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Analysis of Steel Bridge Frame Reinforcement Using External Prestressing Method Due to Moving Loads

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Abstract – Strengthening bridges using the external prestressing method has proven effective in addressing structural damage and enhancing bridge performance. This method involves installing prestressed cables outside the steel frame to improve strength and stability. The steel truss bridge analyzed in this study conforms to the SNI 1725:2016 class A steel bridge standard. The structure is a truss bridge with a span of 60 meters, a width of 9.13 meters, and a height of 6.3 meters. Structural analysis was conducted using SAP2000 v22, focusing on efficient modeling and selecting external prestressing for steel truss bridges. The study compared three prestressing cable tensions for strengthening the bridge frame and evaluated responses under moving loads. Results show a 50% reduction in deflection forces on the reference steel frame bridge. Deflection comparisons at object point 7 and joint object U3 highlight the superior performance of the Type 2 Cable Bridge. This bridge achieves the lowest deflection reduction, with decreases of 46.68% at 40 km/h, 48.60% at 50 km/h, and 49.91% at 60 km/h, demonstrating the best analytical performance among the configurations analyzed.

Keywords: Steel Bridge Reinforcement, External Prestressing Method, Moving Load Analysis

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1. Introduction

The steel truss bridge was first introduced in Indonesia around 1990. Over time, challenges arise, including increased load and traffic volume, excessive weight from repeated asphalt overlays, and a decline in structural durability. These factors lead to higher stress on bridge elements and more significant deflection [1][2][3].

The external prestressing method is an effective solution for enhancing the serviceability and capacity of bridges. This method involves applying force through cables or steel rods placed outside the bridge structure to reduce tensile stress on the truss[4]. Reinforcement can be applied to individual or multiple truss elements or the entire structure. For the prestressing system to function effectively, cables must be anchored at designated points and aligned properly using specific tendon configurations [5][6].

The external prestressing method offers several advantages, including implementing it without requiring traffic closures and simplifying the equipment installation[7][8][9]. Its design allows for easy inspection of cables and anchorages due to their external placement while also enabling the tensioning and eventual replacement of prestressing cables when necessary [10].

However, this method has certain drawbacks. A thorough assessment of the bridge's condition is essential to ensure the deck, girders, and trusses can accommodate the additional stresses. The external placement of cables makes them more susceptible to corrosion and vandalism. During cable tensioning, movements in the bridge deck components, both vertical and horizontal, can generate secondary stresses that may damage the deck plates or truss elements. Additionally, on steel truss bridges, applying axial forces may cause local stability issues, necessitating localized reinforcements at the anchor points or modifications near the truss elements closest to the anchorages [11].

The decision to reinforce a bridge using this method should be based on specific conditions, such as visible physical damage that poses safety risks, excessive deflection or vibrations causing discomfort for vehicles as identified in detailed bridge condition surveys, evidence of increased vehicle loads based on load measurement tests, or measured steel stresses approaching permissible limits [12].

The principle of strengthening with External Prestressing (EP) is to simplify the application of axial loads combined with uplift forces to enhance the flexural and shear capacity of beam structures or components. The increase in stiffness provided by external prestressing can reduce deflection and vibration during the service life [13][14]. The stress range at critical locations can also be reduced, improving fatigue resistance performance. The deformation or downward deflection due to applied loads on the bridge can also be minimized.

Similar to conventional prestressing systems, particularly in prestressed concrete bridges, external prestressing applies a compressive force combined with an eccentric moment to increase flexural capacity and improve the crack condition of a girder [15][16]. Implementing this prestressing system involves installing anchors, tendons, and deviators on the bridge structure.

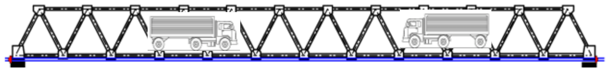
Stress can be applied using prestressing cables, either as single strands or bundled strands [17][18][19]. In certain situations, stress application uses high-tensile steel bars, which can be tensioned with hydraulic jacks or a bolt-tightening system.

Structural analysis in this study uses the SAP2000 v22 software program. Modeling and selecting efficient prestressing in the design of steel frame bridges for bridge reinforcement, especially when considering external prestressing. At the end of this study it is shown by comparing 3 prestressing cable tensions on bridge frame reinforcement with the external prestressing method. A loading simulation was carried out, which can respond to the form of strain due to moving loads and axial force capacity to the dynamic response of the bridge structure stability of approximately 50% of the deflection force on the steel frame reference bridge if given a moving load. After that, choose the bridge that has the lowest settlement. The review point is determined for comparing deflection at point object 7 and joint object U3 and for the review of the step at number 25

In this study, the speed of vehicles crossing the bridge is 40km/h, 50km/h, and 60km/h. This speed is selected based on specific considerations related to the reference guidelines (SNI 1725-2016) regarding "in the Loading of Steel Frame Bridges." This speed allows the collection of accurate data on the impact of vehicle speed on the bridge structure and overall system performance. External Prestressing Cables Type 1, 2, and 3 are prestressing cables that must be taken from the guidelines for this study. The guidelines are taken from Strengthening Australian Steel Frame Bridges with External Prestressing Methods 2004. More efficient reinforcement is reinforcement with external prestressing with support rods that can provide smaller deflection resistance with the prestressing force used on the frame bridge.

2. Methodology

The methodology for this study begins with developing an experimental approach to analyze the effects of vehicle speed and external prestressing cable types on the structural performance of steel frame bridges. The bridge model is designed according to the specifications outlined in SNI 1725-2016, incorporating external prestressing cables classified as Type 1, Type 2, and Type 3, based on the "Strengthening Australian Steel Frame Bridges with External Prestressing Methods 2004" guidelines. Vehicle speeds of 40 km/h, 50 km/h, and 60 km/h are selected as loading conditions to simulate real-world scenarios and evaluate their impact on the bridge structure, shown in Figure 1.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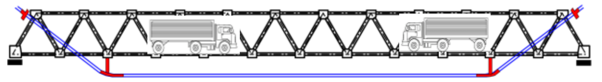
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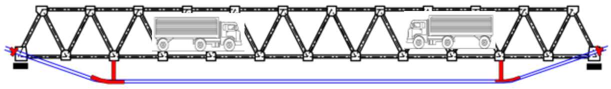
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Figure 1. Examples of the placement of cables that may be used in steel truss bridges: a) Type 1; b) Type 2; c) Type 3.

2.1. Bridge Parameter

Figure 2 shows the details of various steel profiles used to construct a bridge. The profiles are categorized as BSB and BSA for the first and BSD for the second. Lengths range from 4.9 to 6.7 meters, with varying weights depending on the profile dimensions. The total weight for all components in the first set (BSB and BSA) is 27,463.4 kg, while the second set (BSD) totals 25,962.9 kg. The overall total weight of all components is 53,426.3 kg. The deck frames include GMT, GP, and GMU profiles with dimensions ranging from 450×200 to 900×350 mm. The total weight of these deck frames is 45,997.3 kg. For the top bracing, profiles BIU and BIA with dimensions of 300×200 mm and 150×150 mm are used, with a combined total weight of 7,859.0 kg. The handrails consist of a 200×75 mm channel profile with a total weight of 6,072.0 kg. The combined weight of all components ensures the structural stability and durability of the bridge. The reinforced concrete bridge deck has a length of 60 meters, a width of 7 meters, and an average thickness of 25.5 cm. It has a total volume of 107.10 m³ and weighs 257,040 kg. The reinforced concrete sidewalk, measuring 60 meters in length and 2 meters in width, has a thickness of 52 cm, a volume of 62.40 m³, and weighs 149,760 kg. The trapezoid steel sheets cover an area of 60 meters by 91.13 meters, with a unit weight of 51.26 kg/m², totaling 28,080 kg. The overlay asphalt concrete layer is 60 meters long, 7 meters wide, and 5 cm thick, with a volume of 21 m³ and a weight of 48,300 kg. These materials contribute to the overall stability and performance of the bridge.

The total weight of the steel truss bridge structure is divided into two main components: "Steel Truss Bridge" and "Bridge Deck and Sidewalk." For the "Steel Truss Bridge" component, the weights of its parts are as follows: the side truss weighs 106.9 tons, the bridge floor truss weighs 46.0 tons, the wind bracing truss weighs 7.9

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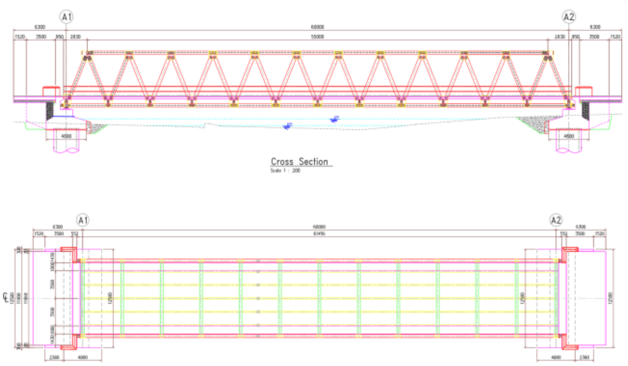
tons, handrail weighs 6.1 tons, bolts weigh 6.4 tons, and plates and other components weigh 25.7 tons. The total weight of this component is 198.9 tons. For the "Bridge Deck and Sidewalk" component, the reinforced concrete bridge deck weighs 257.0 tons, the reinforced concrete sidewalk weighs 149.8 tons, trapezoid steel sheets weigh 28.1 tons, and the asphalt overlay weighs 48.3 tons. The total weight of this component is 483.2 tons. Overall, the total weight of the bridge structure is 682.1 tons.

Figure 2. Bridge strucure



2.2. Deviator

A deviator is a supporting device designed to facilitate the formation of a prestressed cable profile (layout) according to specific requirements. The deviator's construction can be designed as shown in Figure 3 or other shapes as needed, as long as it fulfills its function. The radius of curvature of the prestressed tendon alignment at the deviator must not be smaller than 6 times the radius of the tendon, as shown in Figure 3.

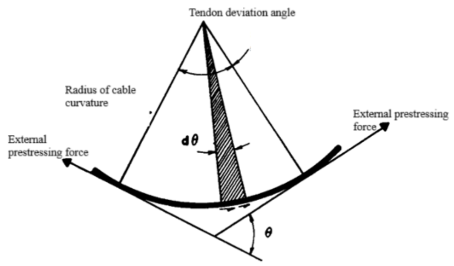


Figure 3. The curvature shape of the cable on the deviator

2.3. Cable

The ASTM Grade 270 strands are available in 13 mm (0.5 inches) and 15 mm (0.6 inches). The 13 mm strand has a diameter of 12.7 mm, a nominal area of 98.7 mm², and a nominal weight of 0.775 kg/m. Meanwhile, the 15 mm strand has a nominal area of 140 mm² and a nominal weight of 1.1 kg/m. Both strands have a yield strength of 1670 MPa, an ultimate tensile strength of 1860 MPa, and a modulus of elasticity of approximately 195 GPa. The yield load for the 13 mm strand is 183.7 kN, while for the 15 mm strand, it is 260.7 kN. The relaxation rate for both strands is a maximum of 2.5%.

2.4. Vehicle Parameter

At this stage is the input vehicle load, which includes the dynamic load generated by a standard truck crossing the bridge. The simulations include analysis of different vehicle weights and load distributions that affect bridge performance during varying speeds, as shown in Figure 4. The selection of two truck lanes is also intended to capture the overall behavior of the bridge, ensuring that the analysis considers realistic traffic conditions and load interactions that may influence structural response and durability. By incorporating two truck loading lanes, the study aims to represent the combined effects of vehicle speed crossings, which can increase stress variations and more accurately simulate real-world operational conditions [20]. This approach provides a comprehensive understanding of the bridge's performance and helps design effective reinforcement strategies. To convert the truck's speed from km/h to m/s, divide the distance in meters by the time in seconds. For example, 40 km/h equals 40 meters per 3.6 seconds, which gives 11.1 m/s. Similarly, 50 km/h converts to 13.8 m/s, and 60 km/h converts to 16.6 m/s using the same method.

Truck loading based on SNI 1725-2016 is 500 kN, consisting of 50 kN positioned on the front axle, and the remainder is divided equally between the following 2 axles, 225 kN each, as shown in Figure 5. The contact area of a truck wheels, consisting of one or two wheels, is assumed to have a rectangular shape with a length of 750 mm and a width of 250 mm.

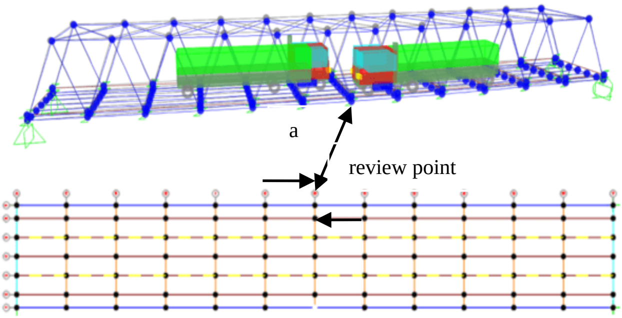


Figure 4. a) Truck model simulation; b) Lane plane truck

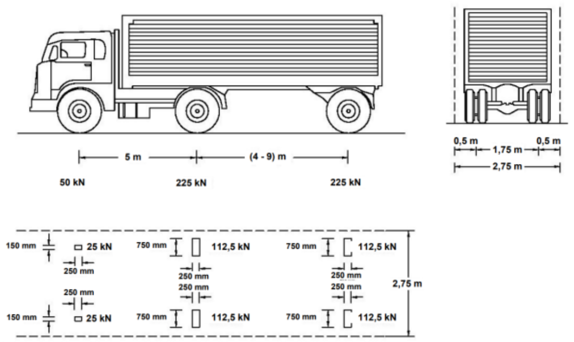


Figure 5. Truck dimension and axle load

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3. Result and Discussion

3.1. Displacement Analysis

The observation points for comparing deflection and axial force capacity and increasing the bridge structure's dynamic stability when trucks move across the bridge are at point object 7 and joint object U3. After that, the running results of the stress distribution on the bridge are seen and differentiated as to which ones can result in the lowest deformation and deflection, shown in Table 1.

Table 1
Comparison of vehicle speed and displacement at point 7

Bridge Type	40 km/h	50 km/h	60 km/h
Normal	-0.00467 mm	-0.00537 mm	-0.00607 mm
1	-0.00231 mm	-0.00335 mm	-0.00384 mm
2	-0.00218 mm	-0.00261 mm	-0.00303 mm
3	-0.00247 mm	-0.00345 mm	-0.00409 mm

Furthermore, from the discussion table data above on point object 7, and joint object U3, the deflection that occurs when a truck vehicle moves across a truss bridge with additional prestressing cables is compared to which one gets the lowest running results. The deflection data from the run analysis results are below in Table 1. Type 3 Cable Bridge shows a percentage result of around 49.46% for a speed of 40 km/hour, for a vehicle speed of 50 km/hour, and for a vehicle speed of 60 km/hour 63.26%. Type 1 Cable Bridge shows percentage results of around 52.89% for a speed of 40 km/hour, 64.24% for a vehicle speed of 50 km/hour, and 67.38% for a vehicle speed of 60 km/hour. Type 2 Cable Bridge has the lowest results in percentage, around 46.68% for a speed of 40 km/h, 48.60% for a vehicle speed of 50 km/h, and 49.91% for a vehicle speed of 60 km/h, indicating that This bridge has the best analytical performance among the cable bridges analyzed because the reduction in prestressed cable deflection is the lowest compared to other cable reinforcements.

This analysis shows that the comparison of the run analysis results of type 2 prestressing is the prestressing with a minor deflection reduction, namely 49.91%. This analysis indicates that the prestressing force applied to the cable is reasonable and efficient in supporting and strengthening the bridge with the vehicle load moving truck.

Type 2 is the best because this reinforcement is more efficient, namely reinforcement with external prestressing with support rods, which can provide minor deflection resistance. The prestressing force used on truss bridges provides a force that will reduce the tensile stress of the bridge truss using cables above the frame or steel rods placed at the upper end of the bridge structure.

3.2. Cable Type 2

It is known that the dimensions of the type 2 shown in Figure 6, cable after run analysis are as follows: dimensions of cable A to joint B = 10.606 m, cable B to joint C = 40.022 m, cable C to Joint D = 10.606 m,

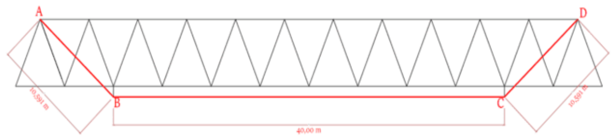

Figure 6. Cable type 2 geometric

The following are the steps for analyzing changes in cable length at a vehicle speed of 60km/hour on prestressed cables:

1. Initial Cable Length: The length of the cable before being subjected to the load of a moving vehicle.From point A to B, B to C, C to D = 10,591 + 40.00 + 10.591 = 61.182 m
2. Final Cable Length: The length of the cable after a prestressing force is applied. From point A to B, B to C, C to D = 10.606 + 40.022 + 10.606 = 61.234 m Change in Cable Length = 61.234 - 61.182 = 0.052

So it is known that the length dimensions of the Type E cable before the run analysis before being given a moving vehicle load is 61.182 m, and after being given a moving vehicle load is 61.234 m, the change in cable length that occurs is 0.052 m or if it is made into millimeters 52 mm. Figure 7 shows a steel truss bridge under a moving load, with color-coded stress distribution indicating compression in the top chord, tension in the bottom chord, and some diagonals. As the load moves, stress shifts, with peak forces near the midspan and supports. Cable strengthening can redistribute loads to enhance safety, reducing stress in critical members. High-tensile cables or fiber-reinforced composites must be carefully designed with secure anchorage to prevent failures. Dynamic effects from moving loads require damping to control vibrations, while fatigue resistance is crucial for long-term durability. Properly placed cables improve load distribution, structural stability, and bridge longevity, ensuring safety under repeated train crossings.

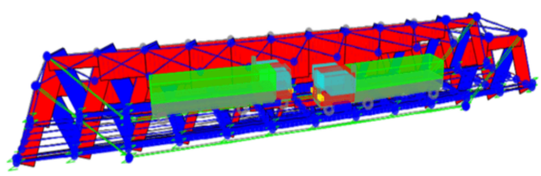

Figure 7. Axial force of steel bridge due to moving load

Based on the results of the analysis that has been carried out, it is found that the maximum moment force that arises due to the maximum load on joint 7 is 407,485 kN. From Figure 8 the bridge frame is safe because no data shows that the bridge frame is overstressed, and the picture also shows that in the picture after run analysis, there are no red frames, the frame is safe to use, and also

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the addition of external prestress cables is secure and efficient to use as a steel truss bridge strengthening.

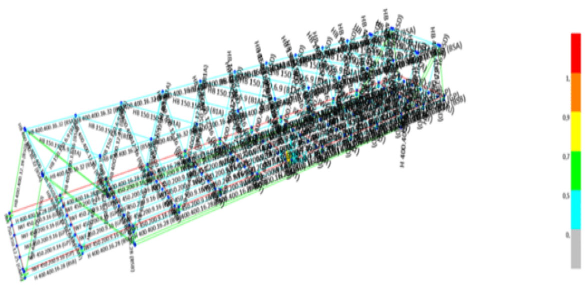

Figure 8. Stress ratio control for bridge structure

4. Conclusion

Based on the results of calculations and analysis that have been carried out on the data presented above, the following important conclusions can be drawn:

1. For the strand or external prestress diameter used in this research, a strand with a diameter of 98.7 mm (millimeters) was used for the left side of the strand, 2 strands, and for the right side of the strand, 2 strands. The viewing points determined for comparison of bridge structures when trucks move across the bridge are at point object 7 and joint object U3.
2. From this analysis, it is known that the comparison of the results of the run analysis of type E prestressing is the prestressing with the smallest reduction in deflection, namely 49.91%. This shows that the prestressing force applied to the cable is good enough and efficient to support and strengthen the bridge by the load of a moving truck. And the bridge frame is safe because no data shows that the bridge frame is overstressed and also, after run analysis, there are no red frames, the frame is safe to use for adding external prestressing cables to strengthen the steel frame bridge.

For further research, it is necessary to carry out more in-depth planning regarding steel frame bridge structures. It includes a detailed analysis of the foundation and the most suitable materials to ensure the strength and durability of the structure. Apart from that, it is also essential to consider environmental and geographical aspects that can affect the performance of the steel truss bridge. To increase the dynamic stability of the bridge structure when trucks move across the bridge, it is necessary to add more efficient reinforcement apart from external prestressing to prioritize strength with a longer service life than the reinforcement.

Acknowledgments

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