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# Structural Behaviour of Tied-Arch and Bowstring Bridges: A Review of Analytical, Numerical, and Experimental Studies

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**Abstract:** ***Tied-arch, or bowstring, bridges are widely adopted for medium-span crossings because they combine the load-carrying efficiency of the arch form with a self-balancing tie that eliminates horizontal thrust at the supports. While their in-plane response under gravity loads is comparatively well established, their out-of-plane behaviour under wind, seismic, and asymmetric traffic actions continues to attract active research. This paper reviews published work on the design, analysis, stability, and monitoring of tied-arch and bowstring bridges, organised thematically into design optimisation, dynamic and construction-stage behaviour, stability and bracing systems, skewed and curved bridge response, and structural health monitoring. The review identifies that although considerable attention has been given to hanger arrangement, rise-to-span ratio, and geometric nonlinearity, comparatively little work addresses the influence of alternative bracing configurations on the combined displacement, force distribution, and economy of steel bowstring bridges designed to Indian loading standards, indicating a clear direction for further study.***

**Keywords:** Tied-arch bridges, Bowstring bridges, Structural stability, Bridge design, Structural health monitoring

## 1. Introduction

The arch has long been valued in bridge engineering for its ability to carry transverse loads chiefly through axial compression, a consequence of its funicular geometry. Historic examples such as the Roman-era Pont du Gard demonstrate the durability of the form, while modern tied-arch (bowstring) bridges extend the concept by introducing a tension tie between the arch springing, allowing the horizontal thrust generated by the arch to be resisted internally. This makes vertical-only reactions available at the supports, permitting lighter foundations and application on weaker soils or elevated piers.

A bowstring bridge superstructure typically comprises an arch rib in compression, a tie girder in tension, vertical or inclined hangers, transverse cross beams, and a lateral bracing system connecting the ribs. Although the in-plane load path of such a system is relatively direct, the slenderness of the arch rib in the lateral direction makes out-of-plane stability - governed by wind, seismic, and asymmetric live loads - a significant design consideration. This has motivated a substantial body of analytical, numerical, and experimental research over the past several decades, reviewed below.

## 2. Structural Characteristics Relevant to the Review

Arch bridges are recognised for their efficient management of vertical loads, converting gravity effects into compressive thrust along the curvature of the rib. However, their out-of-plane response is comparatively less favourable: the same geometry that provides in-plane strength results in high slenderness in the lateral direction, making the structure susceptible to spatial buckling under lateral or asymmetric loading. Under strong wind, seismic, or unbalanced traffic action, the arch no longer behaves as a planar element but as a slender three-dimensional member subject to combined axial force, biaxial bending, and torsion. Consequently, design of the arch rib, hangers, and bracing must account for the coupled in-plane and out-of-plane interaction, including geometric nonlinearity and large-deflection effects, an area that has received sustained research attention.

## 3. Thematic Review of Literature

### 3.1 Design Optimisation and Conceptual Studies

Martins et al. (2026) [1] formulated an automated optimisation framework, combining three-dimensional finite element analysis with a gradient-based algorithm, to minimise the construction cost of bowstring tied-arch concrete bridges while meeting safety and serviceability requirements. Their results identified the Nielsen hanger arrangement and a rise-to-span ratio near 1:5 as the most efficient configuration, though the work was confined to static loading on concrete bridges, leaving dynamic, wind, seismic, and fatigue behaviour of steel bowstring bridges as open questions.

Li et al. (2022) [5] proposed a Hellinger-Reissner variational formulation as a rapid alternative to full finite element modelling for preliminary tied-arch design, reporting close agreement with numerical benchmarks at markedly reduced computational cost, although the method remained restricted to linear elastic behaviour without construction-stage, fatigue, or dynamic effects. Complementary optimisation-oriented studies by Granata (2011) [17], Trentini et al. (2025), and Rana (2013) [20] discuss cost- and topology-based approaches to bridge and viaduct design, underscoring a broader trend toward computational optimisation in modern bridge engineering.

### 3.2 Static, Dynamic and Construction-Stage Behaviour

Sheen et al. (2024) [2] compared conventional tied-arch and network-arch hanger layouts for a 160 m steel tied-arch bridge modelled in MIDAS Civil under AASHTO loading, finding that inclined network hangers reduce bending moments, shear forces, and deflections relative to vertical hangers, though the study did not extend to wind, seismic, or fatigue effects. Zou et al. (2024) [3] examined the dynamic response of a concrete-filled steel tube tied-arch bridge under moving train loads, showing that dynamic amplification increases with train speed and that bridge stiffness governs vibration control, while noting that highway, wind, and seismic loading fell outside the scope of their railway-focused model.

Xiang et al. (2024) [4] combined numerical simulation with field monitoring to assess stresses and deformation during the integral lifting erection of a steel pipe arch bridge, confirming that construction-stage stresses remained within permissible limits when the lifting sequence was carefully controlled, though long-term service, fatigue, seismic, and wind behaviour were not addressed. Ravikant et al. (2019) [12] compared IRC, Eurocode, and AASHTO-based girder designs in STAAD Pro, concluding that the governing design code materially affects both structural response and project economy, while Yogesh and Singh (2020) [8] performed nonlinear finite element analysis of tied-arch bridges under IRC loading [25] in MIDAS Civil, optimising the rib to satisfy an L/800 deflection limit and demonstrating the advantage of nonlinear analysis over conventional linear methods.

### 3.3 Stability, Buckling and Bracing Systems

Several studies have focused specifically on out-of-plane stability and lateral bracing. Lonetti et al. (2019) [11] carried out a nonlinear instability analysis of tied-arch bridges under vertical loading, showing that buckling behaviour is highly sensitive to initial stress state and geometric imperfection. Vican et al. (2016) [15] compared beam- and shell-element idealisations for out-of-plane stability of bowstring arches, concluding that shell models more reliably capture buckling and lateral stability than simplified beam models. Outtier et al. (2006) [18] validated elastic-plastic finite element predictions of lateral buckling in steel tied-arch bridges against experimental strain measurements, confirming the importance of including material nonlinearity.

Earlier foundational work by Kuranishi and Yabuki (1984) [23] used three-dimensional finite element analysis to demonstrate that deck stiffness, bracing arrangement, and connection detailing strongly influence lateral and torsional buckling resistance, recommending that the bridge be analysed as an integrated system rather than through isolated member checks. Wang et al. (1992) [21] and Chan et al. (1990) [22] further established the value of computer-based and field-measurement approaches respectively for predicting stresses, deflections, and dynamic amplification in highway bridges, while Chu et al. (1971) [24] proposed one of the earliest stiffness-matrix formulations for curved girder bridges, laying groundwork for later finite element techniques.

### 3.4 Skewed and Curved Bridge Behaviour

Rahna Sajeeb et al. (2021) [6] modelled reinforced concrete skew bridges with skew angles of 0°, 15° and 30° in STAAD Pro, finding that increasing skew angle substantially alters internal force distribution and increases analytical complexity, while Mebin Mathew et al. (2021) [7] compared straight and horizontally curved bridges, showing that curvature introduces additional torsional moments and centrifugal effects requiring more detailed analysis than straight-span assumptions allow. Ajay D. Shahu et al. (2016) [14] similarly discussed the role of software such as STAAD Pro and MIDAS Civil in modelling complex skewed bridge geometries and loading, reinforcing the value of computational tools for accurate member sizing.

### 3.5 Historical Development, Comparative and Monitoring Studies

Santhosh Kumar et al. (2019) [9] traced the evolution of bowstring girder bridges from timber and wrought-iron construction to modern steel and reinforced concrete forms, highlighting how computational analysis has progressively improved prediction of stress distribution and deformation. Gollapudi et al. (2019) [10] studied the effect of rise-to-span ratio and hanger arrangement on bowstring bridge behaviour in STAAD Pro, and Maulik Patel et al. (2017) [13] compared bowstring girder bridges against semi-through plate girder bridges, concluding that the bowstring form offers material and economic advantages, particularly where construction space is limited.

On the monitoring side, Anjaly R. Krishnan et al. (2015) [16] used modal analysis and artificially induced stiffness reduction to demonstrate that mode-shape curvature methods can successfully localise damage in bowstring girder bridges, while Ren et al. (2004) [19] validated finite element dynamic predictions against ambient wind- and traffic-induced vibration measurements on a steel arch bridge, confirming the reliability of modal testing for structural health assessment.

## 4. Synthesis of Key Findings

| Theme | Representative studies | Key insight |
|---|---|---|
| Design optimisation | Martins (2026), Li (2022), Granata (2011) | Computational optimisation reduces cost and material demand; mostly limited to static/linear conditions |
| Dynamic & construction-stage behaviour | Sheen (2024), Zou (2024), Xiang (2024) | Hanger layout and stiffness govern dynamic amplification; construction-stage stresses need explicit checking |
| Stability & bracing | Lonetti (2019), Vican (2016), Outtier (2006), Kuranishi & Yabuki (1984) | Out-of-plane stability is sensitive to bracing arrangement, imperfections and material nonlinearity |
| Skew & curvature | Rahna Sajeeb (2021), Mebin Mathew (2021) | Skew and curvature significantly alter force distribution, requiring detailed FE analysis |
| Monitoring | Anjaly Krishnan (2015), Ren (2004) | Modal/vibration-based methods are effective for damage detection and validation |

## 5. Research Gap

The reviewed literature demonstrates extensive coverage of finite element modelling, stability and buckling behaviour, dynamic and seismic response, damage detection, and design optimisation for tied-arch and bowstring bridges, with most attention directed toward rise-to-span ratio, hanger configuration, geometric nonlinearity, and bridge curvature. However, comparatively few studies provide a systematic comparison of different lateral bracing configurations (such as K-type, X-type, and Vierendeel-type systems) for steel bowstring girder bridges designed specifically to IRC loading provisions, and fewer still examine the combined influence of bracing type on displacement, axial force, bending moment, stability, and material economy within a single consistent MIDAS Civil framework. This gap motivates the present line of investigation into bracing-system comparison for IRC-compliant [25, 26] steel bowstring arch bridges.

## 6. Conclusion

This review has traced the development of research on tied-arch and bowstring bridges across design optimisation, dynamic and construction-stage analysis, stability and bracing, skew/curvature effects, and structural health monitoring. While the in-plane behaviour of these bridges is now well characterised, their out-of-plane stability under wind, seismic, and asymmetric loading remains an area of active enquiry, particularly regarding the comparative performance of different bracing systems under regional loading codes such as the IRC. Addressing this gap can help establish clearer, code-consistent guidance for bracing selection in medium-span steel bowstring bridge design.

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