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OUT-OF-PLANE BUCKLING STABILITY IN TIED-ARCH BRIDGES: AN ANALYTICAL APPROACH

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ABSTRACT

This research investigates the out-of-plane buckling behavior of tied arch bridges through a comprehensive analysis of critical buckling forces under varying deck slab thicknesses of 500 mm and 300 mm. The first mode of out-of-plane buckling is examined to determine the normal critical out-of-plane buckling force (Ncro) at the supports, following the guidelines outlined in EN:1993 Part 2. The study introduces two critical buckling force values, Ncro M1 for a 450 mm thick slab and Ncro M2 for a 250 mm thick slab, to evaluate the influence of deck thickness on structural stability. Results reveal that cable forces are typically lower than Ncro, indicating a tendency for buckling to occur in specific cables prior to reaching the overall critical load. Models with lower arch rise ratios demonstrate greater susceptibility to buckling, while those with higher ratios and increased cable counts show enhanced stability. Notably, the findings indicate a tendency for Eurocode predictions to overestimate out-of-plane critical buckling forces, suggesting potential safety concerns in relying solely on these guidelines. This study emphasizes the importance of tailored analytical models for accurately assessing the buckling resistance of tied arch bridges and offers insights for improving design practices to enhance structural safety.

Keywords: Tied Arch Bridges, Out-of-Plane Buckling, Critical Buckling Force, Deck Slab Thickness, Structural Stability.

1. INTRODUCTION

Tied arch bridges serve as a remarkable integration of structural integrity and visual appeal, frequently utilized to cover vast distances in both urban and rural settings. These bridges efficiently manage vertical loads through their arch components while minimizing deflection and movement. By harnessing the tensile strength of cables, tied arch bridges achieve a stability that not only enhances their aesthetic qualities but also their functionality. Nonetheless, the overall stability of these structures is influenced by several factors, including the arch rise ratio and the thickness of the deck slab. The study of buckling behavior is essential since it can profoundly impact the structural soundness and usability of tied arch bridges. Buckling can manifest in two main forms: in-plane and out-of-plane, each posing unique challenges to stability. In-plane buckling is typically associated with lateral loads and dynamic loading conditions, whereas out-of-plane buckling often occurs under vertical loads or moments, potentially leading to severe structural failures if not properly managed.

This research focuses on investigating the out-of-plane buckling characteristics of tied arch bridges, specifically examining the normal critical buckling force and its variations with different deck slab thicknesses, such as 500 mm and 300 mm. Through a systematic comparison of critical buckling forces across various configurations and conditions, the study aims to provide a thorough understanding of how these parameters affect the bridge's overall stability. Additionally, the analysis utilizes guidelines from EN:1993 Part 2, ensuring that the outcomes are consistent with established engineering standards. The findings will identify potential discrepancies between conventional Eurocode predictions and the actual buckling capacities of tied arch bridges, particularly concerning possible overestimations that could pose safety risks.

Ultimately, this study seeks to offer valuable insights that will assist engineers and designers in making educated choices about the design and reinforcement of tied arch bridges. By emphasizing the relationship between deck slab thickness and buckling behavior, the research aims to enhance safety and resilience in infrastructure development, thereby contributing to advancements in the field of structural engineering.

2. METHODOLOGY

This section outlines the methodology adopted for examining the out-of-plane buckling behavior of tied arch bridges, with a particular emphasis on the critical buckling forces influenced by varying deck slab thicknesses. The analysis was carried out using SAP 2000, following a structured approach to ensure thorough evaluation and accurate outcomes.

2.1 Model Development

A total of twenty-five unique arch models were developed to specifically assess out-of-plane buckling, incorporating diverse cable configurations and arch rise ratios. The study considered arch rise ratios ranging from 0.1 to 0.5, facilitating a comprehensive analysis of how different geometric configurations impact the structural stability. Each model was designed to evaluate two distinct deck slab thicknesses: 500 mm and 300 mm.

2.2 Finite Element Modeling

The modeling process in SAP 2000 encompassed several essential steps:

- Defining Geometry: Each model was meticulously constructed to accurately reflect the geometric characteristics of the arch, including the shape, cable configurations, and deck slab dimensions.
- Assigning Material Properties: Relevant material properties were allocated to the models based on established design codes, ensuring realistic simulations of structural behavior.

2.3 Out-of-Plane Buckling Analysis

The focus of the analysis was on the out-of-plane buckling behavior, implemented through the following procedures:

- Initial Mode of Out-of-Plane Buckling: The first mode of out-of-plane buckling was evaluated to determine the eigenvalue necessary for calculating the normal critical out-of-plane buckling force at the supports. This eigenvalue is vital for assessing the bridge's stability under vertical loads and moments.
- Calculation of Critical Buckling Forces: The normal critical out-of-plane buckling force (Ncro) was determined in accordance with the guidelines specified in EN:1993 Part 2, particularly clause D.3.4. The following parameters were analyzed:

Ncro M1: The critical buckling force corresponding to a 450 mm thick deck slab.

Ncro M2: The critical buckling force for a 250 mm thick deck slab.

This analysis is crucial in understanding how different deck slab thicknesses affect the out-of-plane stability of the arch models.

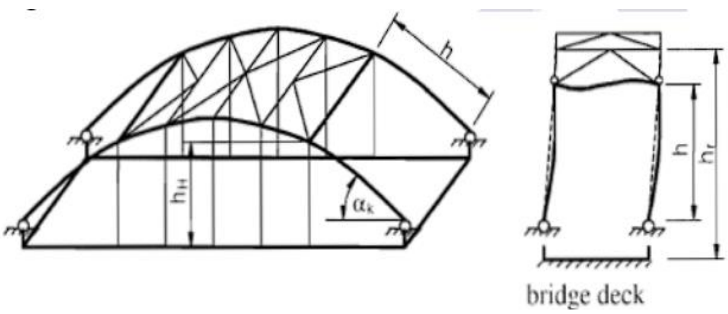

Figure 2: Buckling of arches

2.4 Data Collection and Analysis

Results from the out-of-plane buckling analysis were systematically documented and examined, focusing on:

- **Comparative Analysis:** A comparison of critical buckling forces (Ncro, Ncro M1, and Ncro M2) across all models was conducted to discern the impact of various deck slab thicknesses, cable configurations, and arch rise ratios on out-of-plane stability.
- **Statistical Evaluation:** The study calculated percentage changes in buckling forces (δ1 and δ2) to evaluate the differences among Ncro, Ncro M1, and Ncro M2. This assessment provided insights into the influence of slab thickness on the buckling behavior of the bridge.

2.5 Result Interpretation

The collected data were organized into structured tables, highlighting key aspects such as:

- **Assessment of Out-of-Plane Buckling Behavior:** A thorough evaluation of the relationships between the normal critical buckling force and cable forces, especially regarding their correlation to the overall critical load and stability.
- **Design Implications:** The findings from the analysis aimed to guide design practices and reinforcement strategies necessary to improve the stability of tied arch bridges, particularly in terms of out-of-plane buckling.

3. MODELING AND ANALYSIS

This section elaborates on the modeling framework implemented for evaluating the out-of-plane buckling characteristics of tied arch bridges. Utilizing SAP 2000v14, the analysis emphasizes critical parameters, including the arch rise ratio, cable arrangements, and cross-sectional dimensions of various bridge members. The following sections outline the specific elements incorporated into the modeling process, along with the material properties and boundary conditions pertinent to out-of-plane buckling analysis.

3.1 Arch Model Parameters

Arch Rise Ratio (f/L): The analysis includes five distinct arch rise ratios, spanning from 0.1 to 0.5. These ratios define the relationship between the arch rise (f) and the total length of the arch (L = 310 m). A lower rise ratio signifies a flatter arch, which may exhibit greater susceptibility to out-of-plane buckling under specific loading scenarios. In contrast, a higher rise ratio generally contributes to enhanced stability and greater resistance against buckling, making it essential to assess their impact on the bridge's structural performance.

Cable Configurations (m): Each arch rise ratio is examined for five different cable configurations, specifically with 1, 3, 5, 7, and 10 cables. This variability is crucial as it allows for a comprehensive investigation into how different cable layouts affect the out-of-plane buckling behavior of the bridge. Increasing the number of cables typically enhances structural stability by providing additional support and improving load distribution.

3.2 Cross-Sectional Details

The main arch rib is modeled as a rectangular box section with dimensions of height: 5500 mm, width: 4500 mm, and thickness: 85 mm. This robust design is intended to effectively support loads imposed on the arch while offering sufficient resistance to out-of-plane buckling. Constructed as a rectangular box section, the tie member features dimensions of height: 4000 mm, width: 4500 mm, and thickness: 35 mm. This component is essential for maintaining the structural integrity of the arch by resisting tensile forces and contributing to overall stability. The crossbeam is designed with a rectangular section measuring height: 4000 mm, width: 2500 mm, and thickness: 30 mm. This member plays a significant role in distributing loads throughout the arch and enhancing the bridge's rigidity against out-of-plane deflections. Modeled as a hollow circular section, the arch cross beam has a diameter of 2500 mm and a thickness of 25 mm. This configuration provides a balance of strength and flexibility, allowing the arch to better withstand out-of-plane buckling. Designed as an I-section, the longitudinal girders feature a top and bottom flange width of 800 mm, flange thickness of 40 mm, web thickness of 35 mm, and a total depth of 3000 mm. The geometry of the I-section is beneficial for resisting bending moments and stabilizing the overall bridge structure. Cables are represented as cable elements with a diameter of 200 mm. Accurate modeling of these cables is vital, as they provide the necessary tensile forces to counteract compression in the arch, maintaining overall structural stability. The deck is modeled as a composite beam with a thickness of 600 mm, integrated with the I-section longitudinal girders. This substantial thickness contributes significantly to the bridge's rigidity and load-bearing capacity.

3.3 Material Properties

The steel utilized in various bridge members has a yield strength of 335 MPa, an elastic modulus of 200 GPa, and a Poisson’s ratio of 0.3. These properties ensure adequate strength and flexibility under loading conditions. The cables are made of high-strength steel with a yield strength of 950 MPa, an elastic modulus of 200 GPa, and a Poisson’s ratio of 0.35. These enhanced properties enable the cables to efficiently carry tensile loads while minimizing deformation. The concrete used for the deck slab is designed with a compressive strength of 40 MPa, an elastic modulus of 35,580 MPa, and a Poisson’s ratio of 0.35. These characteristics provide the necessary compressive strength and stability for the bridge deck.

3.4 Boundary Conditions

The modeling employs specific boundary conditions to accurately simulate real-world behavior. At one end of the arch, two nodes are fully restrained from translation, allowing only in-plane rotation. Conversely, the remaining two nodes at the opposite end can translate longitudinally while still permitting in-plane rotation. This setup closely resembles realistic loading scenarios, facilitating a thorough investigation of the bridge’s out-of-plane buckling response.

3.5 Out-of-Plane Buckling Analysis

This study addresses the first mode of out-of-plane buckling to assess the structural integrity of tied arch bridges against such failures. The primary focus of this analysis is to establish the normal critical out-of-plane buckling force and to compare results across two different deck slab thickness scenarios: 500 mm and 300 mm.

The analysis begins by examining the first mode of out-of-plane buckling to ascertain the corresponding eigenvalue, which is crucial for calculating the normal critical out-of-plane buckling force at the bridge supports. The Normal Critical Buckling Force (Ncro) is calculated in accordance with clause D.3.4 of EN:1993 Part 2, a standard that provides guidance on evaluating the buckling stability of steel structures, particularly in the context of arch bridges.

Mathematical Model for Out-of-Plane Buckling

- Ncro M1: This value indicates the out-of-plane critical buckling force for a 450 mm thick deck slab.
- Ncro M2: This value reflects the critical buckling force for a 250 mm thick deck slab.

4. RESULTS AND DISCUSSION

By analyzing and comparing Ncro with Ncro M1 and Ncro M2, the study aims to elucidate how varying deck slab thickness influences the critical out-of-plane buckling force at the supports. The results aim to clarify the impact of slab thickness on the bridge's out-of-plane stability and to determine whether a thicker or thinner deck slab contributes to improved resistance against out-of-plane buckling. The findings from the out-of-plane buckling analysis are consolidated in Table 2. This table illustrates various models along with their respective arch rise ratios, cable configurations, and computed values for Ncro, Ncro M1, and Ncro M2, along with the percentage differences (D1 and D2) between the forces exerted by the cables and the critical buckling forces.

The values for Ncro, Ncro M1, and Ncro M2 indicate the bridge's ability to resist out-of-plane buckling. Observations reveal that the forces in cables 1 and 2 are typically lower than Ncro, implying that the bridge may experience buckling in these cables before reaching the overall critical load. The percentages (D1 and D2) reflect the distance of cable forces from the overall buckling force. Models with lower arch rise ratios, such as 0.1, tend to exhibit larger differences between Ncro and the forces in cables 1 and 3 (higher D1 and D2 values). This observation suggests that flatter arches are more susceptible to buckling in individual modes before reaching the critical load. Conversely, models with higher rise ratios (e.g., 0.4 or 0.5) show smaller discrepancies between these forces, indicating greater stability and a reduced risk of buckling.

The analysis also indicates that models with a higher number of cables, such as cables 7 and 10, display smaller differences between Ncro and the critical buckling forces for individual modes. This finding highlights the enhanced stability and buckling resistance of the structure as the number of cables increases, as additional cables provide further support to the arch. Some models exhibit notably high D1 and D2 values, particularly at a rise ratio of 0.5 with cable 5, indicating substantial differences between Ncro and the buckling forces for individual modes. This implies that certain design configurations—characterized by fewer cables or lower rise ratios—may be prone to out-of-plane buckling at significantly lower loads than the overall critical buckling force, necessitating further reinforcement or evaluation to mitigate early buckling risks.

Table 1. Out-of-plane critical buckling at support

Model	Arch Rise	Cables	N_{cro} (in kN)	$N_{cro,}$ M1 (in kN)	$N_{cro,}$ M2 (in kN)	D1 (%)	D2 (%)
A	0.1	1	310000	223000	223500	27.5	27.8
B	0.1	3	348000	227000	226000	24.50	34.80
C	0.1	5	410000	230000	229000	44	43.9
D	0.1	7	383000	233500	234000	38.8	39
E	0.1	10	398000	236000	236500	40.1	40.3
A	0.2	1	270000	181000	181500	35	34.8
B	0.2	3	290000	191000	189000	35	34.8
C	0.2	5	360000	195000	193000	45.5	44.8
D	0.2	7	335000	210000	209000	37	37.5
E	0.2	10	320000	220000	218000	32	32.5
A	0.3	1	180000	135000	134000	25	26
B	0.3	3	200000	157000	156000	35	36
C	0.3	5	240000	145000	143000	27	28
D	0.3	7	220000	170000	168000	22	22.5
E	0.3	10	240000	185000	183000	21	22
A	0.4	1	150000	94000	93000	31	32
B	0.4	3	140000	105000	103000	28	29
C	0.4	5	170000	115000	112000	34	34.5
D	0.4	7	155000	125000	122000	20	21
E	0.4	10	170000	138000	136000	19	19.5

A	0.5	1	85000	53000	52000	41	42
B	0.5	3	87000	63000	61000	30	31
C	0.5	5	120000	67000	66000	43	43.5
D	0.5	7	100000	73000	71000	28	29
E	0.5	10	120000	79000	77000	33	34

The values in N_{cro}, N_{cro} M_1, and N_{cro} M_2 show the structure's stability in resisting out-of-plane buckling. Cable 1 and cable 2 forces are typically lower than N_{cro}, indicating that the bridge may buckle in this specific cable before reaching its overall critical load. The percentages (δ_1 and δ_2) highlight how far the cable 1 and cable 2 forces are from the overall buckling force. Models with a lower arch rise ratio (e.g., 0.1) generally show larger differences between N_{cro} and the cable 1 and cable 3 forces (δ_1 and δ_2 are higher). This suggests that flatter arches (with a lower rise ratio) are more prone to buckling in individual modes before reaching their overall critical load. In contrast, models with a higher rise ratio (e.g., 0.4 or 0.5) tend to have smaller differences between these forces, indicating that they are more stable and have a lower risk of buckling. Bridges with more cables (e.g., cables 7 and 10) tend to have smaller differences between N_{cro} and the critical buckling forces for individual modes, implying that the structure becomes more stable and resists buckling more effectively when more cables are used. This makes sense because additional cables provide more support to the arch, preventing buckling. Some models show very high δ_1 and δ_2 values (e.g., 0.5 at cable 5), indicating a significant difference between N_{cro} and the buckling forces for individual modes. This suggests that for certain designs (e.g., models with fewer cables or lower arch rise ratios), the structure may buckle out of plane at a much lower load than the overall critical buckling force. Therefore, these designs may need further reinforcement or re-evaluation to prevent early buckling.

5. CONCLUSION

- The results of the analysis reveal that the provisions outlined in Eurocode Part 3 tend to forecast higher critical buckling forces for tied-arch bridges, especially when factoring in end portal effects.
- The mathematical models created in this study indicate that the actual critical buckling forces might be lower than those anticipated by Eurocode, signaling a potential discrepancy between design assumptions and actual performance.
- Exclusively adhering to Eurocode guidelines may lead to overly cautious designs, resulting in misallocated resources and unnecessary increases in material usage.
- This overestimation of buckling resistance could foster unsafe assumptions about the bridge's behavior under specific load scenarios, heightening the risk of structural failure.
- The findings emphasize that important aspects such as load distribution, dynamic responses, and material characteristics need to be carefully evaluated during the design phase to maintain structural efficiency.
- Should engineers overrate critical buckling forces, they might neglect vital reinforcement strategies essential for addressing potential buckling risks in certain designs or complex loading conditions.
- The study encourages a more integrated approach, combining established codes with empirical data from mathematical modeling, to provide a more accurate evaluation of out-of-plane buckling resistance in tied-arch bridges.
- Future research should aim to enhance predictive models and investigate the effects of various design parameters to deepen the understanding of buckling phenomena in tied-arch bridges, ensuring that designs remain safe, reliable, and cost-effective.

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