

Effect of Initial Arch Rib Angle Variation and Arch Height on Structure Performance of Tied Steel Arch Bridge

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Article Information	ABSTRACT
Article History Received : June 18, 2025 Revised : June 30, 2025 Published : July 12, 2025	Efficient use of materials in the tied arch bridge can be reach by optimizing it. This article examined initial arch angle and the top height effects. The use of initial angle (20°, 25°, 30°) combined with different top arch height (0,5 – 0,6 meter) is based on rise-span ratio 1:8 – 1:6,67. 9 bridge models are produced from these variations. This study aimed to minimizing deflection and weight for optimizing structural performance, thus decrease steel use also CO ₂ emissions for support Indonesia toward SDGs 2045. 3D model was analyzed using FEM (Finite Element Method) Software with a 250 kg mid-span load using the tributary method, which is simulating pedestrian weight transferred through the floor plate and tie chord. Analysis results showed that the arch initial angle and the top height affect the structural performance. With the best performance is showed by type 1.3 with 20° initial angle and top arch height (0,6).
Keywords: <i>Deflection;</i> <i>Initial Arch Angle;</i> <i>Rise-Span Ratio;</i> <i>Structural Performance;</i> <i>Model Scaled Bridge.</i>	

INTRODUCTION

Bridges are one of the important infrastructures in the transport aspect as well as supporting the economy and connecting regions in Indonesia (Lindawati et al., 2022; Nopiah et al., 2024). Based on data from (Kementerian PUPR, 2023). the National Road Condition Book 2023 2nd Semester Edition, of the 18,926 national bridges in Indonesia, 85.65% (16,210) bridges have a status of mild to severe damage, therefore routine supervision and innovation in bridge maintenance methods are needed which can facilitate monitoring of bridge health as well as, efficient use of bridge materials.

Commonly material which is used in bridges is a steel, according to (Fahimuddin et al., 2023; Qiu et al., 2024; Zhou et al., 2024) although it is subject to corrosion if improperly maintained, it is flexible, installation is not too complicated, and has good strength in resisting internal forces (tensile, compressive, and moment). However, the production of steel materials through smelting plants has a negative impact on the environment due to the amount of pollution caused, based on data obtained from (Schino, 2018; V. & Sheriff, 2024). 17-27% of CO₂ emissions in the world come from steel production with every 1 ton of steel production generating 1.91 tons of CO₂ (World Steel Association, 2024). Therefore, structural performance optimization is needed to reduce use of steel, decrease emissions and support Indonesia toward number 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 13 (Cimate Action) goals in SDGs (Sustainable Development Goals) (Alisjahbana & Murniningtyas, 2018).

One type of bridge is a tied arch bridge. The strength of a tied arch bridge depends on the arch as the main structure, the arch function is to receive compressive forces and moments arising

from the distribution of loads from the bridge floor to the hanging cables held by the arch (Brunn, 2016; Finke, 2016). This bridge is ideal for use as a long span bridge and more economically favourable than trusses, tied cables, and suspension system because the structural weight is lighter and required fewer materials to build, besides it can become an icon of an area due to its beautiful parabolic shape (de Ville de Goyet, 2020; Husen et al., 2021).

FEM (Finite Element Method) based software is often used as a tool for structural analysis, which can be a solution to determine the optimal design (Zhu et al., 2023). However, its use for analysis is limited to optimizing the shape of the pennant after the design and configuration have been modelled (Latif & Saka, 2019). Bridge design optimization can be done by changing the number and configuration of spacings between hangers after the arch design has been modeled (Alfarisi et al., 2025; Tan & Yao, 2019). According to the study of (Bathista et al., 2024). the configuration of the spacing between hangers getting closer to the center will result in a stronger structural system and also be weight efficient which directly makes for good structural performance.

However, before the optimization of the hanger, it is necessary to optimize the shape of the arch, based on the study (Songbes & Leman, 2023). The Rise-span ratio of 60 meters span tied arch bridges, is quite influential on the strength of the arch in resisting the internal forces that occur, with the conclusion that the optimum rise-span ratio number is 1:8 - 1:2. Unfortunately, that study only modeled the arch with a rise-span ratio, it is not yet known how the initial angle of the arch rib is also affecting the structural performance. Therefore, this research will be optimizing rise-span of the arch rib ratio with the initial angle, it is hoped that the results of this study will reduce the use of materials also CO₂ emissions while still considering structural performance and SDGs (Sustainable Development Goals) aspect.

RESEARCH METHODS

Methodology

Reducing weight and controlling deflection is becomes a way to structural performance optimization for tied arch bridges. The arch rib plays an important role in receiving the load distributed from the suspension then countering the compressive axial and large moment forces that happen due to the load, therefore optimizing the starting angle and peak height of the arch can reduce the material used. The author create a flowchart as showed in **figure 1**, to find the optimal initial angle and height of the top arch. Literature study became first step of the author to find prior research that is similar in some way and uses the invention.

FEM (Finite Element Method) based software was used as a tool for the bridge model/design analysis process. The modeled bridge geometry included variations in the initial arch angle and top arch height as independent variables as well as the spacing between hangers, bridge width, and bridge length as fixed variables. Thereafter, modeling the load combinations and loading applications required in performing the analysis.

After the modeling is complete, structural checks are needed to ensure that the structure can withstand the loads and internal forces that occur, which can later be indicated by the force capacity ratio that does not exceed the limit according to (SNI 1729:2020). “Spesifikasi Baja Untuk Bangunan Struktural”, in addition, the deflection value is also controlled so that the result does not exceed the permissible limit according to (RSNI T-03-2005) “Perencanaan struktur baja untuk jembatan” and for loading using tributary loads as shown in Figure 1, as well as for combinations based on (SNI 1725:2016)

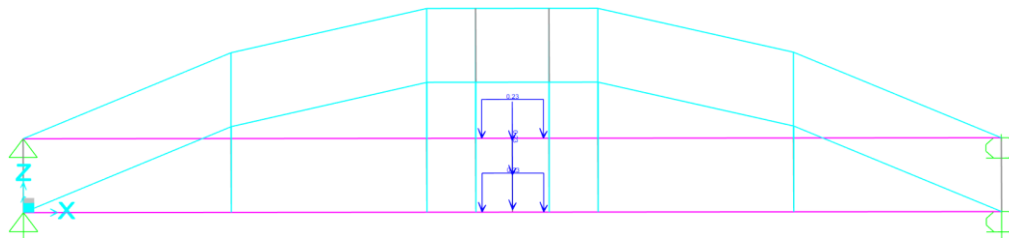


Figure 1 Illustration of the live load that occurs

After analyzing the model through the software, further evaluation and analysis of the capacity ratio limit and deflection of the structure are carried out. In this stage, the inner forces, deflection and the bridge structural weight will be analyzed for comparison between models and types. The method is expected to yield the optimal starting angle and arch height, which can decrease maintenance costs and materials.

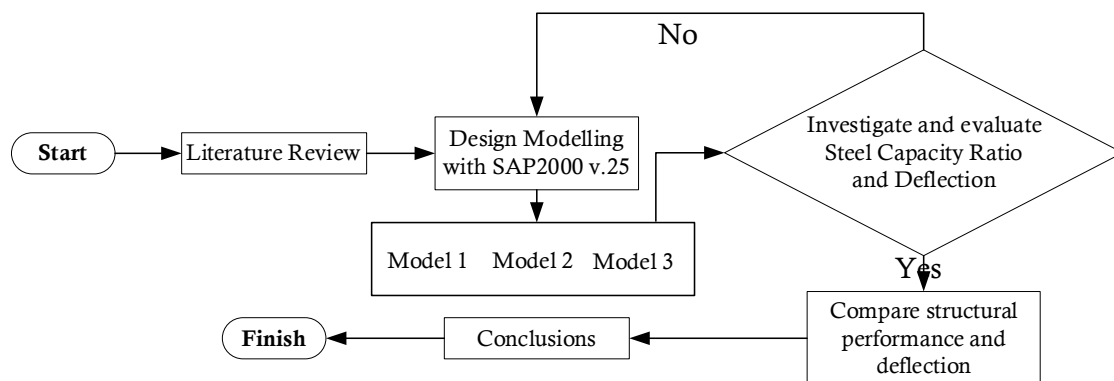


Figure 2 Flow Methodology for Optimization of Initial Angle and Height of Arch-rib on Tied Arch Bridges

These methods certainly have boundary, if the model applied to actual bridges, it need further research and analysis, because the author used small-scale experimental models. In addition, the load modelling is done with the application of evenly distributed loads only in the middle span of the bridge and does not take into account actual loads such as wind or rain. Nonetheless, this methodology can still be considered for decision-making for tied arch bridges blueprint.

Materials

The primary structure of the arch bridge consists of the arch rib, hanger, bottom chord, and tie chord. Since the research was only conducted use a small scaled model bridge, The bracing, and stringers are not required. However, structural materials for the bridge profile elements, is sourced from materials that are widely used and available in the market, the following material data is shown in **Table 1**.

Table 1 Materials Grade Specifications For The Bridge

Materials	Specification	Values
SS304	Yield Strength (Fy)	215 MPa
	Ultimate Stress (Fu)	505 MPa
	Density-	8000 Kg/m ³
	Young's Modulus	193000 MPa
SS400	Yield Strength (Fy)	245 MPa
	Ultimate Stress (Fu)	400 MPa
	Density-	7850 Kg/m ³
	Young's Modulus	200000 MPa

Source: (JIS G3101, 2021)

Bridge Structure Modelling

The author uses FEM (Finite Element Method) based software, to simplify and facilitate the analysis process.

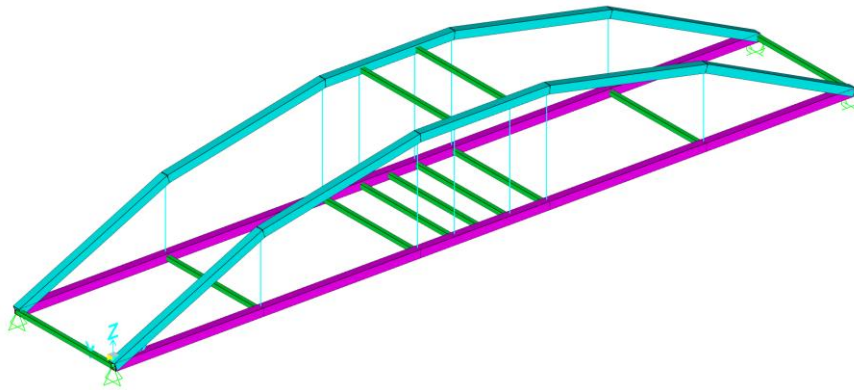


Figure 3 Isometric view of modelling with FEM (Finite Element Method) based software

This research uses a scaled model bridge to simplified modelling and accelerate analysis. With the same top arch height at each variable of initial arch angle and defined based on a rise-span ratio (L/f) are 1:8 - 1:6.67 (Songbes & Leman, 2023). As well as the initial starting angle of the arch rib from 20° - 30° (in increments of 5°). The bridge model has the following geometry: 4 m span, 0.6 m width, joint-roller support, height that varies with the initial angle variable, the optimal distance between hangers (0.8 - 0.85 - 0.2 - 0.3 - 0.2 - 0.85 - 0.8) and have a role as pedestrian bridge. The profile used is the result of the experiment, namely: 4x4x0.2 cm box (top chord), 4x4x0.1 cm box (bottom chord), 2x2x0.14 cm (tie chord), and 7x7 $\varnothing$ 6 mm SS 304 steel cable (hanger).

Initial Angle and Arch Height Configuration

In this bridge model, the arch becomes the main structure to resist the internal forces resulting from the loads acting on the bridge, therefore configuration optimisation can improve efficiency in terms of either structural performance or cost



Figure 4 Bridge modelling notation

The optimization used the three variables of initial arch angle, while the arch height also consisted of three configurations as sub-types: (1), (2), and (3), which will be shown in **Table 2**

Table 2 Bridge Model Configuration

Type	Initial Arch Angle (r°)	Arch Height (f)	Rise/Span ratio
1.1	20°	0,5	1:8
1.2	20°	0,55	1:7,27
1.3	20°	0,6	1:6,67
2.1	25°	0,5	1:8
2.2	25°	0,55	1:7,27
2.3	25°	0,6	1:6,67
3.1	30°	0,5	1:8
3.2	30°	0,55	1:7,27
3.3	30°	0,6	1:6,67

Bridge Loading

Structure's own dead load (DL) and live load (LL) is applied in the analysis without any other loads because, the author only examine the weight, maximum internal forces, mid-span deflection, and structural performance to determine the profile and cross-section dimension requirements, considering that the bridge load represents pedestrians gathered in the middle of a bridge span.

A tributary load at the middle of the span are applied with 250 kg live load (LL) based upon (SNI 1725:2016). The load combo used is strength 1, which is 1.1 (DL) + 1.8 (LL), without considering the wind load.

Deflection

Based on the regulation (RSNI T-03-2005). $L/800$ is used for the bridge maximum deflection, which indicate in this case it is 5 mm. With this maximum deflection, all types of bridge configurations analyzed in this study must meet this value, if any type of model later exceeds the deflection limit, it can be concluded that the model fails and changes are needed to make it eligible.

Steel Capacity Ratio and Internal Force Analysis

According (SNI 1729:2020), For single and double symmetrical structural members that retain flexural and compressive loads, a check must be made for the combination of forces acting in one of the most critical bar elements using equation H1, equation (1) is used when the ratio between axial force required is less than 0.2, but if it is more than 0.2 then equation (2) is used.

$$\frac{P_r}{P_c} + \frac{8}{9} \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \leq 1.0 \quad (1)$$

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \leq 1.0 \quad (2)$$

With details, P_c (capacity of axial force, kN), P_r (required axial strength force, kN), M_c (capacity of flexural force, kNm), M_r (required flexural strength, kNm). However, the use of FEM (Finite Element Method) software also automatically calculated moment and axial force capacities and verified manual using Microsoft excel as tool for calculate, based on SNI 1729:2020. If there is a slight difference, the largest from the two will be taken.

The nominal of tensile force is calculated sequentially using the equation (SNI 1729:2020), using D2 section as follows: equation (3) is yielding strength at the gross cross-section, and equation (4) is breaking strength at the net cross-section.

$$\phi P_{nt} = 0.9 F_y A_g \quad (3)$$

$$\phi P_{nt} = 0.75 F_u A_e \quad (4)$$

With, F_y (yield strength, MPa), A_g (the gross area of structural component, mm^2), F_u (breaking strength, MPa), and A_e (netto area of structural component, mm^2). Furthermore, the compressive force capacity is calculated using the equation (SNI 1729:2020), E3 section, as follows: F_{cr} (critical stress) is times by A_g (gross area), equation (5), and for F_{cr} (critical stress) nominal use, equation (6).

$$\phi P_{nc} = 0.9 F_{cr} A_g \quad (5)$$

$$F_{cr} = (0.658^{F_y/F_e}) F_y \quad (6)$$

For the calculation of structural design against flexure with compact wings and body using (SNI 1729:2020), F7 section, the nominal bending force, M_n , should be taken as the lowest value under plastic moment and lateral torsional buckling conditions, the local buckling conditions of the wing and body are not applicable as all profiles are compact.

$$M_n = M_p = F_y Z_x \quad (7)$$

With, Z_x (plastic modulus, mm^3), when $L_p \leq L_b$, then it can be calculated by equation (7), when the lateral torsional buckling condition applies with $L_p < L_b \leq L_r$, nominal M_n become, equation (8). However, if $L_r < L_b$, the M_n nominal become, equation (9).

$$M_n = C_b \left((M_p - (M_p - 0.7F_y S_x) \left(\frac{L_b - L_p}{L_b - L_p} \right)) \right) \leq M_p \quad (8)$$

$$M_n = 2EC_b \frac{\sqrt{JAg}}{L_b} \leq M_p \quad (9)$$

With, L_b (length of element, mm), L_p (the limit of unreinforced length for the yield strenght limit state, mm), S_x (the elastic modulus of section, mm^3), J (torsional constant, mm^4), and L_r (length limit for unreinforced laterally with inelastic lateral torsional buckling state, mm).

Structure Performance

According to (Alfarisi et al., 2025). A data ranking approach is used by the authors to evaluate the structural performance of each model by examining mid-span deflection and bridge weight. By using mathematical formula, performance scores will be generated on a scale from 0 to 1, with 1 representing optimal performance and 0 indicating poor performance.

$$\text{Value} = 0,5 \left(\frac{\text{weight}_{\min}}{\text{weight}_i} \right) + 0,5 \left(\frac{\text{Deflection}_{\min}}{\text{Deflection}_i} \right) \quad (10)$$

RESULTS AND DISCUSSION

The analysis examines how the configuration of arch height and initial arch angle influence the structural performance that focusing on axial, moments and shear force. Since this research aim is the initial arch angle and the top height of the arch or basically the variable effect mostly on the arch rib, analysis and results will be focused within the arch rib structure only (Liu et al., 2023). Meanwhile the total of structural weight and deflection will be also checked for analyzing the structural performance. The internal forces for analysis will use an envelope values for critical conditions. And for the last step, the structure must be ensured safely by checking the capacity ratio using FEM (Finite Element Method) based software and manual equations based on (SNI 1729:2020, 2020).

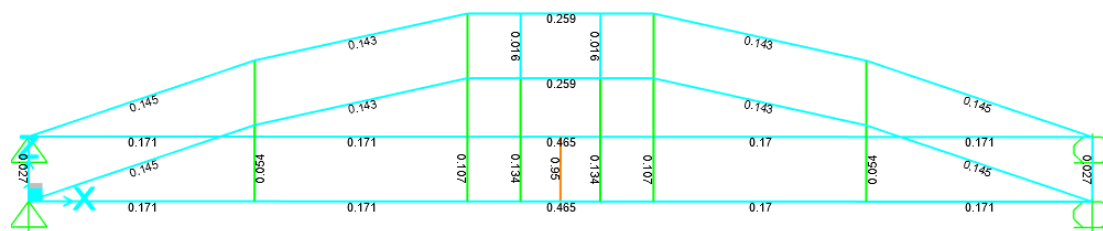


Figure 5 Capacity ration from FEM (Finite Element Method) based software analysis results

Arch Rib Structural Analysis

Moment, shear, and compressive axial capacity is determined for The analysis of arch rib strength. The capacity analysis was carried out based on SNI 1729:2020, the following analysis results are showed up in Figure 6. The results show that, type 3.3 has the smallest compressive axial force. As for the moment, the smallest force is obtained in type 3.1. After averaging, the compressive force in all variations is 6.37%, the moment is 27.95% and the shear force is 17.74% of the available capacity. Type 3.3, has the lowest axial compressive force percentage of 5.63%, type 3.1 has 13.27% which is the lowest moment percentage and type 1.3 has 15.89% which is the lowest shear percentage.

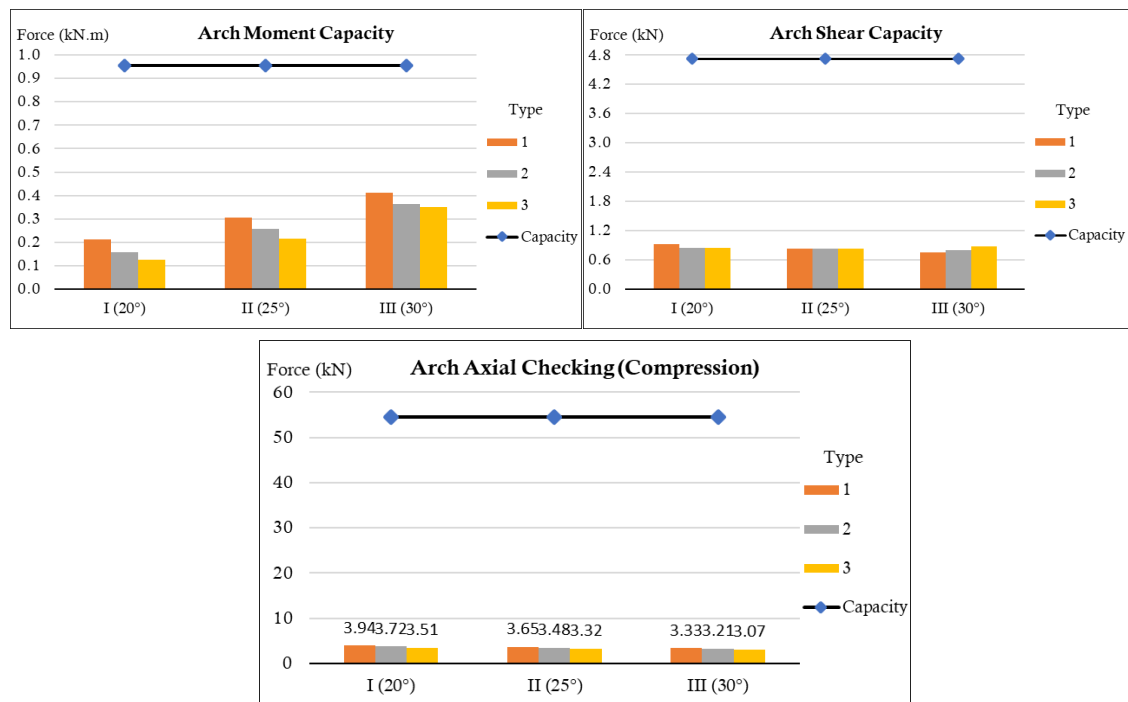


Figure 6 Comparison chart of moment, shear, and axial (compression) force in arch structure

Deflection Analysis

Based on the results, all variations in types 3.1 - 3.3 and 2.3 were declared failed because the deflection that occurred exceeded the requirements with a value of (>5 mm), while all variations in types 1 and 2 (2.1 and 2.2), met the deflection requirements with a value of (<5 mm), but structural performance analysis was still carried out to all types of models because the focus of this research is to find the effect of variations in the initial arch angle and height of the top arch with deflection and structural weight.

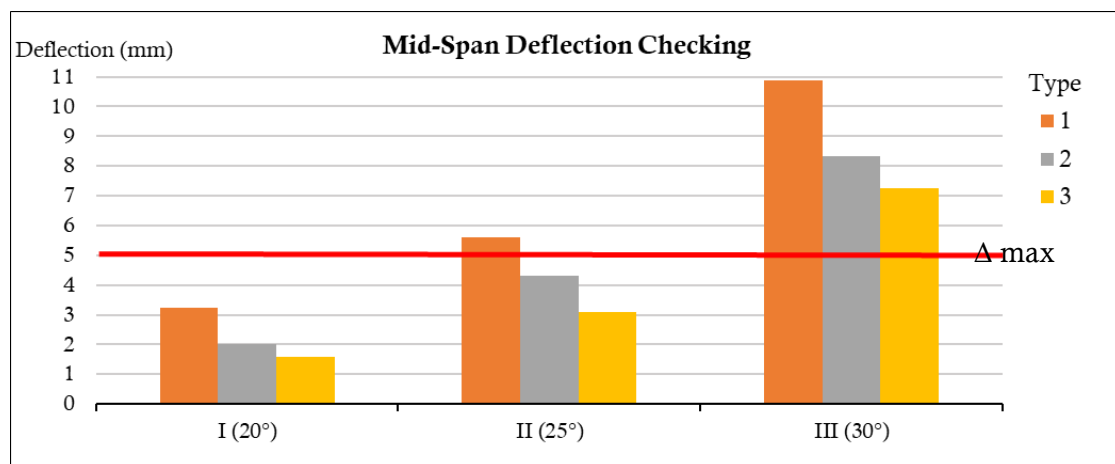


Figure 7 Comparison chart for mid-span deflection from each type of bridge

Structural Element Weight Analysis

According to analysis, type 1 with (20° initial arch angle and 50 cm arch height) is the lightest model, from this it can be seen, use of 20° initial arch angle can reduce the structural weight compared to 25° or 30° initial arch angle which is shown in type 2 and 3. The average percentage is 0,54% (compared to type 2) and 1,59% (compared to type 3).

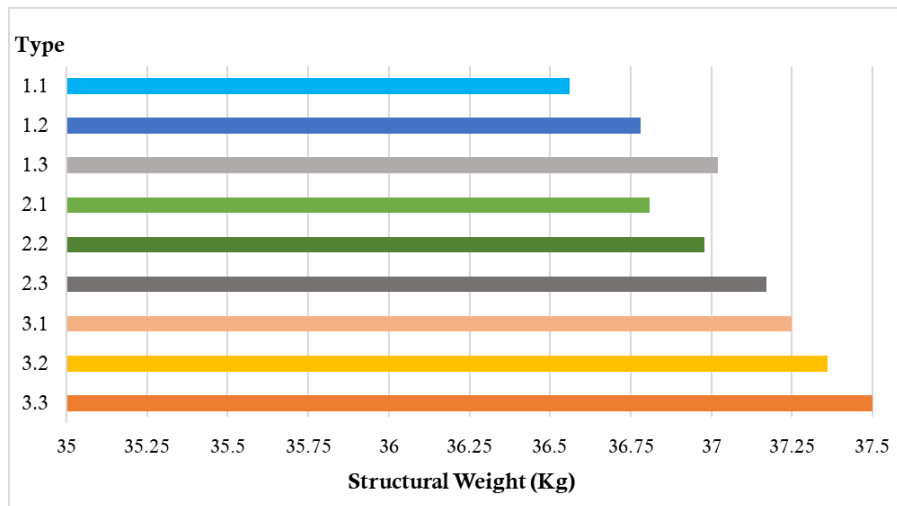


Figure 8 Structure weight comparison chart from each type of bridge

Structural Performance Analysis

As shown below by **Figure 9**, type 1.3 is has the highest structural performance rating with almost perfect score (0,99), also the model has smallest mid-span deflection (1,587 mm).

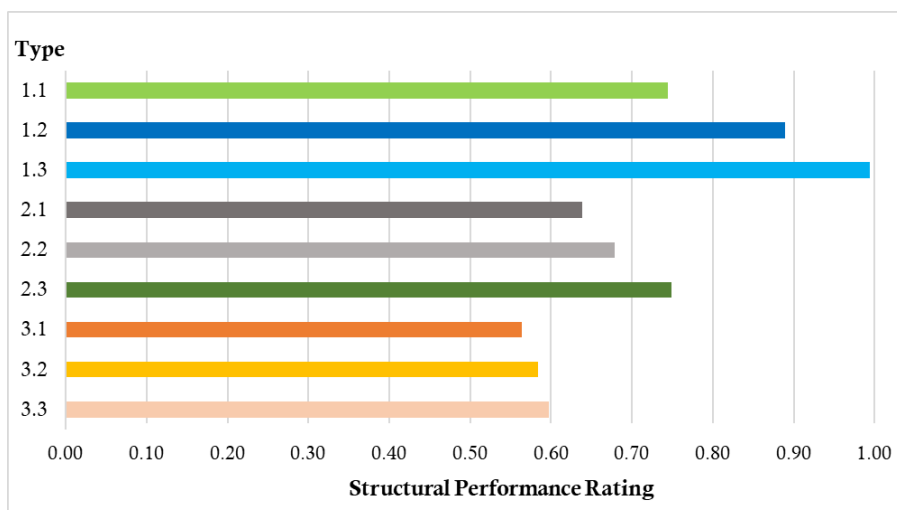


Figure 9 structural performance values Comparison chart from each type of bridge

CONCLUSION

This research proves that there is an effect of starting angle and arch height on bridge performance. Type 1.3, a starting angle of 20° with a top arch height (0.6 m), provides optimal performance with deflections that are still within safe limits. Type 1 also has a lighter weight compared to types 2 and 3 which are heavier, this also shows that there is an effect between the height of the arch and the force in the bridge element, it is recommended that future researchers can examine this effect with variables in the form of a new loading layout for giving the best way to apply load on the bridge and the People's Representative Council of the republic indonesia with Ministry of Public Works and Housing can consider this research to support the Indonesia SDGs (Sustainable Development Goals) in 2045.

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