Fırat Üniversitesi Deneysel ve Hesaplamalı Mühendislik Dergisi

Kemer Taşıyıcı Sistemli Yığma Taş Köprülerin Geometrik Özellikleri Üzerine Parametrik Çalışma

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Öz

Bu araştırmada, açıklık boyutları, yükseklik ve kemer kalınlığı gibi ayırt edici özellikler göz önünde bulundurularak yığma kemerli köprülerin hesaplamalı modelleri oluşturulmaya çalışılmaktadır. Kemer genişliği modelleme süreci boyunca sabit bir parametre olarak tutulmuştur. Bu hesaplamalı temsillerin oluşturulması amacıyla sonlu elemanlar analiz yazılımı olan, ANSYS sürüm 16 kullanılmıştır. Bu köprülerin yapısal bütünlüğünü ve yük taşıma kabiliyetlerini değerlendirmek için, yükleme senaryoları hem köprünün orta bölümüne hem de kemer açıklığının dörtte birine uygulanmıştır. Bu amaçla benimsenen analitik metodoloji statik itme analizidir. Daha sonra, çalışmada kemerlerin geometrik özelliklerinin yük taşıma kapasiteleri üzerindeki etkisi derinlemesine incelenmiştir. Bu araştırmanın bulguları, tamamen yıkılmış ya da kısmen yıkılmış olan tarihi köprülerin tekrardan inşa edilebilmesine rehberlik etme ve bilgilendirme konusunda potansiyel fayda sağlamaktadır.

Anahtar kelimeler: Yığma, Kemer köprü, İtme analizi

*Yazışılan yazar

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Parametric Study on The Geometric Properties of Masonry Stone Bridges with an Arch Carrier System

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Abstract
In this research, computational models of masonry arch bridges were constructed, taking into account distinctive features such as span dimensions, height, and arch thickness, while the arch width was maintained as a constant parameter throughout the modeling process. The finite element analysis software, ANSYS version 16, was utilized to create these computational representations. To evaluate the structural integrity and load-carrying capabilities of these bridges, loading scenarios were applied to both the center section of the bridge and a quarter of the arch span. The analytical methodology adopted for this purpose was static thrust analysis. Subsequently, the study delved into the influence of the geometrical characteristics of the arches on their load-carrying capacity. The findings of this research hold potential utility in guiding and informing the reconstruction of historic bridges that have been completely or partially demolished.

Keywords: Masonry, Arch bridge, Pushover analysis

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1. Introduction

Built to cross natural obstacles such as rivers and valleys, arch bridges have played a vital role in various civilizations over the centuries. While some of the arch bridges, which form an integral part of transportation networks, have stood the test of time and continue to fulfill their intended functions, others have become a popular destination for visitors and can be visited with guided tours.

Today, the construction of new structures has become relatively easy, but the assessment and maintenance of existing structures pose significant challenges. The conservation and restoration of bridges, symbols of our historical heritage, requires complex calculations and assessments. For example, when assessing the mechanical properties of the constituent elements of a historic masonry structure, precise results can be obtained through experimental techniques. In contrast, non-destructive methods used to preserve the historical integrity of these structures provide imprecise material information.

Similarly, while experimental studies can provide precise information on structural behavior under varying loads, the use of finite element analysis through a number of emerging technological platforms provides preliminary insights into structural behavior. Given the inherent complexity of determining the stiffness and reliability of heterogeneous structures in a nonlinear system, finite element analysis plays an important role in facilitating and accelerating the evaluation of various load carrying scenarios.

Bridges are conventionally engineered and constructed to accommodate the anticipated service loads. The assessment of intricate vertical movements in existing arch bridges can be effectively achieved through the development of precise computational models. Among the methodologies employed for the investigation of arch bridges, finite element analysis stands out as a prominent technique. The analysis of masonry arch bridges has garnered significant attention from numerous researchers, with a comprehensive compilation of these studies presented in the accompanying Table 1 for reference.

Table 1. Literature review

A. C., Aydin, and S. G.(Özkaya, 2018) [1]	The authors of this study conducted a comprehensive investigation aimed at elucidating the structural response of single-span masonry arch bridges when subjected to specific loading conditions. This analysis was conducted utilizing the pushover analysis method, which enables the assessment of structural behavior under gradually increasing loads until failure or a predefined limit state is reached. To facilitate this analysis, finite element simulations were employed, leveraging the capabilities of the ANSYS software program.
Galasco et al. (2006) [2]	In their research, the authors employed the static pushover analysis method to meticulously monitor and record the magnitude of horizontal displacement exhibited by a masonry structure in a systematic and incremental manner. This method enables a detailed examination of the structure's response to progressively applied lateral forces, facilitating a comprehensive understanding of its behavior under such loading conditions.
S. Resemini, and S., Lagomarsino, (2007) [3]	Within their study, the authors undertook a comprehensive examination encompassing both pushover and dynamic analyses of a three-dimensional (3D) masonry bridge. The outcomes derived from the dynamic analyses served to corroborate and validate the findings obtained from the pushover analyses. This convergence of results between the two analytical methods underscores the robustness and consistency of their research outcomes.
M., Yazdani, and M. S. Marefat, (2013) [4]	In order to assess the seismic performance of a reinforced concrete bridge with an arch design, the authors employed a nonlinear static analysis method, commonly referred to as a pushover analysis. This analysis method was applied to the bridge structure, focusing on its response to lateral forces in the horizontal direction. Through this approach, the authors aimed to evaluate how the bridge would behave under seismic loading conditions, particularly emphasizing its resistance and deformation characteristics.

Table 1. Literatüre review (Continue)

Y. C. Loo, (1995) [5]	In their study, the authors investigated a nonlinear finite element approach suitable for the progressive collapse analysis of masonry arch bridges. Among the various material properties investigated in their case study, only the influence of the wall tensile strength σ_t and the (post-cracking) stress softening parameter N on the collapse behavior of the arch bridge was investigated.
Pelà et al. (2013) [6]	Within their research, the authors conducted a comparative assessment to gauge the efficacy of nonlinear static analysis in relation to a comprehensive suite of 84 nonlinear dynamic analyses. The examination was carried out with a particular focus on a critical node positioned at the center of mass of the bridge structure. The results of this investigation indicated that the selected node at the center of mass exhibited superior performance, highlighting its effectiveness in capturing the bridge's seismic behavior compared to the extensive set of nonlinear dynamic analyses.
Caglayan et al. (2012) [7]	In their study, the authors created a three-dimensional finite element model of the reinforced concrete bridge through the utilization of finite element analysis software. This model was meticulously calibrated by incorporating structural parameters derived from both dynamic and static tests. Subsequently, the calibrated finite element model was harnessed as a tool for conducting structural evaluations, enabling a comprehensive assessment of the bridge's behavior and performance characteristics.
Choo et al. (1990) [8]	In their research, the authors delved into an examination of the structural behavior of masonry arch bridges, employing the finite element method as their analytical approach. They further undertook a comparative analysis by juxtaposing the outcomes of their finite element simulations with empirical data obtained from experimental tests conducted on brick arch bridges. This investigative strategy allowed the authors to assess the accuracy and validity of their computational model by contrasting it with real-world experimental observations, thereby enhancing the comprehensiveness and reliability of their findings.
Çakır et al. (2015) [9]	In their study, the authors developed a new approach for determining the most suitable arch form for different loadings in the loading analysis performed with the help of finite element program.
A., Brencich, and R. Morbiducci, (2007) [10]	The authors endeavored to bridge the gap between ancient masonry arch bridges and contemporary scientific knowledge. In pursuit of this objective, they engaged in the modeling and analysis of these historical structures through the utilization of computer software. Their focus revolved around estimating the load-carrying capacities of bridges featuring diverse geometrical configurations, primarily by conducting vertical loading analyses. This approach allowed them to glean insights into the structural performance and capacity of these bridges, effectively aligning their historical significance with modern analytical methodologies.
Bayraktar et al. (2010) [11]	The authors of the study engaged in a comprehensive exploration of the dynamic properties of the masonry bridge, encompassing analytical and experimental predictions of key characteristics such as natural frequency, mode shapes, and damping ratio. To achieve this objective, they harnessed the finite element method as a computational tool. In their pursuit of accuracy, they refined their bridge models to minimize disparities between the results obtained from experimental modal analyses and their corresponding analytical counterparts. This iterative process of model improvement and validation allowed for a more precise and reliable assessment of the bridge's dynamic behavior.
S., Toker, and A.İ., Ünay, (2004) [12]	In their research, the authors endeavored to employ mathematical modeling techniques to simulate the response of an arch sample, designed to represent typical examples of arched stone bridges, when subjected to various load scenarios. Through these mathematical models, they sought to gain insights into how such bridges would behave under different types and magnitudes of loads, thereby contributing to a better understanding of their structural performance and resilience.

Table 1. Literatüre review (Continue)

Callaway et al. (2012) [13]	The authors of this study conducted an investigation to assess the influence of backfill on the load-bearing capacity of a masonry arch bridge. To carry out this examination, they utilized a set of 27 small-scale arch bridges in their experimental analyses. Subsequently, they compared the outcomes obtained through their experimental testing with the analysis results generated using Ring 3.0 analysis software. This comparative analysis enabled them to evaluate the correspondence between their empirical findings and the computational predictions, shedding light on the impact of backfill on the structural performance of masonry arch bridges.
T., Uçar and G., Şakar (2021) [14]	The authors present an approach to simplify the solution of arches under vertical loads and their modeling in computerized analysis programs has presented.
Boothby et al. (1998). [15]	In their study, the authors performed analyses to investigate the behavior of masonry arch bridges under truck load. Their analyses with finite element program It has been guiding in modeling masonry arch structures, determining material properties for infill and selecting stiffnesses.
Ş., Sözen M., Çavuş (2020). [16]	In their study, the authors investigated the earthquake performance of a sample bridge that has undergone geometric form changes over time using ANSYS finite element program. They performed static and time domain analysis for both the old and the new state of the bridge and investigated the stress and deformation conditions. It is concluded that the change in geometric form has a positive effect on the earthquake performance of the bridge.
A., Özmen, and E., Sayın, (2020). [17]	In their study, the authors performed linear analyses to determine the behavior of a single span masonry bridge under earthquake action. The seismic response of the bridge was evaluated by using the acceleration records of the 2011 Simav and 2002 Sultandagi earthquakes in the solid model obtained using ANSYS finite element program.
E., Yılmaz, G., Sayın, E., Sayın, A., Özmen, (2022). [18]	In their study, the authors investigated the single span Murat Bey Bridge as a numerical application. A three-dimensional finite element model was created with SAP2000 finite element program. Time-history analysis method was applied for the seismic evaluation of the bridge. Acceleration records of 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes were used in the dynamic analysis, and the displacement and stress graphs obtained as a result of the analysis were analyzed.
Zampieri et al (2020) [19]	In this study, the authors conducted a study to evaluate the vertical load capacity of single span masonry bridges. The study was carried out for the retrofitting of the bridges considered. Analyses were performed for pre-strengthening and post-strengthening.

2. Material and Method

Numerous methodologies have been developed for assessing the performance of masonry arch bridges, with the finite element method being one of the prominent approaches. This method encompasses both linear elastic and nonlinear elastic analyses. Linear elastic finite element analysis allows for the calculation of deformations within masonry arch bridges but does not provide insights into the collapse mechanism or collapse load. Consequently, it primarily serves to estimate the structural behavior of the bridge.

In contrast, nonlinear static pushover analyses are employed to determine the maximum displacement and, consequently, the collapse load of the structure. This method, as described by M.S. Marefat et al. [20], was utilized in the study to assess the behavior of masonry arch bridges under vertical loading conditions. The capacity curves generated through pushover analyses furnish valuable information regarding the maximum load-bearing capacity and associated maximum displacement from initial cracking to the point of collapse. The material properties used in the computational models were derived from existing literature, ensuring accuracy and consistency in the analytical approach.

The material properties employed in the modeling of the bridges under investigation within the context of the study have been documented and are available in Table 2 of the work authored by Barış Sevim and colleagues. [21] This table likely provides essential details regarding the mechanical characteristics and properties of the materials used in the computational models, ensuring transparency and replicability in the research methodology.

Table 2. Material properties

Materials Properties	Modulus of Elasticity (MPa)	Poisson Ratio	Mass Density (kg/m³)	Value of Cohesion (N/mm²)	Angle of Friction	Compressive strength (N/mm²)	Tensile strength (N/mm²)
Arch Stone	3000	0.25	1600	-	-	5	0.03
Spandrel Walls	2500	0.20	1400	-	-	5	1
Backfill Material	1500	0.05	1300	0.03	34º	-	-
Foundation Rock	15000	0.20	2350	-	-	5	1
Loading Plate	-	200000	0.3	-	-	-	-

In the process of creating finite element models using ANSYS software for the masonry structures, an assumption was made that the material behavior of masonry is akin to that of concrete. Consequently, the concrete material model was chosen for the ANSYS finite element models. ANSYS offers a range of material properties suitable for reinforced concrete elements, and within this framework, the Willam-Warnkle (1975) [22] criterion, employing a five-parameter SOLID65 element, was integrated into the software for the analysis. For boundary conditions, it was assumed that all degrees of freedom were constrained in all directions at the base or ground level of the bridge, which is a common approach in structural analysis to represent the bridge's connection to its foundation.
The Willam-Warnke model with five parameters was used as the material model. These parameters are given in Table 3.

Table 3. Willam-Warnke failure surface parameters

Parameter	Definition
f_t	Ultimate uniaxial tensile strength
f_c	Ultimate uniaxial compressive strength
f_{cb}	Ultimate biaxial compressive strength
f_1	Ultimate compressive strength for a state of biaxial compression superimposed on hydrostatic stress state (ζh)
f_2	Ultimate compressive strength for a state of uniaxial compression superimposed on hydrostatic stress state (ζh)

The Willam-Warnke model is based on the tensile and compressive strengths of the stone to study the fracture behavior of the material. This model shows the plastic behavior of single span masonry arch bridges more realistically. However, in the analysis of structural systems such as masonry structures, where it is reasonable to assume that materials exhibit negligible tensile strength under compressive loads, the application of the Willam-Warnke model alone may be considered appropriate as it avoids problems of stress localization between material elements. Figure 1 presents a uniaxial stress-strain relationship, providing a graphical representation of the material's behavior.

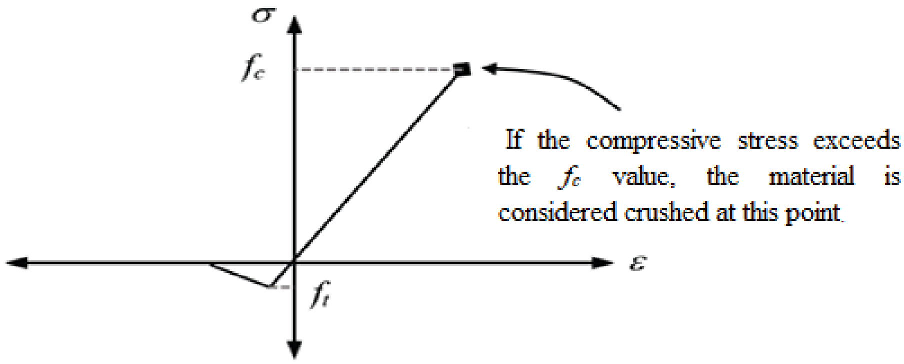


Figure 1. Willam-Warnke uniaxial stress state in ANSYS (version 16) [23]

The finite element software ANSYS (version 2016) [23] was utilized to conduct the structural analyses of the bridges.

Masonry structures exhibit variations based on construction techniques, material properties, and geometric characteristics. In this study, the width of the retaining walls (spandrel wall widths) and the width of the arches were held constant, while the arch span, arch height, and arch thickness were allowed to vary. Spandrel wall width and Arch width are the same in all models and are 0.3m and 2.6m respectively. Table 4 presents the geometric properties of these bridges.

Table 4. Geometrical properties of the model bridges

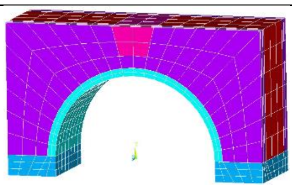
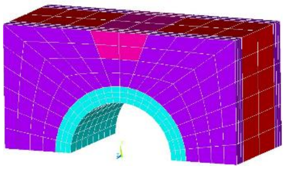
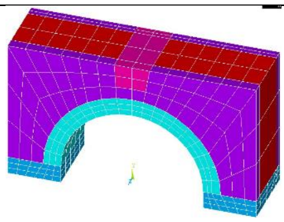
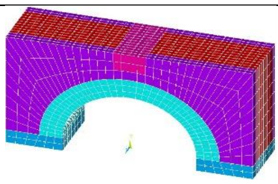
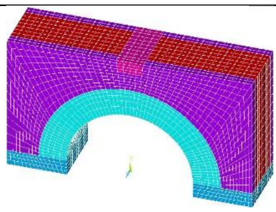
Bridge Model No	Arch radius(r)	Arch thickness(t)	Arch height(h)	Total length
 Model 1a	2m	0.2m	3.2m	4.4m
 Model 1b	2m	0.3m	3.3m	4.6m
 Model 1c	2m	0.5m	3.5m	5.0m
 Model 1d	2m	0.7m	3.7m	5.4m
 Model 1e	2m	0.9m	3.9m	5.8m

Table 4. Geometrical properties of the model bridges (Continue)

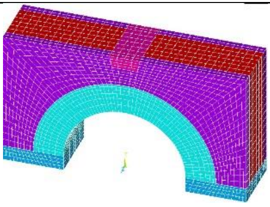
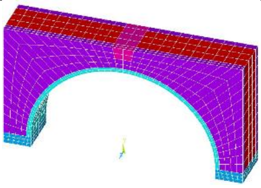
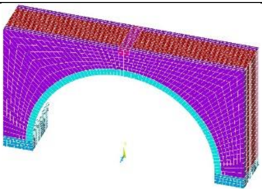
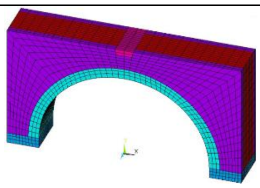
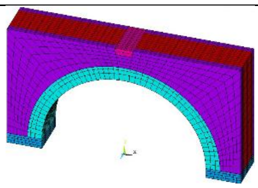
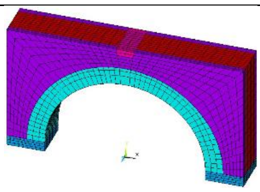
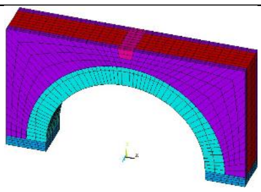
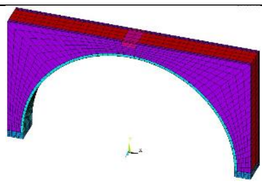
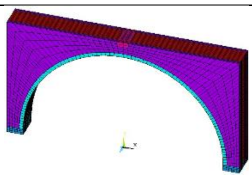
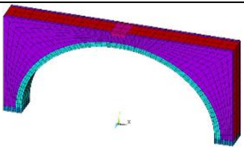
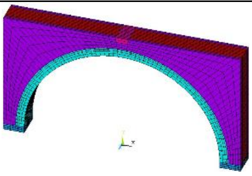
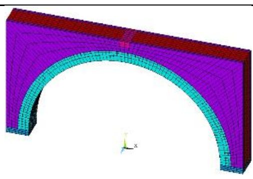
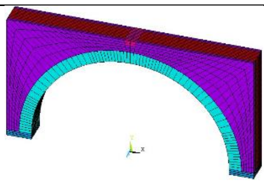
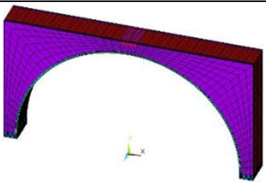
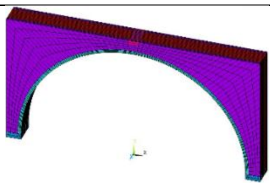
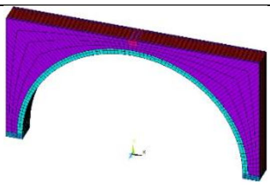
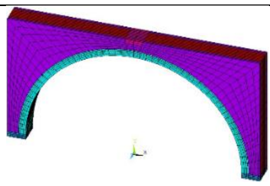
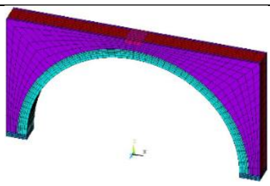
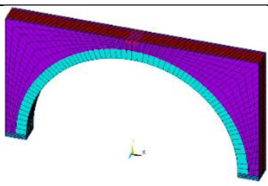
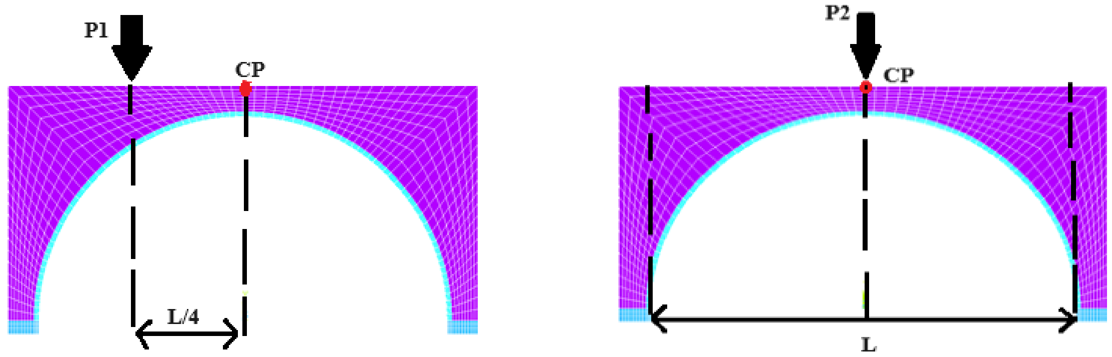
 Model 1f	2m	1.0m	4.0m	6.0m
 Model 2a	4m	0.2m	3.2m	4.4m
 Model 2b	4m	0.3m	3.3m	4.6m
 Model 2c	4m	0.5m	3.5m	5.0m
 Model 2d	4m	0.7m	3.7m	5.4m
 Model 2e	4m	0.9m	3.9m	5.8m
 Model 2f	4m	1.0m	4.0m	6.0m
 Model 3a	6m	0.2m	3.2m	4.4m
 Model 3b	6m	0.3m	3.3m	4.6m

Table 4. Geometrical properties of the model bridges (Continue)

 Model 3c	6m	0.5m	3.5m	5.0m
 Model 3d	6m	0.7m	3.7m	5.4m
 Model 3e	6m	0.9m	3.9m	5.8m
 Model 3f	6m	1.0m	4.0m	6.0m
 Model 4a	8m	0.2m	3.2m	4.4m
 Model 4b	8m	0.3m	3.3m	4.6m
 Model 4c	8m	0.5m	3.5m	5.0m
 Model 4d	8m	0.7m	3.7m	5.4m
 Model 4e	8m	0.9m	3.9m	5.8m
 Model 4f	8m	1.0m	4.0m	6.0m

3. Experimental Results

In accordance with findings from prior literature studies, specifically referencing the work of Cavicchi and Gambarotta [24], loading conditions were applied to two distinct locations on the arch of the bridges. A total of 24 bridge models were considered for analysis, and these loadings were implemented both at the center of the arch and at a position corresponding to one-quarter (L/4) of the arch span in the vertical direction. In order to calculate the vertical load capacity of the bridge, PD1, PD2 loads were applied as separate analysis cases as vertical displacement load at L/4 of the span length and at the midpoint of the arch, respectively. The reference displacement reading (control) point CP is shown in Figure 2.



L/4 load application

Center load application

Figure 2. Finite element model and load application locations for vertical loads

The loading configurations applied at the center of the arch are visually represented in the Figures 3 below.

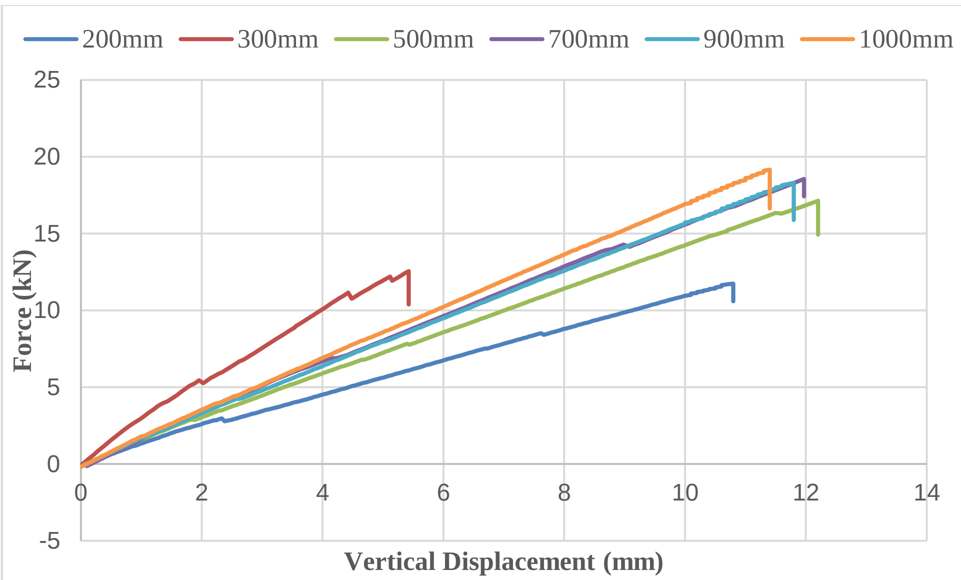


Figure 3. Loading at the center of the arch of a bridge with a radius of 2m

Based on the analyses conducted by applying vertical loads to the midsection of the arches, each with a radius of 2 meters and varying arch thicknesses ranging from 0.2 meters to 1.0 meter, several key findings were obtained:

Maximum Displacement: The largest vertical displacement observed in these analyses was 12.2 millimeters, and it occurred in the bridge with an arch thickness of 500 millimeters.

Maximum Load-Carrying Capacity: The bridge with an arch thickness of 1.0 meters demonstrated the highest total load-carrying capacity, reaching 19.15 kN.

Loading Method: The loads were applied by defining a steel plate in the area where the load was intended. These loads were applied in the form of displacement loads in the vertical direction.

Effect of Arch Thickness: Generally, it was observed that both the total displacement and the total load-carrying capacity increased as the arch thickness increased. This suggests that thicker arches exhibited greater stiffness and load-carrying capacity.

Crack Initiation and Progression: The initiation and progression of cracks were primarily observed in the region where the loading was applied, ultimately leading to the collapse of the bridge.

These findings underscore the importance of arch thickness in determining the structural behavior and load-carrying capacity of masonry arch bridges. Thicker arches tend to offer greater resistance to vertical loads, but eventual cracking and collapse may still occur under excessive loading conditions. The deformation of the bridge models in the 2m radius bridge models in the loading cases applied at the midpoint of the arch span is given in the Figure 4.

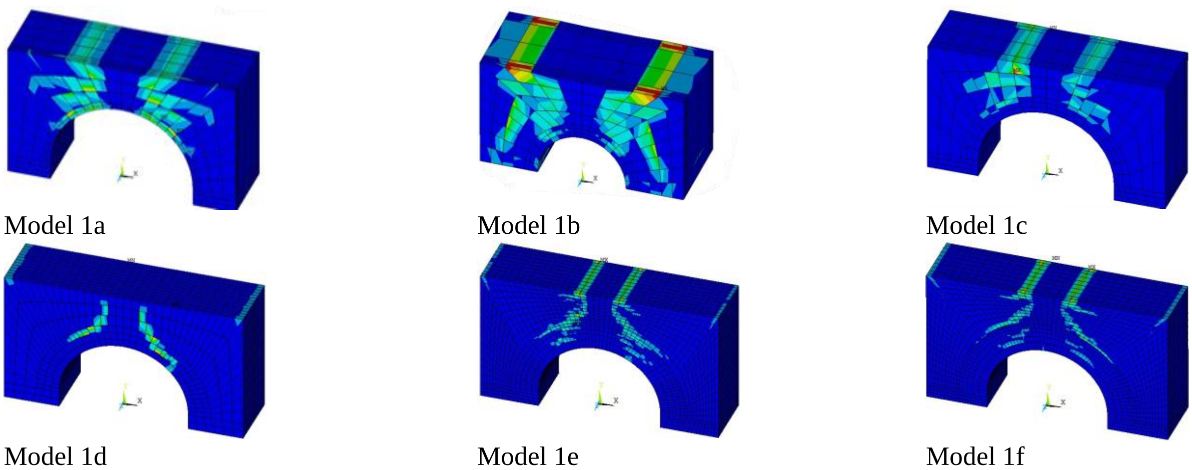


Figure 4. The deformation of the bridge models for midpoint loading case

In the study involving bridges with a larger radius of 4 meters (Figure 5), several notable findings were observed:

Maximum Displacement and Load Capacity: Among the bridges analyzed, the one with an arch thickness of 900 millimeters exhibited the largest displacement, measuring 20.13 millimeters. Additionally, this same bridge displayed the highest load-carrying capacity, with a value of 139.44 kN.

Crack Initiation and Propagation: Similar to the previous analysis, it was observed that crack initiation and propagation predominantly occurred in the region where the load was applied. This behavior is consistent with the earlier findings.

Comparative Displacements: Interestingly, the vertical displacements of the bridges with arch thicknesses 700 mm and 900 mm were nearly identical to each other. This suggests that the arch thickness within this range did not significantly affect the resulting displacements.

Impact of 1-Meter Arch Thickness: However, when the arch thickness increased to 1 meter, both the displacement and load-carrying capacity decreased. This indicates that a 1-meter arch thickness led to reduced structural performance compared to the 0.9-meter arch.

These findings underline the complexity of the relationship between arch thickness and bridge behavior. While thicker arches generally provide higher load capacity, there can be a point beyond which increasing thickness may lead to diminished performance. The specific behavior appears to be influenced by the interplay of multiple factors and structural characteristics.

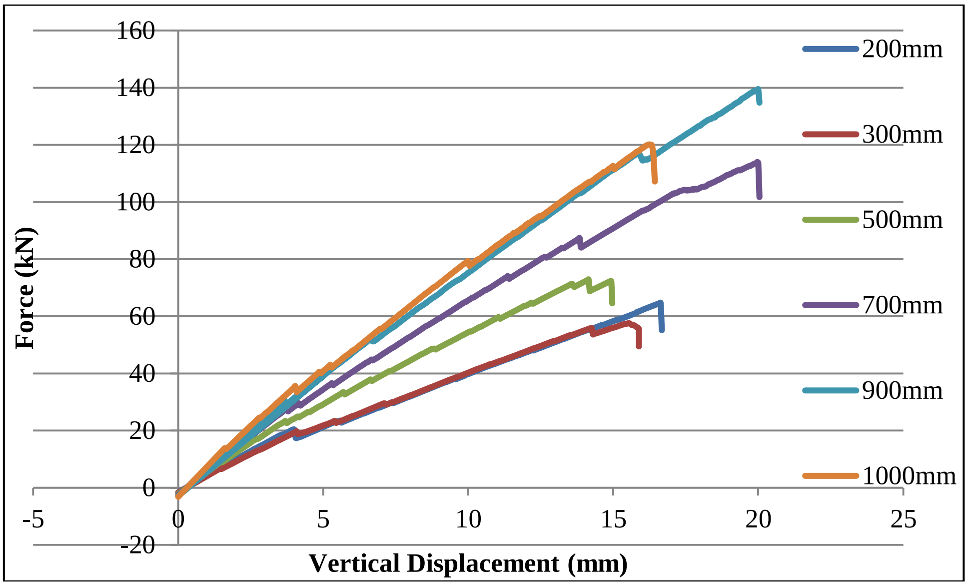


Figure 5. Loading at the center of the arch of a bridge with a radius of 4m

The deformation of the bridge models in the 4m radius bridge models in the loading cases applied at the midpoint of the arch span is given in the Figure 6.

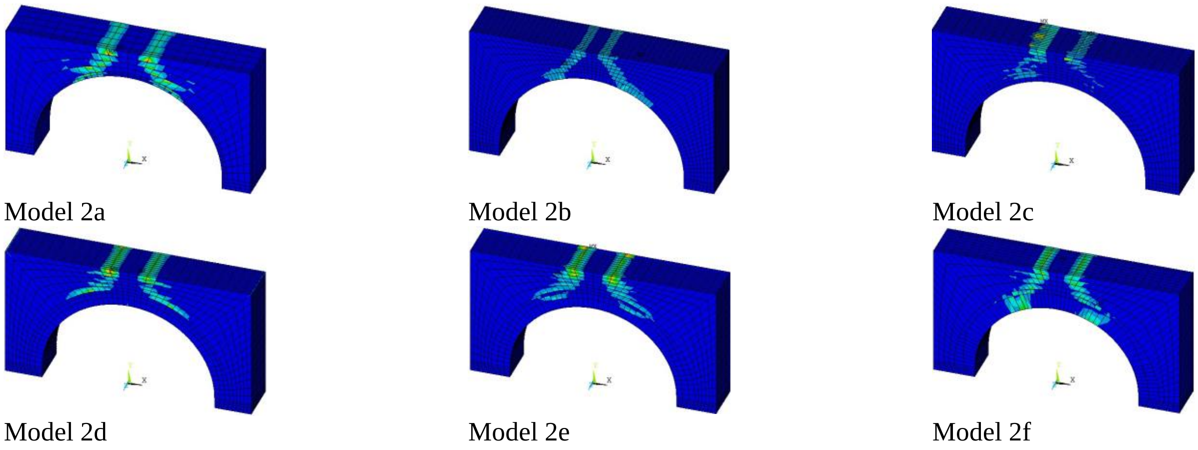


Figure 6. The deformation of the bridge models for midpoint loading case

In the study involving bridges with a larger radius of 6 meters (Figure 7), the following key observations were made:

Maximum Displacement and Load Capacity: Among the bridges analyzed, the one with an arch thickness of 500 millimeters exhibited the largest vertical displacement, measuring 35.23 millimeters. Additionally, this same bridge displayed the highest load-carrying capacity, with a value of 74.94 kN.
Crack Progression: It was noted that the crack propagation was consistent across all bridges, regardless of the specific arch thicknesses. The tensile stresses under vertical displacement load reached the permissible masonry tensile strength, especially in the upper sides of the arch, posing a risk for damage.

Collapse: Ultimately, all the bridges in this study experienced collapse, which was expected given the observed crack progression. The structural behavior reached a point where the bridges could no longer support the applied loads, leading to their collapse.

These findings emphasize that, in the context of bridges with a larger radius of 6 meters, arch thickness significantly influenced both displacement and load-carrying capacity. Thinner arches 500 mm exhibited higher load capacity but also experienced larger displacements before reaching the point of collapse. Additionally, it is noteworthy that the crack progression behavior remained consistent across all bridges, contributing to their eventual failure.

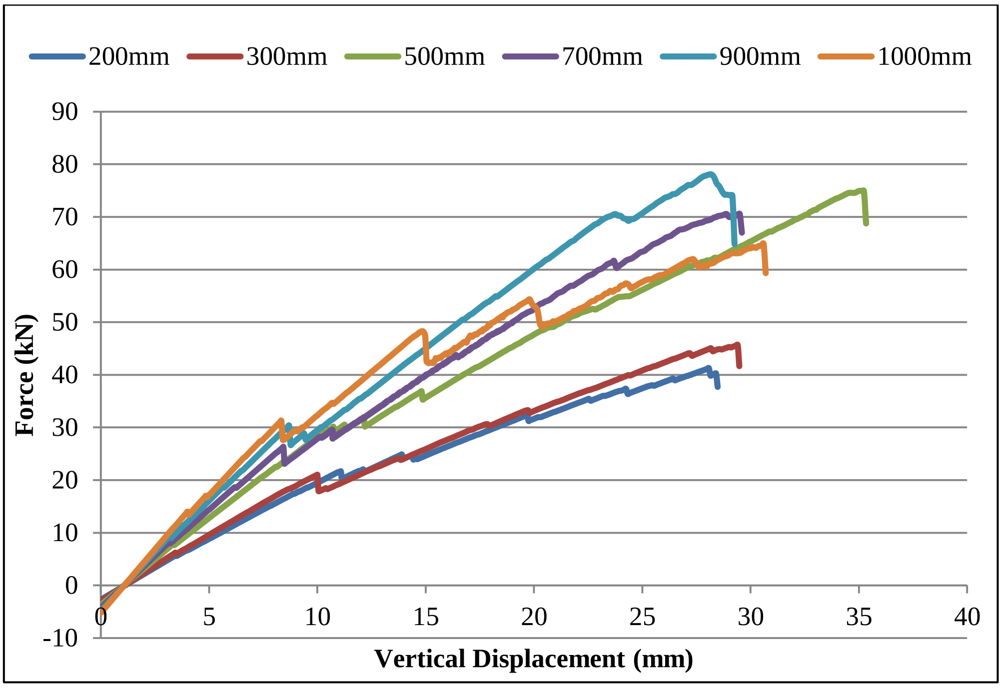


Figure 7. Loading at the center of the arch of a bridge with a radius of 6m

The deformation of the bridge models in the 6m radius bridge models in the loading cases applied at the midpoint of the arch span is given in the Figure 8.

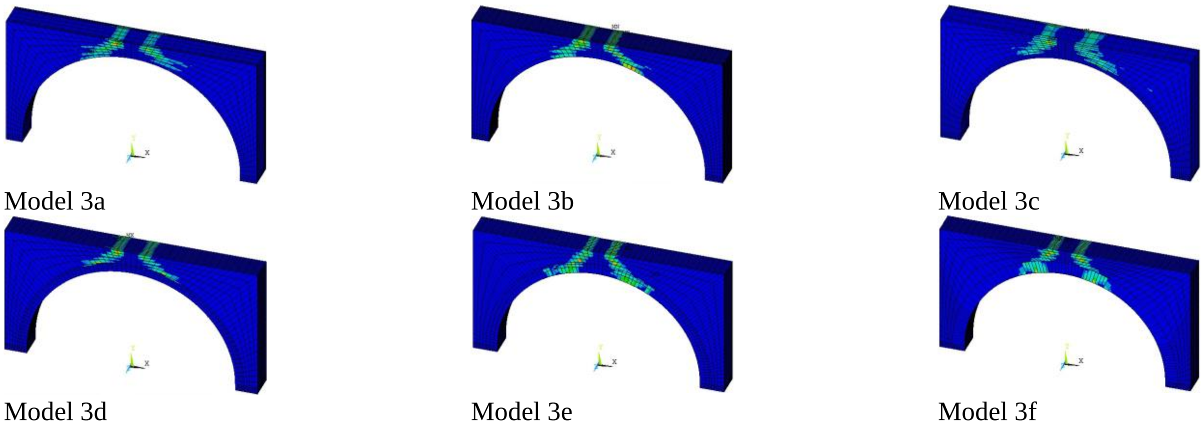


Figure 8. The deformation of the bridge models for midpoint loading case

In the study of bridges with a larger radius of 8 meters (Figure 9), several key findings were identified:

Maximum Displacement: The bridge with an arch thickness of 200 millimeters exhibited the largest vertical displacement, measuring 45.93 millimeters. This bridge had the highest displacement among the bridges analyzed in this study.

Maximum Load-Carrying Capacity: The bridge with an arch thickness of 900 millimeters demonstrated the highest load-carrying capacity, with a value of 89.36 kN. This bridge exhibited the greatest load-bearing capability among the bridges considered.

Consistent Crack Progression: Similar to previous observations, the progression of cracks was consistent across all bridges, irrespective of their specific arch thicknesses. Tensile stresses under vertical displacement load reached the permissible masonry tensile strength, especially in the upper sides of the arches, posing a risk for damage.
Failure Mechanism: In the vertical loading analyses, the failure mechanism was generally consistent across the bridges. This suggests that the load-induced structural failure had similar characteristics across different bridges.

Effect of Arch Radius and Height: It was noted that as the arch radius and arch height increased, both displacement and load-carrying capacity also increased. This trend indicates that larger arch dimensions resulted in greater structural performance and capacity to withstand vertical loads.

These findings highlight the influence of arch thickness, radius, and height on the structural behavior of masonry arch bridges. Thicker arches and larger arch dimensions generally contributed to higher load capacity and reduced displacement before reaching the point of collapse. The deformation of the bridge models in the 8m radius bridge models in the loading cases applied at the midpoint of the arch span is given in the Figure 10.

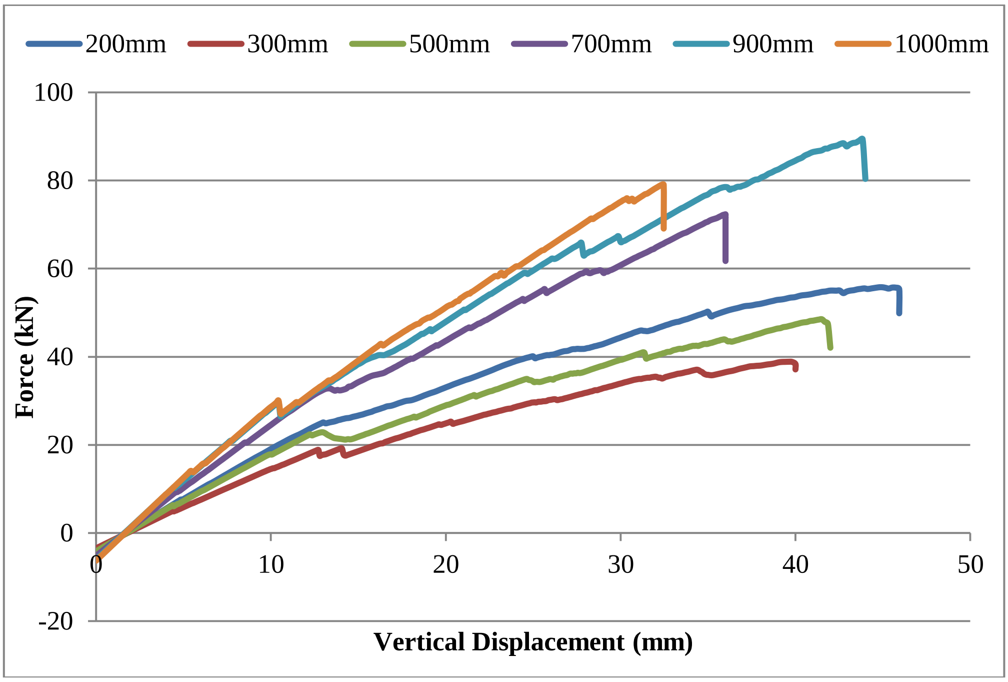


Figure 9. Loading at the center of the arch of a bridge with a radius of 8m

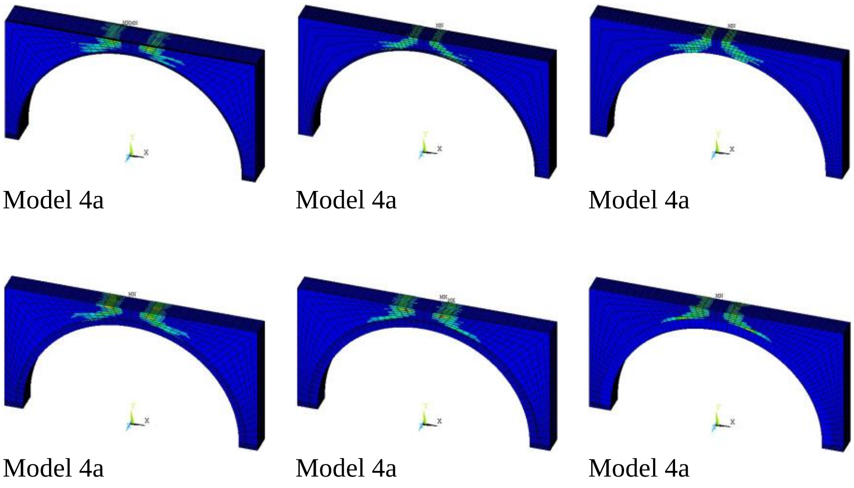


Figure 10. The deformation of the bridge models for midpoint loading case

In the study involving a bridge with an arch radius of 2 meters (Figure 11), the bridge with an arch thickness of 500 millimeters exhibited the following notable characteristics when subjected to loading at the L/4 part of the arch span:

Maximum Displacement: The bridge with an arch thickness of 500 millimeters demonstrated the largest vertical displacement, measuring 13.67 millimeters. This displacement value represents the greatest deflection observed among the bridges analyzed in this specific loading condition.

Maximum Load-Carrying Capacity: Additionally, the same bridge with an arch thickness of 500 millimeters exhibited the highest load-carrying capacity, with a value of 15.98 kN. This bridge demonstrated the greatest load-bearing capability among the considered bridges when loaded at the L/4 span point.

These findings emphasize the significance of arch thickness in determining the structural behavior and load-carrying capacity of masonry arch bridges, particularly under loading conditions applied at the L/4 part of the arch span. Thicker arches tend to provide greater stiffness and load capacity, resulting in reduced displacement and higher load-bearing capability.

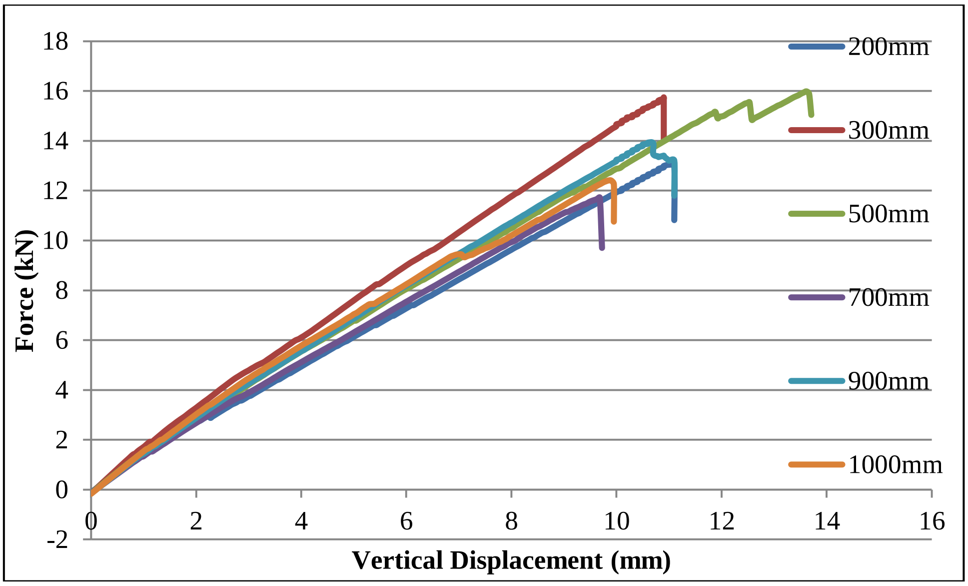


Figure 11. Loading condition of the arch L/4 span of the bridge with radius 2m

The deformations and stresses in the bridge models for L/4 span loading cases in 2m radius bridge models are given in the Figure 12.

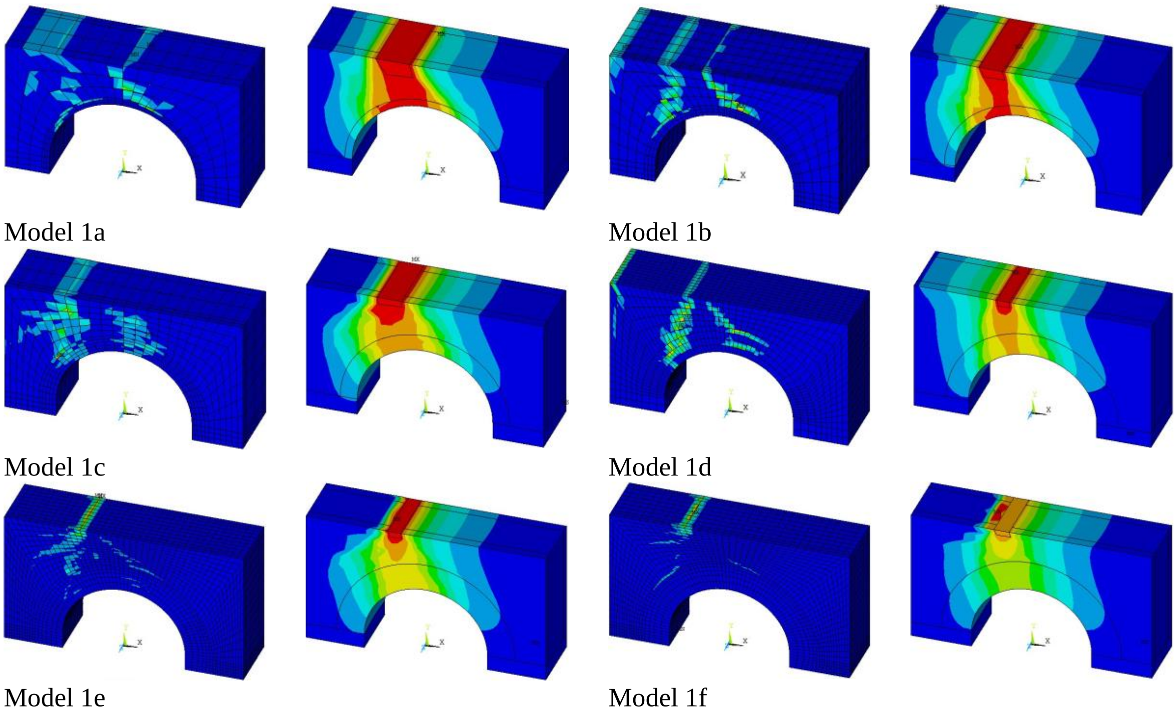


Figure 12. The deformations and stresses in the bridge models for L/4 span loading cases

In the study involving a bridge with an arch radius of 4 meters (Figure 13), the bridge with an arch thickness of 200 millimeters exhibited the following noteworthy characteristics when subjected to loading at the L/4 part of the arch span:

Maximum Displacement: The bridge with an arch thickness of 200 millimeters demonstrated the largest vertical displacement, measuring 16.12 millimeters. This displacement value represents the greatest deflection observed among the bridges analyzed in this specific loading condition.

Maximum Load-Carrying Capacity: Additionally, the same bridge with an arch thickness of 200 millimeters exhibited the highest load-carrying capacity, with a value of 106.22 kN. This bridge demonstrated the greatest load-bearing capability among the considered bridges when loaded at the L/4 span point.

These findings underscore the influence of arch thickness on the structural behavior and load-carrying capacity of masonry arch bridges, particularly under loading conditions applied at the L/4 part of the arch span. Thicker arches tend to offer enhanced stiffness and load capacity, resulting in reduced displacement and increased load-bearing capability.

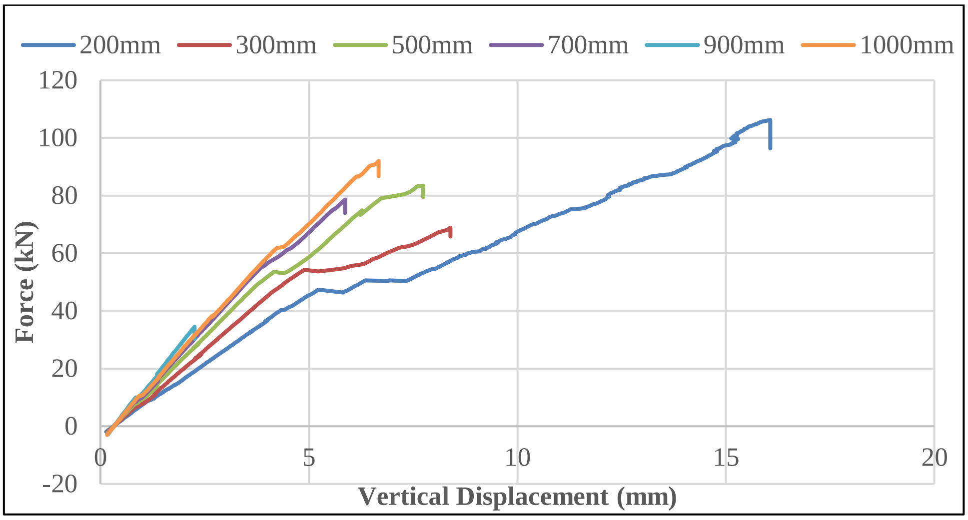


Figure 13. Loading condition of the arch L/4 span of the bridge with a radius of 4m

The deformations and stresses in the bridge models for L/4 span loading cases in 4m radius bridge models are given in the Figure 14.

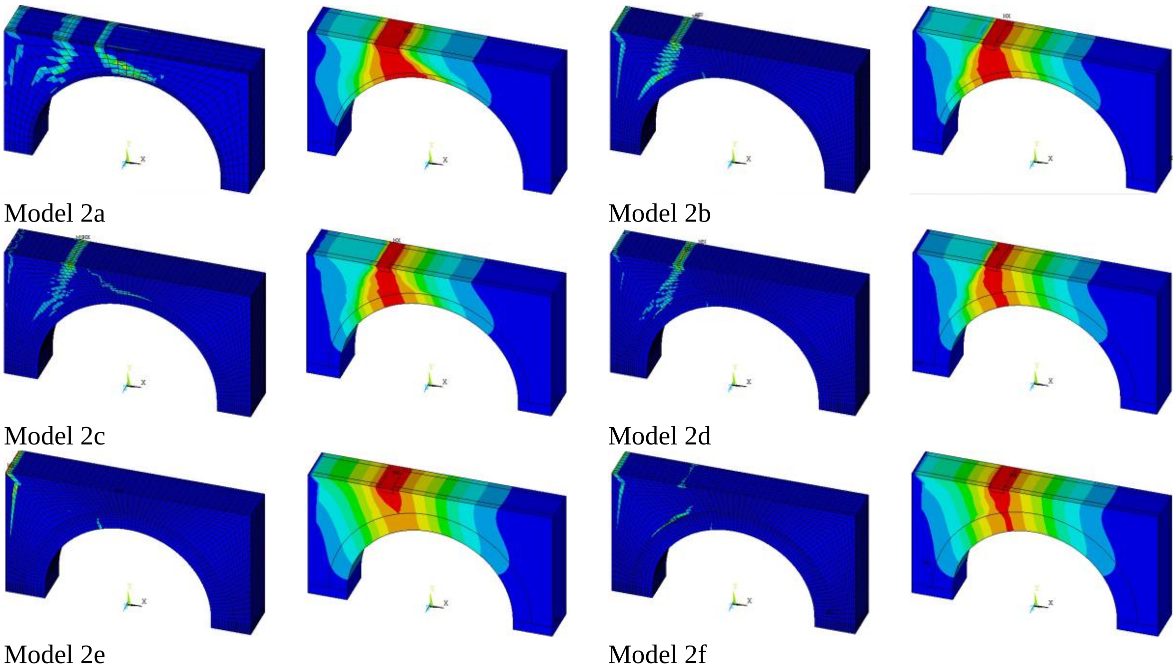


Figure 14. The deformations and stresses in the bridge models for L/4 span loading cases

In the study involving a bridge with an arch radius of 6 meters (Figure 15), several notable findings were identified for different arch thicknesses:

Maximum Displacement for 30 mm Thickness: Among the bridges analyzed, the one with an arch thickness of 30 millimeters exhibited the largest vertical displacement, measuring 11.72 millimeters. This bridge had the highest displacement among the bridges considered.

Maximum Load-Carrying Capacity for 700 mm Thickness: The bridge with an arch thickness of 700 millimeters demonstrated the highest load-carrying capacity, with a value of 94.84 kN. This bridge exhibited the greatest load-bearing capability among the analyzed bridges.

Collapse Mechanism Consistency: In general, the collapse mechanism was observed to be similar across the various bridges, indicating that the behavior leading to collapse was consistent in principle.

Crack Propagation Variation for 300 mm Thickness: Interestingly, it was noted that in the case where the arch thickness was 300 millimeters (0.3 meters), the progression of cracks differed from the other bridges. Instead of progressing uniformly, the crack propagation in this case moved toward the middle section of the arch.

These findings highlight the impact of arch thickness on the structural behavior and load-carrying capacity of masonry arch bridges with a 6-meter radius. Thicker arches tend to offer enhanced load capacity, while variations in crack propagation patterns can occur depending on the specific arch thickness. Tensile stresses have reached the permissible masonry tensile strength and pose a risk for damage.

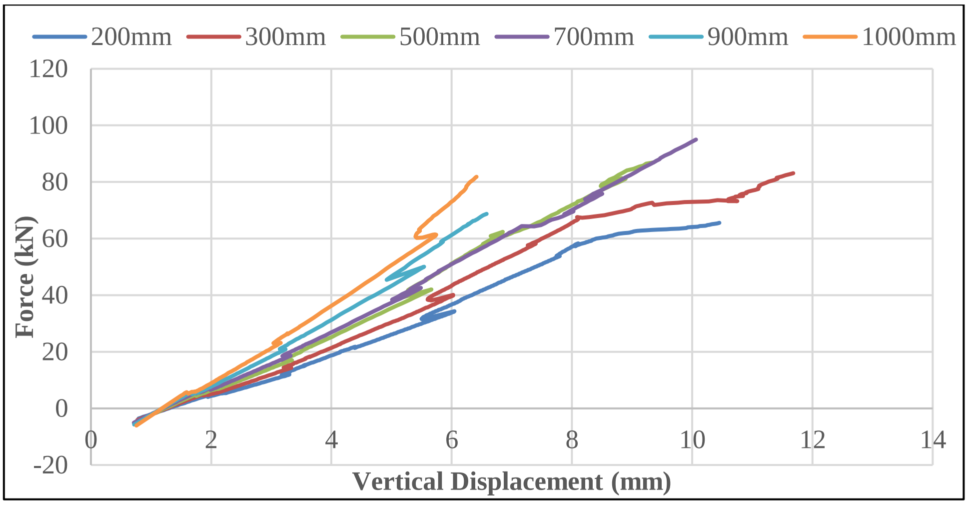


Figure 15. Loading condition of the arch L/4 span of the bridge with a radius of 6m

The deformations and stresses in the bridge models for L/4 span loading cases in 6m radius bridge models are given in the Figure 16.

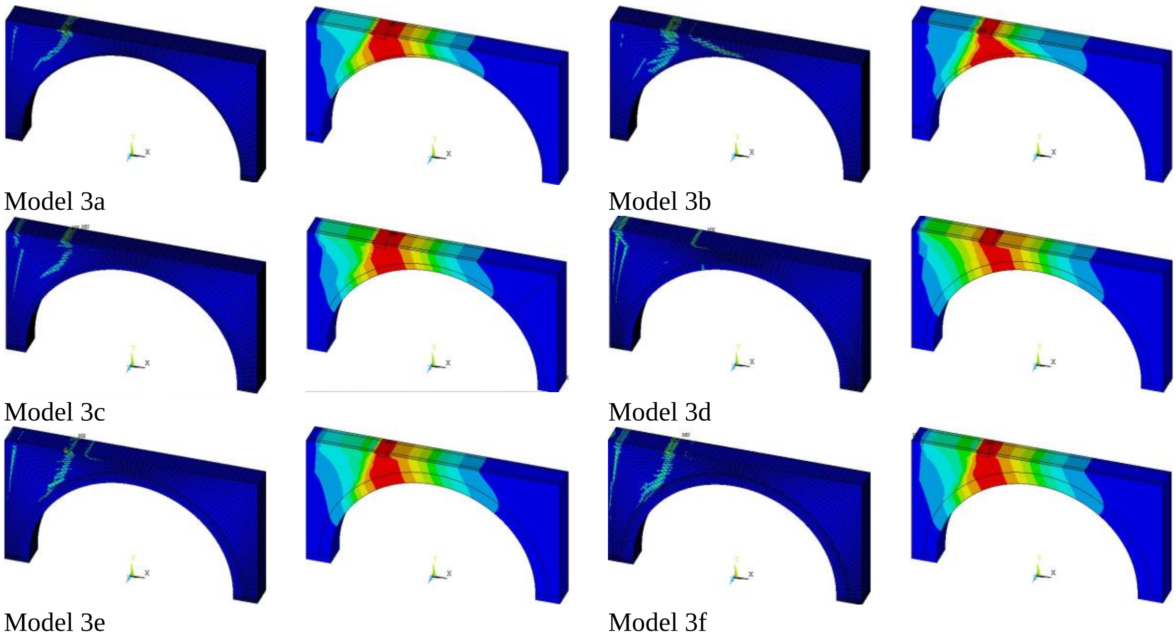


Figure 16. The deformations and stresses in the bridge models for L/4 span loading cases

In the study involving a bridge with an arch radius of 4 meters (Figure 17), the bridge with an arch thickness of 900 millimeters exhibited the following notable characteristics when subjected to loading at the L/4 part of the arch span:

Maximum Displacement: The bridge with an arch thickness of 900 millimeters displayed the largest vertical displacement, measuring 24.12 millimeters. This displacement value represents the greatest deflection observed among the bridges analyzed in this specific loading condition.

Maximum Load-Carrying Capacity: Additionally, the same bridge with an arch thickness of 900 millimeters exhibited the highest load-carrying capacity, with a value of 15.87 kN. This bridge demonstrated the greatest load-bearing capability among the considered bridges when loaded at the L/4 span point.

These findings underscore the significance of arch thickness and geometry, specifically the arch radius and height, in determining the structural behavior and load-carrying capacity of masonry arch bridges. It's observed that, in general, as the arch span and height increase, both displacement and load-carrying capacity tend to increase as well, indicating that larger arch dimensions contribute to improved structural performance. Additionally, it was noted that crack propagation patterns remained consistent among bridges with an 8-meter radius, suggesting similarities in the behavior of these bridges under the applied loads. The tensile stresses in the arch with 300mm arch stone thickness exceed the allowable masonry tensile strength and pose a risk for damage.

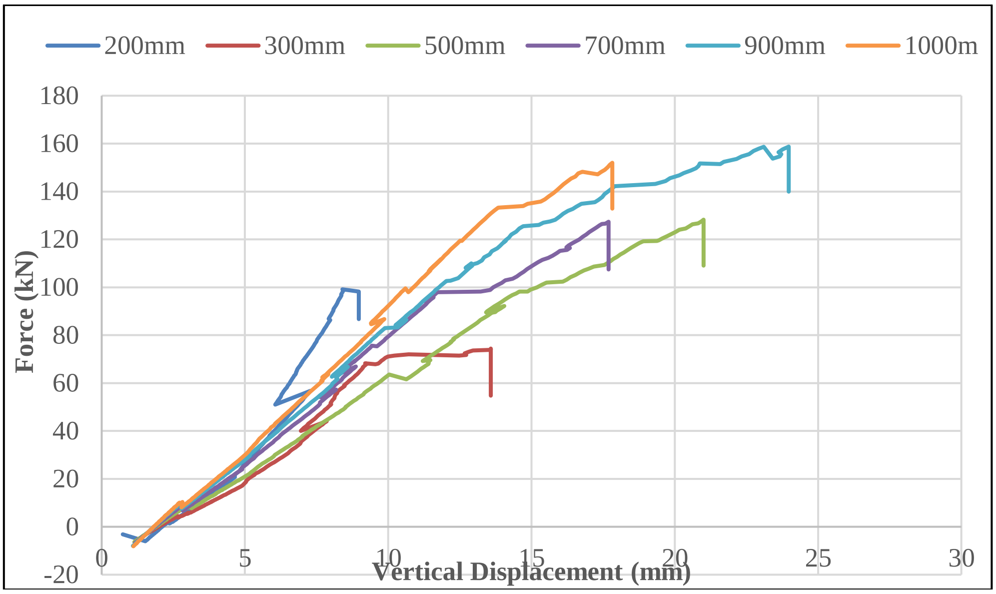


Figure 17. Loading condition of the arch L/4 span of the bridge with a radius of 8 m

The deformations and stresses in the bridge models for L/4 span loading cases in 8m radius bridge models are given in the Figure 18.

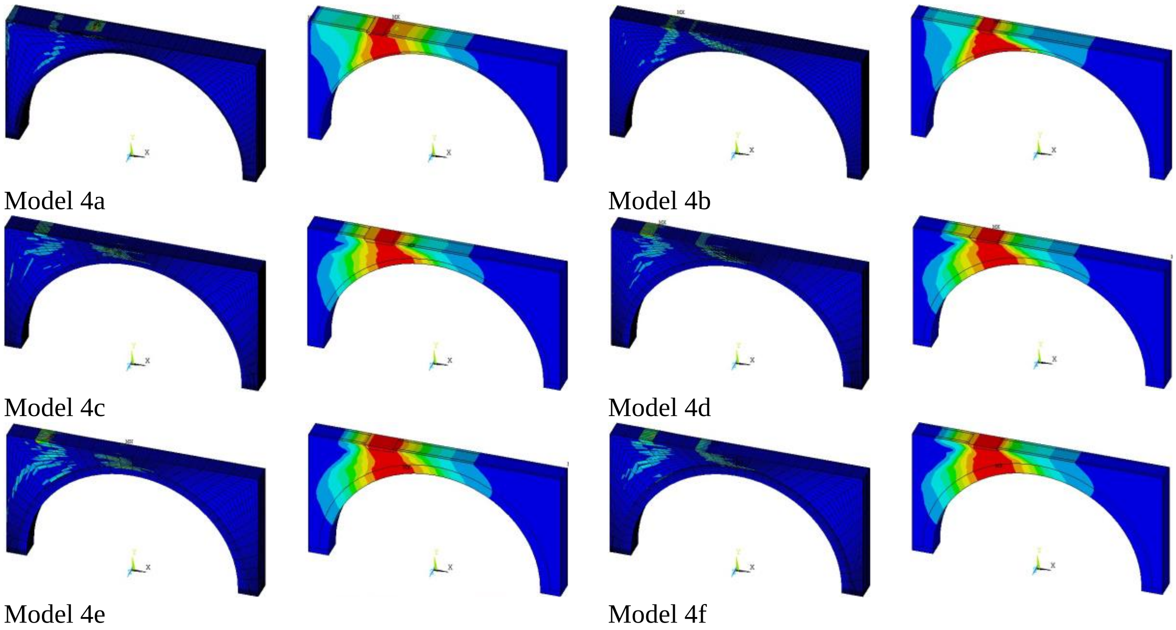


Figure 18. The deformations and stresses in the bridge models for L/4 span loading cases

4. Conclusions

The study carried out to evaluate the total load carrying capacity of bridges reveals a consistent trend where the increase in arch span and height corresponds to higher values for both displacement and load carrying capacity. This is true for both loading conditions considered in the study. In the analysis for both loading cases, it was determined that the most ideal bridge model has a radius of 8 m and an arch thickness of 900 mm.

These findings underline the importance of arch span and height as critical factors affecting the structural behavior of bridges using arch support systems. The observed relationship between these parameters and the load carrying capacity and displacement of the bridge provides valuable insights into the behavior of such historic arch bridges.

This study may be useful in providing preliminary information for the reconstruction of historical arch bridges that existed in the past but were destroyed by natural disasters over time and whose construction materials have survived to the present day.

5. Author Contribution Statement

In the study carried out, Author 1 contributed to the formation of the idea, making the design and literature review, evaluating the results obtained, obtaining the materials used and examining the results, spelling and checking the article in terms of content.

6. Ethics Committee Approval and Conflict of Interest

"There is no conflict of interest with any person/institution in the prepared article"

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