G-Tech : Jurnal Teknologi Terapan
Vol. 9, No. 4, October 2025, p. 1955-1965
E-ISSN: 2623-064X | P-ISSN: 2580-8737

Numerical Analysis of Arc Geometry Variations on Bending Stability in Tied-Arch Bridges

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Article Information

Article History

Received : September 08, 2025
Revised : October 01, 2025
Published : October 10, 2025

***Keywords*:**
Tied Arch;
Bending;
Modified Eigenvalue Method with SAP2000;
Linear Analysis;
Non-Linear Analysis.

ABSTRACT

Tied-arch bridges are bridges that have high structural efficiency, but are prone to bending instability. This study aims to analyse the relationship between arc geometry variations and the bending stability of tied-arch bridges using the Finite Element Method (FEM) based on SAP2000 software, employing both linear and non-linear approaches. The linear analysis results show that lateral arch deformation occurs, indicating the potential for global lateral instability of the arch. Meanwhile, the non-linear analysis, which considers the significant geometry effect (P-Δ), produces a bending capacity of 7.43-11.69 kN with a maximum deflection of -0.52 mm. Variations in the arch angle were found to affect the critical bending capacity without significantly impacting global deformation. These findings are expected to serve as a valuable reference for designers and structural engineers in determining optimal and efficient arch designs.

INTRODUCTION

Bridges are a crucial component of infrastructure that connect regions and support economic activity (Lai et al., 2023). In Indonesia, with its diverse geography and rapid economic growth, the development of bridge infrastructure has become a significant focus. Based on information from the Ministry of Public Works and Public Housing, the government has allocated a large budget, reaching hundreds of trillions of rupiah annually, for national strategic projects, including the construction of new bridges (DIrektorat Jenderal Bina Konstruksi Kementrian PUPR, 2025). In civil engineering, arch bridges have long been regarded as a practical and aesthetically pleasing structural solution, particularly for spans ranging from medium to long (Liu et al., 2023). Their main advantage lies in their ability to convert vertical loads into axial compressive forces, a highly efficient mechanism (Yang et al., 2023a). However, arch bridges are susceptible to bending (Z. Chen et al., 2022), a failure mode that can be very costly and requires detailed analysis. In the context of tied-arch bridges, which are increasingly popular in Indonesia, a significant design challenge often encountered is uncertainty regarding the most efficient arch geometry to resist bending (Järvenpää et al., 2020). Small changes in geometry can have a significant impact on structural stability, a crucial factor in ensuring the safety and efficiency of bridges.

A literature review reveals that the issue of deformation and structural stability has been thoroughly explored, with recent research focusing on the analysis of the complex behaviour of curved elements (Liu et al., 2023). Studies in the last ten years have discussed the significance of

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geometric factors, such as the ratio of the height of the curve to the span and the arrangement of the curve, in determining the critical bending load capacity. There is also research that explains the relationship between axial force and bending moment (Ma et al., 2020). With advances in computational technology, numerical analysis using the Finite Element Method (FEM) has become a standard and reliable method (Shabana, 2019). However, although many geometric factors have been studied, studies specifically investigating the effect of variations in the angle of inclination of the arc segment on tied-arch bridges with constant span and height are still minimal. Most previous studies have focused on the height-to-span ratio or the general shape of the curve, without discussing in detail how the slope angle of the arch segment contributes to bending stability. This knowledge gap underscores the need for further research to address this void, particularly in elucidating the quantitative relationship between the arch angle and the bending stability capacity of the structure.

Based on this background, this study has a precise and clear objective: to assess the effect of arc geometry variations on the bending stability of tied-arch bridges using the Finite Element Method (FEM) with both linear and non-linear approaches. Several bridge models with the same span, height, and material will be compared, with differences in the angle of inclination of the curved segments. With similar area loading, a bending analysis is performed to reveal the relationship between angle variation and stability, allowing for the identification of the most efficient arc geometry and the most vulnerable to bending.

The results of this study are expected to make a significant contribution to the civil engineering sector. Scientifically, this study will deepen our understanding of the complex relationship between arch geometry and the bending capacity of tied-arch bridges, in line with the latest research in this field. Practically, the results serve as a valuable reference for designers and structural engineers in determining arch designs that are not only attractive but also optimal in terms of safety and structural efficiency. By determining the most effective geometry, this study has the potential to reduce material usage without compromising strength and stability, thereby contributing to a reduction in overall bridge construction costs and carbon emissions from material production and transportation (K. Chen et al., 2024).

RESEARCH METHODS

The research methodology includes literature study, bridge modelling using SAP2000 v.22, and both linear and non-linear bending stability analysis on arc angle (α) variations. The research flow is shown in Figure 1.

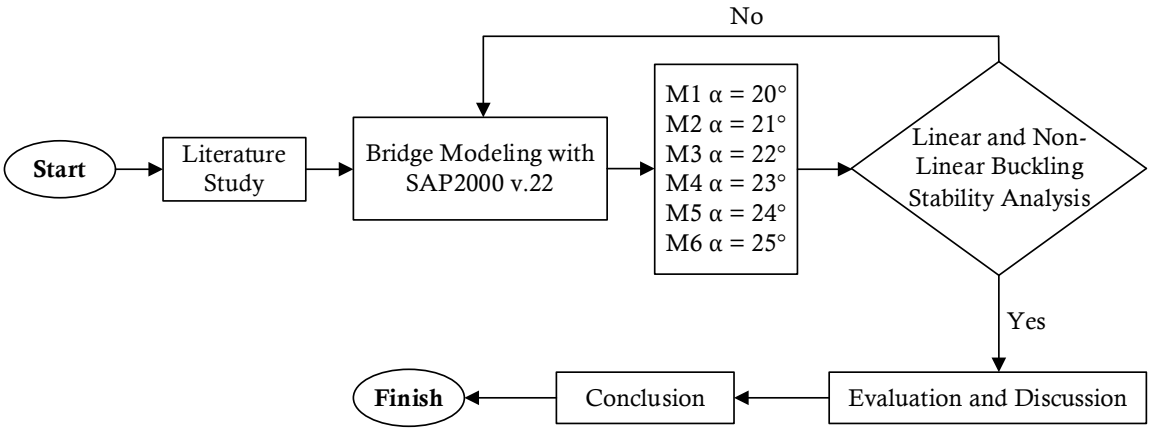

Figure 1. Flowchart of Research Methodology for Numerical Analysis of Arc Geometry Variations on the Bending Stability of Tied-Arch Bridges

Research Design

This study employs a quantitative approach, utilising simulation-based numerical analysis methods that rely on computational power to construct virtual models and accurately reproduce

bending phenomena (Pratama et al., 2019). The method used is the Finite Element Method (FEM), chosen for its ability to solve civil engineering problems that are difficult to handle analytically (Angoshtari & Matin, 2020). The FEM principle works by dividing complex structural domains into small elements (finite elements) that are interconnected through nodes (Li, 2021). With this method, the behaviour of each element can be described through simple equations and combined to obtain an estimated solution for the entire system. This method is highly effective because it converts problems that cannot be solved analytically into numerical problems that computers can handle. This enables the analysis of structures with complex geometries, nonlinear materials, and complex loading conditions. This analysis utilises SAP2000 software, a finite element method (FEM)-based application that can perform static and dynamic analyses, as well as two- and three-dimensional modelling (Lallotra & Singhal, 2017). This application was chosen because it supports nonlinear bending analysis and allows for efficient modelling of steel beam structures using frame elements.

Material Specifications

The primary material used for bridge components is structural carbon steel, although its characteristics may vary depending on the specific application. Material specifications are selected based on the properties of steel, which is considered homogeneous, isotropic, and exhibits linear elastic behaviour until it reaches its melting point (Z. J. Zhang et al., 2023). The material properties used in modelling are sourced from relevant technical standards and systematically compiled to ensure the reproducibility of the research. Material properties for the main structural profiles and suspension cables are determined separately. Table 1 presents the material properties details for the structural carbon steel profiles used in arches, tie beams, and cross girders, referring to the BJ 37 profile data.

Table 1. BJ 37 Material Specifications

Specifications	Value	Unit
Modulus of Elasticity (E)	200000	Mpa
Poisson's Ratio (v)	0,3	-
Yield Strength (Fy)	240	MPa
Tensile Strength (Fu)	370	MPa

(Badan Standarisasi Nasional, 2015)

Meanwhile, for the hanger cables, steel wire rope with different specifications, namely SS 316 Ø6 mm, is used. The hanger cables serve to transfer the load from the deck to the arch and only operate under tension (Reshi et al., 2021). For details on the materials, see Table 2.

Table 2. Material Specifications

Specifications	Value	Unit
Modulus of Elasticity (E)	200000	Mpa
Poisson's Ratio (v)	0,3	-
Yield Strength (Fy)	200	MPa
Tensile Strength (Fu)	500	MPa

(Kementrian PUPR, 2022)

Bridge Structure Types

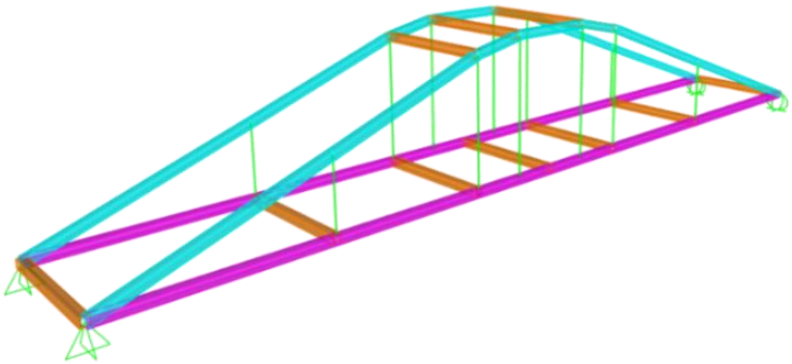

Figure 2. Bridge Structure Model

A tied-arch bridge is a type of bridge that relies structurally on curved beams (arches) and suspension cables (hangers) to support loads. One of the most important features of this type of bridge is the tie beam, which serves to resist the horizontal compressive forces generated by the arches, thereby preventing these forces from being transferred to the foundations (Jiang et al., 2019). As a result, the arch elements become part of the main structure operating under compressive conditions, making them highly susceptible to bending failure. The tied-arch bridge model in Figure 2 has a length of 4.4 meters, a width of 0.6 meters, and a height (y1 = 0.60 meters; y2 = 0.65 meters).

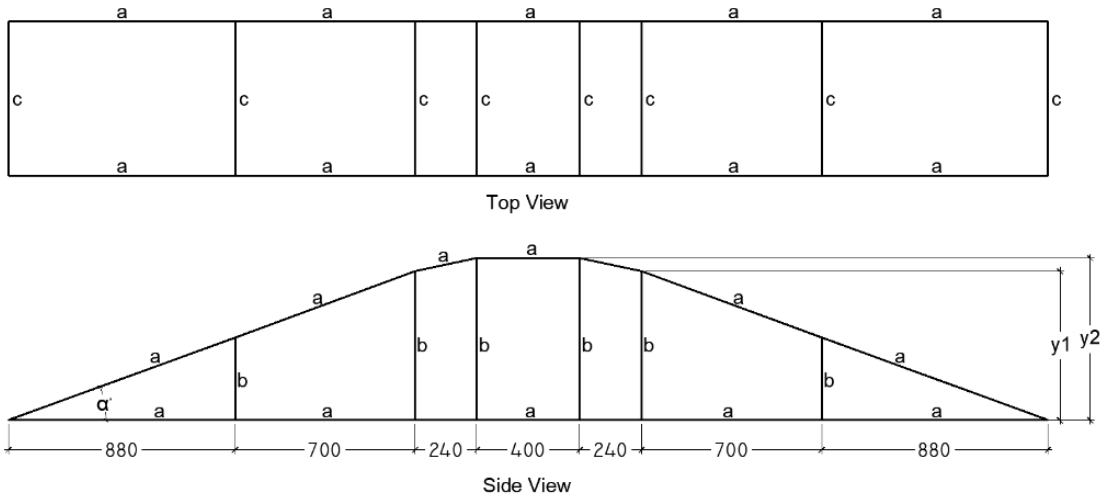

Figure 3. Bridge Size Specifications

Table 3. Bridge Material Specifications

Code	Bridge Material
a	Carbon Steel Hollow 35.35.2 mm
b	SS 316 Ø6 mm
c	Carbon Steel Hollow 30.30.1,5 mm

This bridge consists of separate segments. Each component is modelled using the most appropriate element type to accurately reproduce its structural behaviour, specifically frame or beam elements for arches, tie beams, and cross girders, as well as trusses or cables for suspension cables that can only withstand tensile forces. The structural material specifications for the bridge are presented in Table 3, which is illustrated in Figure 3.

Arc Geometry Variations

This study focuses on arc geometry variations based on the understanding that the shape of the arc in the main support structure can significantly reduce the moment value generated by external loads (G. Zhang et al., 2022). By modifying the geometric angle, the distribution of compressive forces on the arch and its bending stiffness can be fundamentally changed. Thus, bending analysis is not only a secondary safety evaluation, but the essence of the structural behaviour of this type of bridge.

In this study, the length, width, and height of the bridge were set at fixed dimensions and remained unchanged. The primary parameter that was altered was the arc angle (α), as illustrated in Figure 3. This angle was varied in the range of 20° to 25°. This variation was based on previous studies, which demonstrated that small changes in arc curvature could have a significant impact on the bridge's strength. Various configurations were then modelled to analyse the effect of the arc angle on bending stability, as shown in Table 4.

Table 4. Bridge Arch Geometry Variations

Bridge Specimen	Arc Angle (α)
M1	20°
Bridge Specimen	**Arc Angle (α)**
M2	21°
M3	22°
M4	23°
M5	24°
M6	25°

Boundary Conditions and Loading

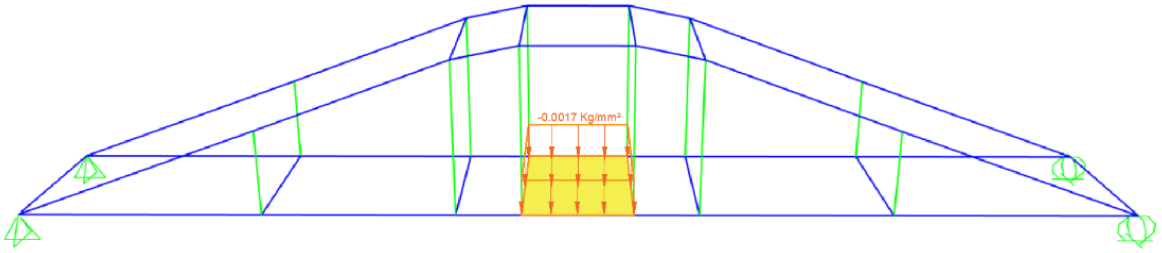

Figure 4. Load Conditions

The boundary conditions in the model are designed to represent the bridge placement conditions in the field. The supports are modelled as pinned supports and roller supports. The loading is applied with the following combination:

$$1{,}1D + 1{,}8L \quad (1)$$

Explanation:
D : dead load (kg)

L : live load (kg)

In accordance with the SNI 1725:2016 standard related to loading (Badan Standardisasi Nasional, 2016). Dead load includes the weight of the bridge structure itself, including steel materials, while live load is modelled as an area load of 400 kg on the middle floor of the bridge. Because the live load is in the form of an area load on the slab, the input into the SAP2000 software is done by converting the total load into a uniform load on the slab, using the formula:

$$q = \frac{W}{A} \quad (2)$$

Explanation:
q = area load (kg/m²)

W = applied load (kg)

A = slab area (m²)

In this study, the slab area used is 600 × 400 mm. This formula refers to the basic principles of engineering mechanics in load distribution (Hibbeler, 2018). Thus, a live load of 0.0017 kg/mm² was obtained. A visualisation of the boundary conditions and load distribution is shown in Figure 4, which presents the layout and loading direction of the bridge model.

Bending Stability

This research is based on structural stability theory, which explains instability as a situation where changes in the shape of a structure or its elements under compressive force result in a loss of load-bearing capacity. The phenomenon of bending is a manifestation of this instability, which occurs when slender structural elements under compressive loads undergo significant lateral deformation that is disproportionate to the increase in load (Taranu et al., 2025). The highest load that a structure can support before bending occurs is called the critical load (Pcr), a concept first proposed by Leonhard Euler (Franklin et al., 2022). To obtain accurate and comprehensive results, this study applies a mutually supportive two-stage approach, namely linear bending analysis and non-linear bending analysis.

Linear Bending

The first stage of analysis was performed using the Eigenvalue Bending Analysis method. This analysis is an effective computational process for estimating the theoretical critical bending load and deformation mode shape (eigenmode shape) of a perfect structure. This approach assumes that the material has linear elastic behaviour and undergoes minimal deformation (Eltaher et al., 2020). The primary outcome of this analysis is the critical load factor (λ), which is a load multiplier that characterises the state of the structure when it reaches theoretical bending. The critical load factor formula is:

$$\lambda = \frac{P_{cr}}{P_{app}} \quad (3)$$

Explanation:
λ = critical load factor

Pcr = critical load (kN)

Papp = design load (kN)

Linear bending analysis is an instrumental initial diagnostic tool for identifying the most vulnerable parts of a structure to instability. Additionally, the initial bending mode shape generated by this analysis serves as the basis for modelling initial geometric imperfections in subsequent nonlinear analyses.

Non-Linear Bending

Although linear bending analysis can provide initial estimates, the results tend to be less efficient because they ignore important elements that occur in real conditions, mainly geometric non-linearity. Thus, the next step is to perform a non-linear bending analysis to obtain more accurate and realistic results. This analysis considers geometric non-linearity, specifically through the P-Delta effect. In SAP2000, P-Delta analysis enables the modelling of structural shape changes resulting from large deformations, where axial forces (P) acting on elements with lateral deformations (Δ) generate additional moments that can reduce the structure's load capacity (Adam et al., n.d.).

Processing and Interpretation of Results

Data from the analysis results will be processed to answer research questions, including Critical Load Factor (λ), Load–Displacement Curve, Critical Bending Load (Pcr), as well as Bending Modes and Deformation Shapes. The analysis focuses on comparing the structural performance of various geometric models, with an emphasis on load-displacement curves that show the effect of geometric changes on critical loads and post-bending capacity. These results will determine the most balanced arch configuration that strikes a balance between material efficiency and bending stability.

RESULTS AND DISCUSSION

The analysis was conducted in two steps: linear bending analysis (eigenvalue bending analysis) and non-linear bending analysis, taking into account the P-Δ effect. The results obtained included the overload factor (λ), load-displacement graphs, maximum bending load values (Pcr), and descriptions of the bending modes. Furthermore, the data is evaluated and discussed to identify the impact of arc geometry variations on the overall bending capacity and stability of the bridge.

Linear Bending Stability Analysis

The results of the linear bending analysis (eigenvalue bending analysis) provide the critical load factor (λ) and the dominant bending mode of the tied-arch bridge with varying arc angles (α). Mode 1 was selected for analysis. Table 5 shows the results of the critical load factor evaluation.

Table 5. Linear Bending Analysis Results

Bridge Specimen	Critical Load Factor (λ)	Critical Load (kN)	Dominant Bending Mode
M1	3,718	14,574	Global lateral bending of the arch
M2	4,491	17,604	Global lateral bending of the arch
M3	4,544	17,811	Global lateral bending of the arch
M4	4,591	17,997	Global lateral bending of the arch
M5	4,641	18,193	Global lateral bending of the arch
M6	4,687	18,373	Global lateral bending of the arch

The first bending mode in Table 5 exhibits lateral curvature deformation, indicating a potential loss of global lateral stability for the arch. The results of the linear analysis show a consistent increase, i.e., the greater the arch angle, the higher the critical bending load that can be withstood. The most efficient model is found in M5 (angle 25°) because it can withstand the most significant critical load with a load factor of 4.687, resulting in a critical load of 18.373 kN. The results of this analysis serve as the basis for determining the initial imperfection in the nonlinear analysis stage.

Nonlinear Bending Stability Analysis

A nonlinear bending analysis was performed to determine the actual bending capacity, taking into account geometric nonlinearity (P-Δ effect). The load-displacement curve (Figure 5) indicates that the structure's capacity fluctuates with variations in the arc angle (α). This phenomenon indicates that changes in geometry affect the stiffness of the structure, where a certain angle provides more optimal conditions for withstanding bending loads.

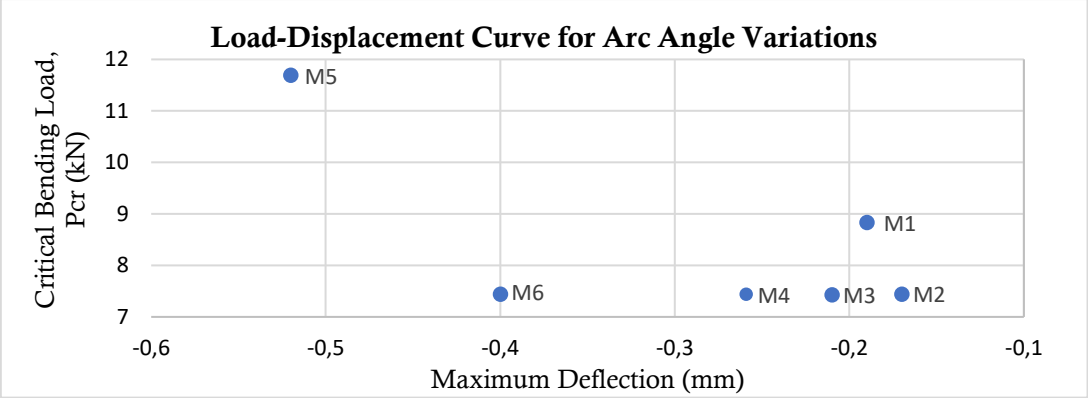

Figure 5. Load-Displacement Curve for Arc Angle Variations

The critical bending load (*Pcr*) is obtained from the maximum point of the curve. The results of the Pcr value evaluation for each angle variation are shown in Table 6 with descriptions taken from Mode 1.

Table 6. Non-Linear Bending Analysis Results

Bridge Specimen	Critical Bending Load (Pcr) (kN)	Maximum Deflection (mm)
M1	8,83	-0,19
M2	7,44	-0,17
M3	7,43	-0,21
M4	7,44	-0,26
M5	11,69	-0,52
M6	7,44	-0,40

According to Table 6 Non-Linear Bending Analysis Results, the critical bending load (Pcr) for arc angle (α) variations of 20°–25° ranges from 7.43 kN to 11.69 kN, with deflections ranging from -0.17 to -0.52. The minimum Pcr value was obtained at M3, with a value of 7.43 kN, while the maximum value was recorded at M5, with a value of 11.69 kN. This model proved to be the most efficient. This difference suggests that the variation in arc angle geometry affects the structure's ability to support critical bending loads, consistent with previous literature studies (Wang & Zhang, 2024).

Evaluation and Discussion

The results of the linear bending stability analysis in the arc angle range of 20°–25° show that the critical load factor (λ) increases consistently from 3.718 to 4.687. This increase indicates that the larger the arc angle, the higher the structure's capacity to withstand critical bending loads. The dominant mode observed is global lateral bending, which is consistent with the finding that arch structures, due to high axial compressive forces, are more prone to global instability than local element failure (Z. Zhang et al., 2024).

Conversely, the results of non-linear bending analysis, which takes into account significant geometric effects (P-Δ effects), yield actual bending capacity (Pcr) in the range of 7.43–11.69 kN and deflection ranging from -0.17 to -0.52 mm. The load-displacement curve (Figure 5) exhibits fluctuations in capacity due to variations in the arc angle, indicating that geometric variations have a significant impact on the structural stability. This phenomenon aligns with a numerical study of instability analysis in tied-arches, which confirms that various geometric configurations and support systems can impact the maximum capacity against instability (Yang et al., 2023b).

A comparison between the two methods — linear and nonlinear — illustrates a fundamental difference. Linear analysis only provides initial estimates and shows consistent increases, but does not reflect post-critical behaviour or in-situ structural deformation. In contrast, nonlinear analysis is capable of accurately reflecting the actual bending capacity and structural

deformation response, making it a more suitable basis for evaluating the stability of tied-arch bridges. These findings align with the literature, which emphasises the importance of considering nonlinear geometric effects to produce more realistic results in the design and evaluation of structural instability (Z. J. Zhang et al., 2023).

In addition, the study findings confirm that increasing the arc angle indeed plays a role in improving bending stability until it reaches an optimal point; however, structural efficiency does not always increase linearly (Silva-Campillo et al., 2023). Beyond a certain angle, adding arc geometry can increase the load and complexity of force distribution, which actually reduces structural effectiveness (Messaoudi & Kiss, 2023). Therefore, an integrated approach combining non-linear numerical analysis with parametric optimisation and experimental validation is required to achieve an optimal arch geometry design in terms of stability and material efficiency (Goldbach et al., 2020).

Thus, non-linear analysis using the finite element method has proven to be more accurate in assessing the actual bending behaviour of tied-arch bridges and can serve as a basis for developing an integrated analysis model that considers geometric effects, materials, and overall structural system interactions.

CONCLUSION

The analysis results indicate that variations in arc geometry have a significant impact on the bending stability of tied-arch bridges. At arc angles of 20°–25°, linear analysis produces a consistent increase in critical bending capacity, reaching a maximum of 18.373 kN at an angle of 25° (M5). At the same time, non-linear analysis provides a lower but more realistic actual capacity in the range of 7.43–11.69 kN, with relatively small deflections (−0.17 to −0.52 mm). Based on Table 6, the most efficient model is M4 (24°) with a Pressure of 11.69 kN. An increase in the arc angle is in line with an increase in the bridge's bending stability until it reaches the optimal angle, after which its effect tends to decrease. Therefore, non-linear analysis is considered more accurate for assessing the stability of tied-arch bridge structures; thus, it is considered more representative in evaluating the stability of tied-arch bridges.

ACKNOWLEDGEMENTS

The author expresses gratitude to God Almighty for His blessings, which made it possible for this article to be completed. The author would also like to thank the Department of Civil Engineering and Planning at the State University of Malang for its support and facilities, the supervising lecturer for his guidance and knowledge, and his parents and friends for their prayers, support, and encouragement.

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