	-	1235.58	-	1333.91	-
PR	2333.76	-	2535.54	-	2737.35	-
QR	-	1137.25	-	1235.58	-	1333.91
QS	-	2333.76	-	2112.95	-	2281.12
RS	1137.25	-	1235.58	-	1333.91	-
RT	1944.8	-	1690.36	-	1824.9	-
ST	-	1137.25	-	1235.58	-	1333.91
SU	-	1555.84	-	1267.77	-	1368.67
TU	1137.25	-	1235.58	-	1333.91	-
TV	777.92	-	845.18	-	912.45	-
UV	-	1137.25	-	1235.58	-	1333.91
UW	-	388.96	-	442.59	-	456.22

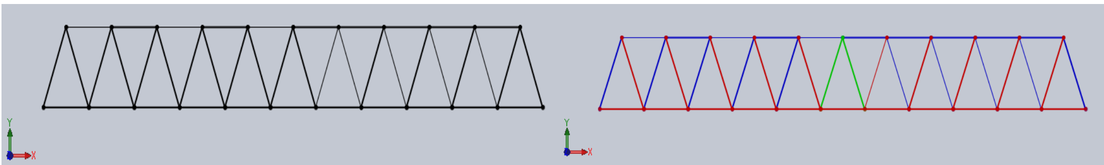

Fig. 4. Reaction Force Structure

D. Joint Load Calculation

Tightening torque on the bolt comes from equation 2.4 and for Proof load from equation 2.5. Type of screw used is M20, with an area of tensile stress is 244.794 mm2 or 0.3794 in2, and assume the burden of proof strength of the bolt used is 55,000 psi. The coefficient used was 0.15 for lubricated. For the bolted connections, the tightening torque is calculated using the formula:

$$T = K\,D\,P$$

Where:

T = Tightening torque (lb-in)
K = Torque coefficient (dimensionless), typically 0.15 for lubricated conditions [14]
D = Nominal bolt diameter (in)
P = Bolt preload or clamping force (lb)

For an M20 bolt (nominal diameter of 0.7874 inches) with a tensile stress area (Ats) of 0.3794 in² and a proof load of 55,000 psi, the preload (P) is calculated as:

$$P = A_{ts}\,(P_L \text{ x } 75\%)$$
$$P = 244.794\ mm^2\ (55{,}000\ psi \text{ x } 75\%)$$
$$P = 0.3794\ in^2\ (55{,}000\ psi \text{ x } 75\%)$$
$$P = 0.3794\ in^2\ (41250\ psi)$$
$$P = 15{,}650.25\ lb$$

Subsequently, the tightening torque (T) is:

$$T = K\,D\,P$$

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T = (0.15) (20 mm) (15,650.25 lb)
T = (0.15) (0.7874 in) (15,650.25 lb)
T = 1,858.451 lb in

This calculation ensures that the bolt is adequately preloaded to maintain joint integrity under service loads [14]. Regarding the structural capacity, the maximum load (Fmax) for a safety factor (FOS) of 1 under normal conditions, using ultimate tensile strength as the allowable stress, is calculated as:

$$\frac{Fmax_1}{FOS_2} = \frac{FOS_1}{Fmax_2}$$

$$\frac{2{,}471.17}{1} = \frac{FOS_2}{1.2663}$$

$$FOS_2 = \frac{2{,}471.17}{1}\ x\ 1.2663\ = 3{,}129.24\ kN$$

Maximum load is 3,129.24 kN for safety factor = 1 at normal conditions with ultimate tensile strength as allowable stress, for the safety factor = 1 with yield strength as allowable stress shown the maximum load is 2,100.48 kN. When considering modified materials with a safety factor of 1.51, the maximum load increases to:

$$\frac{Fmax_1}{FOS_2} = \frac{FOS_1}{Fmax_2}$$

$$\frac{2{,}471.17}{1} = \frac{FOS_2}{1.51}$$

$$FOS_2 = \frac{2{,}471.17}{1}\ x\ 1.51 = 3{,}649.92\ kN$$

E. Results Analysis

These calculations are crucial for ensuring that the bridge design meets the required safety standards under various loading conditions. Maximum load is 3,649.92 kN for safety factor = 1.51 at normal conditions on the modified materials with ultimate tensile strength as allowable stress, for the safety factor = 1.51 with yield strength as allowable stress shown the maximum load is 2,248.76 kN. The external load capacity is determined by subtracting the structure's self-weight from the maximum load:

$$External\ Load = Maximum\ Load - Structure\ Load$$
$$External\ Load = 637{,}709.38\ Kg - 435{,}747.37\ Kg$$
$$External\ Load = 201{,}962.01\ Kg$$

The percentage reduction in maximum stress due to design modifications is calculated as:

$$\Delta\% = \frac{(292.6 - 293.8)}{293.8} x\ 100\%$$

$$\Delta\% = 0.408\ \%(reducing)$$

This indicates a slight reduction in stress, contributing to the overall safety and performance of the bridge structure.

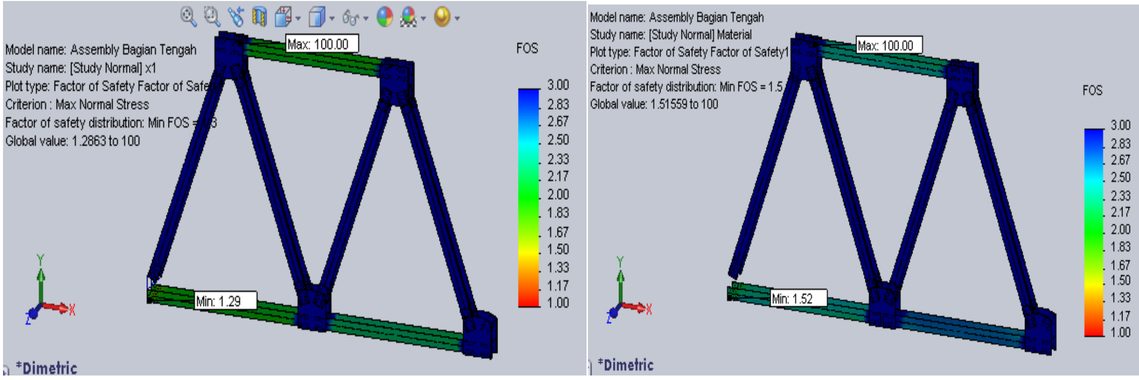

Fig. 5. Normal Stress Simulation with maximum normal load on ASTM A36 material (left) and S355 material (right)

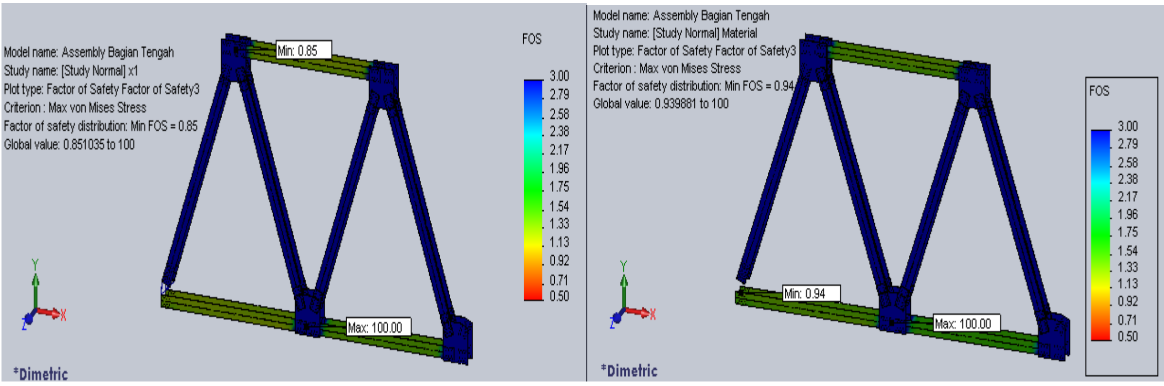

Fig. 6. Von Mises Stress Simulation with maximum triple load on ASTM A36 material (left) and S355 material (right)

The structural redesign incorporating a material upgrade from ASTM A36 to S355 steel aims to enhance the bridge's performance under critical loading conditions. This modification increases the ultimate tensile strength from approximately 400–550 MPa to 470–630 MPa, depending on the material thickness. As a result, the stress experienced by the structure under normal conditions is reduced by approximately 0.408%, and the critical load limit is increased by about 34.443%.

Table 3. Reaction Force Result Table

Parameter	**Existing Design**			**New Design**
Condition	**Normal Condition**	**External Load x2**	**External Load x3**	**Normal Condition**
Material	**ASTM A36**	**ASTM A36**	**ASTM A36**	**S355**
Maximum Stress (MPa)	293.8	319	344.2	292.6
Stress Rate (MPa)	122.4 - 171.4	133 - 186.1	143.5 - 208	121.9 - 170.7
Maximum Displacement (mm)	4,599	4,996	5,393	4,383
Displacement Rate (mm)	1,893 - 3584	2,057 - 4,261	2,220 - 4,500	1,805 - 3,476
Factor of Safety Global Value Normal Stress	1.2663 - <3	1.1809 - <3	1.1 - <3	1.51 - <3
Factor of Safety Global Value von Mises Stress	0.85 - <3	0.78 - <3	0.73 - <3	0.91 - <3
Factor of Safety Normal Stress Rate	2 - 2.33	1.87 - 2.17	1.67 - 1.83	2.33 - 2.67
Factor of Safety von Mises Stress Rate	1.54 - 1.75	1.33 - 1.54	1.13 - 1.33	1.75 - 1.96
Δ% Stress reduces for Normal condition and New Design	0,408%			

The adoption of S355 steel, with its higher yield and tensile strengths, contributes to improved structural performance, particularly under increased loading scenarios. This enhancement ensures greater safety margins and structural integrity for the bridge [15].

IV. Conclusion

Based on the results of the analysis, the maximum load and safety factor of the Warren truss-type steel bridge with bolted joints under a simulated external load of approximately 28 Toyota Avanza vehicles (each with 4 passengers) reached a total external load of 2,471.17 kN. Under this loading, the safety factor using the ultimate tensile strength as the allowable stress was found to be 1.2663, and 0.85 when yield strength was used as the allowable stress.

When external loads were increased by two and three times, the global safety factor values decreased. For external load ×2, the safety factor for ultimate tensile strength was in the range of 1.1809 to <3, and for yield stress was 0.78 to <3. For external load ×3, the safety factor was in the range of 1.1 to <3 and 0.73 to <3 respectively. This indicates that the existing design has limited tolerance under significantly increased loading scenarios.

A material upgrade from ASTM A36 to S355 significantly improved the bridge's structural performance. The global safety factor using ultimate tensile strength as the allowable stress increased to 1.52–<3, and yield stress increased to 0.98–<3 under normal loading conditions. This corresponds to a load-carrying capacity of up to 3,129.24 kN (ultimate tensile strength) and 2,100.48 kN (yield strength). Under modified material conditions, the critical load limit further increased to 3,649.92 kN and 2,248.76 kN respectively.

The critical external load under a safety factor of 1 for the original material was approximately 201,962.01 kg. With the upgraded material, this load increased to approximately 308,071.65 kg. The modification raised the ultimate tensile strength from 400 MPa to 475 MPa, reducing maximum stress by 0.408% and improving load efficiency in critical conditions by approximately 34.443%.

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