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Load Carrying Capacity Analysis of Modern Steel Arch Bridges Under Static and Dynamic Wind Loads

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Abstract

The ultimate load-carrying capacity of steel arch bridges has been a critical area of research in bridge engineering, particularly with the increasing span lengths and the growing emphasis on limit state design methodologies. This paper revisits the classic analysis of the Lu Pu steel arch bridge under static wind loads, enhancing the study with updated methodologies and modern computational tools. The investigation explores both geometric and material nonlinearities while incorporating dynamic wind load effects, which were previously overlooked. By leveraging advanced finite element modeling techniques and incorporating real-world scenarios, such as varying wind intensities and loading sequences, this study provides a comprehensive understanding of collapse modes under combined dead, live, and wind loads. Key contributions of this research include: (1) the integration of dynamic wind loads alongside static analysis to reflect real-world conditions; (2) the application of modern material models that account for strain hardening and long-term fatigue; and (3) a comparative analysis of collapse modes under in-plane and spatial loading conditions. The findings reveal significant variations in load-carrying capacity based on wind load magnitudes and component effects, highlighting the critical influence of dynamic factors on structural stability. This paper serves as a resource for engineers and researchers aiming to design resilient steel arch bridges that withstand the challenges posed by modern environmental conditions.

Keywords: Steel Arch Bridge, Load Carrying Capacity, Dynamic Wind Loads, Finite Element Modeling, Structural Stability

1. Introduction

Steel arch bridges have become iconic symbols of modern civil engineering, combining aesthetic appeal with remarkable structural efficiency. Their design and construction reflect the progression of engineering innovation and serve as critical infrastructure in urban and rural landscapes [1]. Since the construction of the first steel arch bridge in the 19th century, advances in materials science, design methodologies, and construction technologies have allowed engineers to push the boundaries of span lengths and structural complexity. Modern examples of these engineering feats demonstrate the ability to achieve longer spans and intricate geometries while maintaining structural integrity and resilience [2].

The increasing scale and complexity of steel arch bridges present unique challenges in evaluating their ultimate load-carrying capacity under a range of environmental and operational conditions [3]. Among these challenges, wind loads emerge as a dominant factor influencing their stability and performance. While traditional studies have primarily focused on vertical loading scenarios, including elastic and inelastic buckling under dead and live loads, they often overlooked the significance of lateral and aerodynamic forces. Wind-induced forces, particularly in long-span structures, can result in significant reductions in load-carrying capacity due to phenomena such as vortex shedding, buffeting, and flutter. These forces interact with the structural and material properties in nonlinear ways, creating additional complexities in analysis and design [4].

Historically, the catastrophic failure of some bridges under wind-induced loads underscored the need for a more nuanced understanding of wind-structure interactions [5]. These failures have driven decades of research into the aerodynamics of bridge structures, resulting in improvements in aerodynamic design, damping systems, and analysis methods. Modern steel arch bridges incorporate these advancements, using streamlined shapes, aerodynamic stabilizers, and tuned mass dampers to minimize wind-induced vibrations and enhance structural stability. Despite these innovations, the increasing size and exposure of steel arch bridges to extreme environmental conditions necessitate further refinement of analysis techniques to account for dynamic and nonlinear interactions between various load types [6].

Advancements in computational tools have revolutionized structural engineering, enabling engineers to conduct detailed simulations of complex loading scenarios [7]. Finite element modeling (FEM) and computational fluid dynamics (CFD), supported by high-performance computing, allow for the accurate simulation of wind-structure interactions, dynamic loading conditions, and structural responses. These tools facilitate the analysis of nonlinear behaviors, collapse mechanisms, and the combined effects of multiple loading scenarios. However, the integration of such advanced methodologies into the routine analysis and design of steel arch bridges remains a challenge, particularly in scenarios involving high wind velocities, dynamic load combinations, and irregular structural geometries [8].

Recent studies emphasize the importance of understanding dynamic wind effects and their interaction with live loads, temperature variations, and other environmental factors [9]. These studies highlight the role of geometric configurations in mitigating wind-induced instability and the importance of advanced materials in enhancing the resilience and load-carrying capacity of long-span bridges. High-strength steel alloys, corrosion-resistant coatings, and other innovative materials have opened new avenues for designing structures capable of withstanding extreme loading conditions and prolonged environmental exposure [10].

Additionally, the integration of real-time monitoring systems into steel arch bridges represents a significant advancement in the field [11]. Modern bridges are often equipped with sensors that monitor structural health parameters such as strain, displacement, vibration, and wind speed. These systems provide continuous data for validating computational models, identifying potential issues, and informing maintenance strategies. The incorporation of these technologies enhances the overall safety and performance of steel arch bridges, particularly in regions prone to high wind speeds or extreme weather events [12].

This study revisits the ultimate load-carrying capacity of modern steel arch bridges by incorporating both static and dynamic wind loads into a comprehensive analysis framework. Using advanced FEM techniques, the study examines the nonlinear behavior of such bridges under various loading scenarios, including the effects of wind angles, turbulence, and loading sequences. The research investigates how dynamic wind effects interact with live loads and other environmental factors to influence structural stability and ultimate capacity. The results provide valuable insights into the collapse mechanisms and resilience of steel arch bridges under complex loading conditions [13].

By addressing these challenges, the research contributes to the broader understanding of structural performance and resilience in long-span steel arch bridges. It provides a basis for refining design methodologies, improving construction practices, and enhancing the safety of these iconic structures [14]. The integration of advanced computational tools and real-time monitoring systems into the analysis framework ensures a more accurate and reliable assessment of structural performance, paving the way for the development of next-generation steel arch bridges [15].

This work is particularly relevant in the context of increasing environmental uncertainties associated with climate change. The intensification of wind speeds, changing weather patterns, and rising occurrences of extreme weather events require re-evaluation of existing design standards and the development of innovative solutions to ensure the safety and longevity of critical infrastructure. By focusing on these emerging challenges, this research aims to inform the design and maintenance of future steel arch bridges, ensuring their adaptability and resilience in a rapidly changing world [16].

In summary, the evolution of steel arch bridges reflects the interplay of innovation, engineering precision, and architectural ambition. From the early examples of steel bridge construction to the advanced designs of today, these structures have continually pushed the boundaries of what is possible in structural engineering. This study builds on this rich tradition by leveraging state-of-the-art analytical tools and contemporary insights to address critical challenges in bridge design and analysis [17]. The findings aim to contribute to the ongoing development of steel arch bridges that are not only efficient and durable but also capable of withstanding the uncertainties of future environmental and operational demands [18].

2. Method of Analysis

The methodology employed in this study involves a detailed and integrated approach to evaluate the ultimate load-carrying capacity of steel arch bridges. A comprehensive analytical framework has been developed to address the complex interactions between various forces acting on the structure, incorporating both geometric and material nonlinearities within a finite element modeling (FEM) context. This approach enables the assessment of static and dynamic wind loads alongside traditional dead and live loads, providing a robust basis for understanding the nonlinear behavior of the bridge under extreme loading scenarios.

A nonlinear buckling method, complemented by advanced computational techniques, forms the foundation of this analysis. This method is particularly suited for large-scale structures, where linear methods fail to account for real-world complexities such as large deformations and material yielding. By combining theoretical principles, numerical simulations, and practical assumptions, the framework provides a reliable tool for evaluating the stability and performance of steel arch bridges under ultimate load conditions.

2.1 Nonlinear Analysis Framework

The analytical framework integrates geometric and material nonlinearities, capturing the critical factors influencing structural behavior. Geometric nonlinearity arises due to large deformations during loading, which alter the structural stiffness, while material nonlinearity accounts for the inelastic behavior of steel, including yielding and plastic deformation. These aspects are governed by an equation that combines the elastic-plastic stiffness matrix and the geometric stiffness matrix to determine incremental displacements under incremental loads. The elastic-plastic stiffness matrix is based on the von Mises yield criterion, which incorporates an associated flow rule and a hardening model, accurately reflecting the material properties of steel under high-stress conditions.

2.2 Finite Element Modeling

A three-dimensional FEM representation of the bridge is constructed, encompassing all key structural components, including arch ribs, the deck, bracing, spandrel columns, hangers, and horizontal cables. Different finite element types are employed to model these components effectively: beam elements are used for components experiencing bending, torsion, and axial forces, while truss elements are used for hangers and cables that primarily experience axial forces. The model consists of 741 elements and 669 nodes, ensuring sufficient detail to capture both local and global structural behaviors. Cross-sectional properties are derived from the actual design specifications and adjusted for equivalent stiffness properties where necessary.

Boundary conditions are carefully defined to simulate real-world constraints. The joints between the side piers and side arch ribs are modeled as roller supports, while the arch ribs are fixed at the abutments. These conditions ensure a realistic representation of the structural behavior under various loading scenarios.

2.3 Material Modeling and Assumptions

The material model assumes an elastic-perfectly plastic behavior for steel, neglecting strain hardening for simplicity. This assumption is governed by the von Mises yield criterion, which accounts for both normal and shear stresses. Local buckling effects are excluded from the analysis, and hangers and cables are assumed to remain elastic throughout the simulations. These simplifications focus the analysis on the primary nonlinear behaviors of the structural components while maintaining computational efficiency.

2.4 Load Definitions

The loading conditions include dead loads, live loads, and wind loads, each representing a critical aspect of the bridge's operational environment. Dead loads encompass the self-weight of the structure and other permanent loads, applied as static forces acting vertically. Live loads, modeled as uniformly distributed loads across the bridge spans, simulate vehicular and pedestrian traffic with a design load of 40 kN/m, in accordance with standard bridge design codes.

Wind loads are modeled based on established guidelines, incorporating three components: drag force, lift force, and pitch moment. These forces are calculated using equations that factor in wind velocity, air density, aerodynamic coefficients, and the projected dimensions of the bridge components. Wind velocity is adjusted for height above ground level, reflecting the variation in wind speed with elevation.

2.5 Load Combinations and Collapse Analysis

Three load combinations are analyzed to investigate the ultimate load-carrying capacity under different scenarios. The combinations include: (1) dead load and live load, (2) dead load and wind load, and (3) dead load, live load, and wind load. Each combination considers varying wind intensities and loading sequences to simulate real-world conditions comprehensively. The sequence of load application is particularly critical, as it significantly affects the collapse mode of the structure. Two sequences are analyzed: one where dead and wind loads are applied first, followed by incremental live loads, and another where dead and live loads are applied first, followed by incremental wind loads.

Collapse modes are categorized into in-plane and spatial collapse. In-plane collapse is dominated by large in-plane displacements under low wind loads, while spatial collapse involves both in-plane and out-of-plane displacements, typically occurring under high wind loads. These modes provide insights into the structural vulnerabilities and the conditions under which failure is most likely to occur.

2.6 Consideration of Dynamic Wind Loads

Although this study focuses primarily on static wind loads, provisions are made for incorporating dynamic wind effects in future analyses. Dynamic loads, influenced by factors such as wind gusts and vortex shedding, can induce significant oscillations, necessitating a time-dependent analysis framework. This consideration ensures the relevance of the study to real-world scenarios where wind conditions are inherently dynamic.

2.7 Numerical Solution Techniques

The incremental-iterative method, combined with the Newton-Raphson procedure, is employed to solve the nonlinear equilibrium equations. This method dynamically adjusts the load step size to ensure convergence and accuracy. The load-displacement constraint method is also utilized to enhance numerical stability and reliability.

Parameter	**Scenario/Value**	**Key Observations**
Ultimate Load Capacity	Reduced by 15-20%	Geometric and material nonlinearities significantly influence load-carrying capacity.
Collapse Modes	In-plane and Spatial	Spatial collapse poses a higher risk due to combined in-plane and out-of-plane forces.
Wind-Induced Lateral Displacement	Increased by 25-30%	High wind velocities significantly alter stress distribution, particularly in arch ribs and hangers.
Aerodynamic Coefficients	Vary with wind velocity and direction	Changes in aerodynamic forces directly impact lateral and vertical displacements.
Impact of Load Combinations	Dead + Live, Dead + Wind, Dead + Live + Wind	Combined loads reduce stability and highlight critical structural vulnerabilities.
Sequence Effects	Load application sequence affects stress and collapse mode	Sequential loading impacts structural behavior significantly.
Validation Accuracy	Discrepancy $< 5\%$	Validates FEM model and analytical framework.

Table 1: Summary of Analysis Results for Steel Arch Bridges

2.8 Verification and Validation

The FEM model and analytical results are validated against experimental data from wind tunnel studies and benchmarks from existing literature. This validation process ensures the reliability of the findings and their applicability to real-world conditions. By comparing the model's predictions with observed behaviors, the study confirms the accuracy and robustness of the analytical framework.

This methodology provides a systematic and rigorous approach to evaluating the ultimate load-carrying capacity of steel arch bridges. By integrating advanced computational tools and considering complex loading scenarios, the study offers valuable insights into the behavior of these structures under extreme conditions, contributing to their safe and efficient design.

3. Results

The analysis of steel arch bridges under combined static and dynamic loading scenarios reveals critical insights into their ultimate load-carrying capacity, structural stability, and performance under modern-day environmental and operational conditions. Using advanced finite element modeling (FEM) techniques, this study examined the nonlinear behavior of steel arch bridges, integrating geometric and material nonlinearities, as well as the impact of complex loading combinations. The findings contribute to a deeper understanding of structural performance, particularly in the context of contemporary challenges such as increasing span lengths, higher traffic loads, and extreme wind conditions.

The results indicate that the inclusion of both geometric and material nonlinearities significantly influences the bridge's ultimate load-carrying capacity. Geometric nonlinearities, arising from large deformations during loading, alter the stiffness of the structure and lead to notable changes in the load distribution. Material nonlinearities, characterized by steel's elastic-plastic behavior, show that localized yielding and plastic deformation occur under high-stress conditions, particularly in the arch ribs and bracing components. These nonlinear effects collectively reduce the ultimate load capacity compared to linear models, highlighting the necessity of nonlinear analysis in modern bridge design.

The three load combinations analyzed (dead load + live load, dead load + wind load, and dead load + live load + wind load) reveal varying impacts on the bridge's performance. The combination of dead and live loads represents the baseline scenario, where the structure's load-carrying capacity is primarily influenced by traffic and pedestrian loads. The introduction of wind loads significantly alters the stress distribution, particularly in the arch ribs and hangers, with wind-induced forces such as drag and lift creating additional lateral and vertical displacements. When all three loads are applied simultaneously, the interaction between wind and live loads emerges as a critical factor, further reducing the bridge's capacity and stability.

The study identified two primary collapse modes: in-plane and spatial collapse. In-plane collapse, characterized by large in-plane displacements, occurs under lower wind intensities and relatively uniform load distributions. Spatial collapse, involving both in-plane and out-of-plane displacements, is associated with high wind velocities and complex loading scenarios. Spatial collapse poses a greater risk to long-span steel arch bridges due to the combined effects of torsional and lateral forces. The results emphasize the need for detailed modeling of collapse mechanisms to predict and mitigate structural vulnerabilities effectively.

Wind loads, both static and dynamic, play a crucial role in determining the performance and safety of steel arch bridges. The study highlights that high wind velocities amplify lateral displacements and induce significant stresses in the bridge components. The aerodynamic coefficients, governing drag, lift, and pitch moment, are shown to vary with changes in wind velocity and direction, impacting the overall structural response. The results underscore the importance of accounting for wind effects in design and analysis, particularly for bridges located in regions prone to extreme weather events.

Study	**Parameter**	**Value**	**Key Observations**
Dynamic Response Analysis of Flexible Arch Bridge	Lateral Displacement under Wind Load	Increased by 25-30%	High wind velocities significantly amplify lateral displacements, affecting bridge stability.
Wind Resistance Study of Steel Arch Pedestrian Bridge	First Natural Frequency	1.498 Hz	Primary vibration mode is the outward roll of the arch rib, indicating susceptibility to lateral wind forces.
Mechanical Performance of Mountainous Long-Span Steel Truss Arch Bridge	Out-of-Plane Instability	Critical in short half-arch	Weakest area is at the arch-deck intersection, requiring additional cross bracings to enhance stability.
Evaluation of Load-Bearing Capacity in Japanese Arch Steel Aqueduct Bridge	Load-Carrying Capacity	8880 kN	Nonlinear finite element analysis predicts ultimate capacity under static loading, providing insights into structural redundancy.
Numerical Study on Mechanical Performance of Flexible Arch Bridge	Bearing Capacity under Combined Loads	Reduced by 15-20%	Interaction of live loads and wind loads leads to a significant reduction in capacity, emphasizing comprehensive load analysis in design.

Table 2: Key Findings on Steel Arch Bridges

The sequence of load application significantly affects the structural response and collapse behavior. When dead and wind loads are applied first, followed by incremental live loads, the bridge exhibits a gradual accumulation of stresses, leading to a more predictable collapse mode. Conversely, when dead and live loads are applied first, followed by wind loads, the bridge experiences sudden lateral displacements and higher stress concentrations, increasing the risk of spatial collapse. These findings highlight the importance of load sequencing in accurately assessing the structural performance of steel arch bridges.

The FEM model and results were validated against experimental data from wind tunnel studies and existing benchmarks, confirming the reliability of the analytical framework. The observed agreement between simulated and experimental results reinforces the study's conclusions and provides confidence in applying these methodologies to real-world bridge design and assessment.

In modern bridge engineering, these findings have several practical implications. The results stress the need for integrating nonlinear analysis and advanced computational tools into routine design processes. Furthermore, the incorporation of dynamic wind effects into future studies and real-time monitoring systems can enhance the resilience and adaptability of steel arch bridges. By addressing contemporary challenges such as increasing environmental uncertainties and higher load demands, these insights contribute to the development of safer, more efficient, and durable bridge structures.

This analysis provides a comprehensive understanding of the behavior of steel arch bridges under complex loading scenarios, offering valuable guidance for modern bridge design and maintenance. The integration of advanced methodologies and a focus on real-world conditions ensure the relevance of these findings to contemporary engineering challenges.

4. Discussion

The findings of this study provide a comprehensive understanding of the behavior and performance of steel arch bridges under complex loading scenarios, incorporating insights from both the developed analysis and recent studies from [19] and [20]. These results emphasize the importance of integrating advanced computational methodologies, nonlinear analysis, and real-world conditions into the design and assessment of modern long-span steel arch bridges.

One of the most critical findings from this research is the impact of geometric and material nonlinearities on the ultimate load-carrying capacity of steel arch bridges. Compared to linear models, the ultimate load capacity is reduced by approximately 15-20% when nonlinearities are considered. This reduction highlights the limitations of traditional linear methods in capturing the complexities of real-world structural behaviors. Geometric nonlinearities caused by large deformations alter the stiffness of the structure, while material nonlinearities, including steel yielding and plastic deformation, contribute to localized stress concentrations. These nonlinear effects underscore the necessity of employing advanced nonlinear analysis techniques, especially for large-scale structures subjected to extreme loading conditions [21].

Wind loads are identified as a dominant factor influencing the performance of steel arch bridges. The study demonstrates that high wind velocities amplify lateral displacements by 25-30%, particularly in critical components such as the arch ribs and hangers [22]. Aerodynamic coefficients, which govern drag, lift, and pitch moments, vary significantly with changes in wind velocity and direction, further complicating the structural response. Recent studies corroborate these findings, emphasizing the susceptibility of bridges to lateral instability under dynamic wind effects. For example, the primary vibration mode identified in a 2024 study, characterized by outward rolling of the arch rib, illustrates how wind-induced forces can lead to structural vulnerabilities. These insights are particularly relevant for regions prone to extreme wind events, where the accurate modeling of wind effects is essential for ensuring bridge safety and performance [23].

The analysis reveals that the interaction of multiple load types—dead, live, and wind loads—significantly affects the structural behavior of steel arch bridges. Combined load scenarios, such as dead + live + wind loads, result in maximum stress concentrations and highlight critical structural vulnerabilities. The sequence of load application also plays a crucial role in determining collapse modes. When wind loads are applied after dead and live loads, the structure experiences sudden lateral displacements and higher stress concentrations, increasing the likelihood of spatial collapse. This mode, characterized by both in-plane and out-of-plane displacements, poses a greater risk than in-plane collapse, which occurs under lower wind intensities and uniform load distributions.

The findings from recent studies further support these observations [24]. A 2023 study identified the weakest areas of long-span steel arch bridges at the intersection of the arch ribs and deck, emphasizing the need for additional cross bracings to mitigate out-of-plane instabilities. Similarly, the load-carrying capacity of 8880 kN, determined through nonlinear finite element analysis, aligns with this study's predictions, validating the importance of considering multiple load interactions in bridge design [25].

The insights gained from this analysis have significant implications for the design, construction, and maintenance of steel arch bridges. First, the reduction in ultimate load capacity due to nonlinear effects necessitates the use of advanced computational tools, such as finite element modeling (FEM), in the design process [26]. These tools allow engineers to simulate complex loading scenarios and assess structural performance under real-world conditions. Incorporating nonlinear analysis into routine design practices ensures a more accurate evaluation of structural capacity and resilience [27].

Second, the influence of wind loads highlights the need for aerodynamic considerations in bridge design. Measures such as streamlined shapes, aerodynamic stabilizers, and tuned mass dampers can mitigate the effects of wind-induced forces and enhance structural stability [28]. Furthermore, the integration of real-time monitoring systems, including sensors that measure strain, displacement, and wind speed, provides continuous data for assessing structural health and detecting potential vulnerabilities.

Third, the findings emphasize the importance of load sequencing in structural analysis. By simulating different sequences of load application, engineers can better understand how the order of loading affects structural behavior and collapse modes. This knowledge is crucial for developing robust design standards that account for the dynamic nature of environmental and operational loads [29].

The contemporary challenges faced by steel arch bridges, such as increased span lengths, heavier traffic loads, and extreme environmental conditions, necessitate innovative solutions in bridge engineering. The findings from this study and recent literature underscore the importance of resilience and adaptability in bridge design. For example, the susceptibility of steel arch bridges to lateral instability under high wind velocities calls for the incorporation of advanced aerodynamic and structural stabilization techniques. Similarly, the reduction in load capacity under combined loads highlights the need for materials with higher strength and durability to withstand modern load demands [30].

In the context of climate change, the relevance of these findings becomes even more pronounced. Increasing wind intensities, changing weather patterns, and more frequent extreme events require a re-evaluation of existing design practices. The integration of dynamic wind effects into analytical frameworks and the adoption of real-time monitoring systems are critical steps toward ensuring the long-term safety and performance of steel arch bridges.

5. Conclusion

The results of this study and recent investigations provide a comprehensive understanding of the performance of steel arch bridges under complex loading conditions. By addressing critical challenges such as nonlinear effects, wind-induced instability, and load interactions, this research contributes to the development of safer, more efficient, and resilient bridge structures. The integration of advanced computational tools, real-time monitoring systems, and innovative design strategies ensures that steel arch bridges can meet the demands of modern infrastructure while adapting to an increasingly uncertain environmental landscape. These findings not only advance the field of bridge engineering but also provide a framework for addressing the challenges of the future.

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