Structural Behaviour Assessment of a Steel Bowstring Arch Girder Bridge under IRC Loading: A Comparative Study of Bracing Systems

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***Abstract*—This paper presents a structural evaluation of a 50 m span steel bowstring arch girder bridge analysed in accordance with Indian Roads Congress (IRC) codal provisions. A three-dimensional finite element model of the bridge was developed in MIDAS Civil, comprising a curved arch rib, vertical hangers, a longitudinal tie girder, cross beams, and three alternative lateral bracing systems, namely K-type, X-type, and Vierendeel-type. The model was first validated against manually computed results for a two-hinged arch, after which the bridge was subjected to in-plane actions (dead load, superimposed dead load, vehicular live load and temperature effects) and out-of-plane actions (transverse and longitudinal wind, and seismic response spectrum loading as per IRC:SP-114-2018). Vertical and lateral deflections, mode shapes, and serviceability limits were examined for each bracing configuration. The study found that vehicular and temperature loads govern in-plane vertical deflection, whereas wind action dominates the out-of-plane response, and that the K-type bracing arrangement consistently produced the smallest lateral deflections under both wind and seismic excitation. All critical load combinations satisfied the deflection limits prescribed in IRC:24-2010.**

***Index Terms*—Bowstring arch bridge, bracing systems, finite element analysis, IRC loading, MIDAS Civil, response spectrum.**

I. INTRODUCTION

Arch forms have been used in bridge construction since antiquity because their curved geometry converts transverse loads into predominantly axial compression, allowing efficient transfer of load to the supports. The bowstring (tied-arch) configuration extends this principle by connecting the arch springing with a tension tie, so that the outward thrust of the arch is absorbed internally rather than being transmitted to the foundations as an inclined reaction. This makes the form attractive for sites with poor founding conditions, for crossings over railway lines, and for situations where only vertical bearing reactions can be accommodated at the piers.

A typical bowstring arch bridge superstructure consists of a curved compression arch rib, a longitudinal tension tie or bottom girder, vertical or inclined hangers connecting the two, transverse cross beams that carry the deck load to the tie girder, and a lateral bracing system that stabilises the arch against out-of-plane and torsional effects. While the in-plane behaviour of such bridges under gravity loading is well understood, the out-of-plane response under wind, seismic, and asymmetric traffic loading is comparatively more complex and depends heavily on the configuration of the lateral bracing.

Road Over Bridges (ROBs) employing the bowstring form are increasingly used in India to eliminate level crossings and improve connectivity where road and rail alignments intersect. Notable examples include the Godavari (Kovvur-Rajahmundry) bridge in Andhra Pradesh, a bowstring ROB in the Katihar division of Bihar, and the Jagraon bridge in Punjab. Despite this growing application, published literature dealing specifically with the comparative performance of different bracing systems for such bridges under Indian loading standards remains limited.

II. OBJECTIVES

- To study the structural behaviour of a steel bowstring arch girder bridge under IRC loading.

- To analyse the effective bracing pattern against lateral loading.
- To validate the in-plane and out-of-plane loading analysis of the bridge in MIDAS-Civil.

III. DESCRIPTION AND MODELLING OF BRIDGE

A. Bridge Geometry and Material Properties

The bridge considered is a 50 m span (centre-to-centre of bearings) steel bowstring arch girder bridge with an overall length of 51.4 m, a clear span of 48.0 m, a rise of 10 m, and a deck width of 12.6 m accommodating two traffic lanes with a 7.5 m carriageway. Hangers are spaced at 6.25 m along the span, and a 250 mm thick reinforced concrete deck slab is supported on the longitudinal bottom girders.

TABLE I Geometric Parameters of the Bridge Model

Parameter	Value
Bridge type	Bowstring arch girder
Location	Pune
Span (c/c bearings)	50 m
Deck width	12.6 m
No. of lanes	2
Carriageway width	7.5 m
Rise of arch	10 m
Deck slab thickness	250 mm

Structural steel of Grade E250 (yield stress 250 N/mm², ultimate stress 410 N/mm², modulus of elasticity 2×10^5 N/mm²) is used for the superstructure, while the deck slab is of M30 grade concrete (modulus of elasticity 31,623 N/mm²). Steel density is taken as 78.5 kN/m³. Box sections are adopted for the main girder, arch rib, hangers and bracing members, while the cross beams use an ISMB rolled section, as listed in Table II.

TABLE II Cross-Sectional Properties of Superstructure Elements

Element	Section	Depth (mm)	Width (mm)	Thk. (mm)
Main girder	Box	1200	600	12
Arch rib	Box	800	600	18
Cross beam	ISMB	600	210	12
Edge cross beam	Box	640	300	12
Hangers	Box	640	400	18
Bracings	Box	400	360	12

B. Finite Element Modelling

The bridge superstructure was idealised in MIDAS Civil as a three-dimensional frame model. The arch rib was represented as a curved beam element, the longitudinal bottom girder and cross beams as straight beam elements, and the hangers and bracing members as truss elements carrying axial force only. Fixed supports, restraining all three translational degrees of freedom, were applied at the base of the piers. Three separate models were prepared, each differing only in the lateral bracing configuration adopted between the arch ribs: Vierendeel bracing, K-type bracing, and X-type bracing, with all other geometric and section properties held constant to allow a direct comparison of their structural performance.

IV. METHODOLOGY

The analysis followed a sequential procedure: the research objective (assessment of structural behaviour) was first defined, after which the finite element software was validated against an independently solved benchmark problem. The applicable design codes, IRC:6-2017 [1] for loads and load combinations and IRC:24-2010 [2] for the limit state design of steel bridges, were then reviewed to establish the governing load cases and permissible limits. Analysis was subsequently carried out separately for in-plane actions (self-weight, superimposed dead load, vehicular live load, temperature) and out-of-plane actions (wind and seismic loading), before combining the results to check critical load combinations against serviceability criteria.

A. Software Validation

Prior to analysing the bridge, the finite element model was validated using a classical two-hinged arch problem from established bridge engineering literature [4]: a 40 m span arch subjected to three equal 120 kN point loads spaced at 10 m intervals. The reactions, arch thrust and bending moments obtained from the

MIDAS Civil model were compared against the closed-form manual solution, as shown in Table III.

TABLE III Comparison of Manual and Software Results for the Validation Model

Response quantity	Manual	Software	Remark
Vertical reaction	180 kN	180 kN	Match
Arch thrust	455 kN	455 kN	Match
B.M. at A	0.00	0.00	Match
B.M. at C	93.75	93.00	0.8%
B.M. at D	125.00	124.00	0.8%
B.M. at E	93.75	93.00	0.8%
B.M. at B	0.00	0.00	Match

The close agreement, with a maximum deviation of only 0.8%, confirmed the adequacy of the modelling assumptions and element formulations adopted for the subsequent bridge analysis.

V. LOADING CONSIDERATIONS

A. In-Plane Loads

In-plane loads applied to the model, all derived in accordance with IRC:6-2017 [1], comprised: self-weight, computed internally by the software; deck slab load, applied as a uniformly distributed load on the bottom longitudinal girders; superimposed dead load from the crash barrier (10.125 kN/m); wearing coat load of 1.43 kN/m² based on a 65 mm thick layer of 22 kN/m³ density surfacing; vehicular live load corresponding to two lanes of IRC Class A loading or a single lane of IRC Class 70R loading; and temperature effects, with an element temperature rise of 37.5°C and fall of 12.5°C derived from the recorded maximum (43.3°C) and minimum (1.7°C) shade air temperatures as per IRC:6 Annexure F [1].

B. Out-of-Plane Loads

Wind loads were computed as per IRC:6-2017 (Clause 209) [1] for a bridge deck height of 23.5 m above ground level, using a basic wind speed of 39 m/s at the Pune site, a drag coefficient of 1.7 and a gust factor of 2.0. The resulting transverse wind pressures were applied as uniformly distributed loads of 7.2 kN/m, 4.8 kN/m and 2.4 kN/m on the longitudinal bottom girder, arch rib and hangers respectively, while longitudinal wind loads, taken as 25% of the transverse values, were applied on the cross beams, arch rib and bracing members.

Seismic effects were evaluated through free-vibration (eigenvalue) analysis followed by response spectrum analysis. Eigenvalue analysis identified fundamental periods of 0.09 s, 0.05 s and 0.02 s in the X, Y and Z directions respectively, mobilising more than 96% of the total modal mass in each direction. The response spectrum for Seismic Zone III was generated as per IRC: SP-114-2018 [3], adopting a zone factor of 0.16, hard/rock (Type I) soil, 2% damping, an importance factor of 1.2 and a response reduction factor of 3.0.

VI. RESULTS AND DISCUSSION

A. In-Plane Vertical Deflections

Vertical deflections obtained under in-plane loading are summarised in Table IV. Vehicular loading produced the largest vertical deflection (47.25 mm), followed by temperature effects (25.81 mm), with dead load alone contributing 8.04 mm.

TABLE IV Vertical Deflections under In-Plane Loading

Load case	Dz (mm)
Dead load	8.04
Vehicular load	47.25
Temperature load	25.81

B. Out-of-Plane Deflections under Wind Loading

Lateral deflections under wind loading, compared for the three bracing systems, are given in Table V. The K-type bracing arrangement produced the smallest transverse deflection (50.81 mm), considerably less than the X-type (93.02 mm) and Vierendeel-type (166.80 mm) systems.

TABLE V Lateral Deflections under Transverse Wind Loading

Bracing	Dy (mm)	Dx (mm)
K-bracing	50.81	1.18
X-bracing	93.02	0.85
Vierendeel	166.80	0.68

C. Seismic Response

Under response spectrum loading in the Y-direction (RSY) for Seismic Zone III, the maximum lateral displacements recorded were 28.11 mm for K-bracing, 41.87 mm for X-bracing and 54.78 mm for Vierendeel bracing, confirming the same trend observed under wind loading: the K-type arrangement offers the greatest lateral stiffness among the three bracing systems investigated.

D. Serviceability Checks

As per IRC:24-2010 [2], the total deflection due to dead load, live load and impact must not exceed span/600 (83.33 mm for the 50 m span), while the deflection due to live load and impact alone must not exceed span/800 (62.5 mm). Table VI lists the critical load combinations examined for the K-braced configuration at both the serviceability limit state (SLS) and the ultimate limit state (ULS).

TABLE VI Critical Load Combinations and Corresponding Deflections

Stage	Combination	SLS (mm)	ULS (mm)
Construction	DL	8.04	8.04
Long-term	DL+LL/VL	20.95	78.49
Short-term	DL+WL+VL/LL	24.26	75.93
Short-term	DL+EL+VL/LL	7.64	20.35

All computed deflections remain within the prescribed serviceability limits, confirming that the K-braced bowstring arch configuration is structurally adequate under the combined action of dead, live, wind, seismic and temperature effects.

VII. CONCLUSION

- The maximum in-plane vertical deflection of the bowstring arch bridge occurs under vehicular and temperature loading, while wind action is the dominant out-of-plane effect.
- Among the three bracing systems compared, K-type bracing consistently produces the smallest lateral deflections under both wind and seismic (response spectrum) loading, followed by X-type and Vierendeel-type bracing.
- All critical load combinations at both the construction stage and in service satisfy the deflection limits specified in IRC:24-2010.
- Steel bowstring arch girder bridges are a structurally viable option for simply supported spans between 45 m and 150 m, particularly at railway level crossings where other bridge forms may not be feasible.

Future work may examine the influence of varying cross-sectional properties, span length, deck width, arch rise, and hanger arrangement, as well as alternative material grades for the arch, hangers, and deck, to develop broader design guidance for steel bowstring arch bridges.

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REFERENCES

[1] IRC 6: Standard Specifications and Code of Practice for Road Bridges, Section II – Loads and Load Combinations, Indian Roads Congress, 2017.

[2] IRC 24: Standard Specifications and Code of Practice for Road Bridges, Section 5 – Steel Road Bridges (Limit State Design), Indian Roads Congress, 2010.

[3] IRC: SP-114: Guidelines for Seismic Design of Road Bridges, Indian Roads Congress, 2018.

[4] K. S. Rakshit, Design and Construction of Highway Bridges, New Central Book Agency, 2004.