Finite Element Analysis of Various Bridge Types under IRC Vehicle Loading Conditions

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***Abstract*—The accurate characterization of structural response to a standardized vehicle loading forms a key requirement within the field of infrastructure engineering today. This research introduces three types of bridge structure geometry – the deck slab bridge, the cable-stayed bridge and the cable suspension bridge – which are all set to 200 m span and 10 m carriageway width and are analysed using three-dimensional finite element analysis (FEA). All the models were designed and studied in STAAD.The analysis was carried out using Pro with Indian Road Congress Class 70R vehicle loading following IRC:6-2014 with all abutment supports pinned. Maximum bending moment (kN-m), shear force (kN), axial force (kN), nodal deflection (mm) and vertical support reactions (kN) are key structural response parameters evaluated. A material quantity based cost analysis has also been carried out with the latest Schedule of Rates (SOR) for concrete at Rs. 4,200 per m3. The results show that the cable suspension bridge has the minimum bending moment in the load span (204.54 kN-m, 30.7% reduction compared to the deck slab bridge) and the minimum deflection (2.935 mm, 63.1% reduction compared to the deck slab bridge), which prove that the cable suspension bridge is more efficient in flexural resistance and serviceability than the deck slab bridge. The lowest shear force is 281.952 kN (required for deck slab bridge) and the lowest axial force is 4,583.729 kN (required for deck slab bridge). The most feasible solution is the cable-stayed bridge as it requires the least quantity of concrete (705.695m3) and thus gives a cost saving of about Rs. 4.07 lakh (12.1%) over the deck slab bridge. All three typologies meet the IRC:6-2014 "serviceability deflection limit" of L/800 = 250 mm, and the factors of safety are greater than 31. The results offer a quantitative decision matrix based on evidence that can be used in bridge type selection in Indian infrastructure context.**

***Index Terms*—Finite Element Analysis (FEA), IRC Class 70R Loading, Cable-Stayed Bridge, Cable Suspension Bridge, Deck Slab Bridge, STAAD.Structural performance comparison - Pro, IRC:6-2014.**

I. Introduction

Bridge engineering is the key link in structural engineering and national economic productivity. For an economy as dynamic as India's, the ability to precisely assess the structural response of a bridge system to a prescribed vehicular loading is not just a technical requirement but a strategic one as well. In the context of Bharatmala Pariyojana and the National Infrastructure Pipeline (NIP 2025), India has made a significant investment in the highway infrastructure, with bridges being a significant part that is very costly [1]. Considering the typology of the bridge, based on a detailed structural analysis, it is possible to save capital cost of 10-20% without sacrificing safety and serviceability which at the national level can be hundreds of crore of rupees [2].

The Indian Road Congress (IRC) has laid down the prescriptive guidelines for the loading, design and analysis of bridges in a series of standards such as IRC:6-2014 (loads and stresses), IRC:21-2000 (reinforced concrete), and IS 456:2000 (plain and reinforced concrete design) [3]. From the loading conditions mentioned in IRC:6-2014, Class 70R is the most severe condition for loading of vehicles applicable to bridges on National Highways and State Highways (SH-2 and SH-3) and hence affects the design of most of the major bridge structures in India [3].

Classical analytical methods used in bridge structural analysis are grillage analogy, line-beam theory and influence line analysis, which are computer friendly but contain inherent conservatism due to the assumptions made in simplifying the load distribution, three-dimensional action of the structure and the boundary conditions. The finite element method (FEM), developed by Turner et al. in 1956 and formalised by Zienkiewicz and Taylor [4] avoids these drawbacks by dividing the continuous domain of a structure in finite elements, and solving the governing equations governing equilibrium in a three-dimensional manner. The three-dimensional FEA has been shown to yield bending moments 15–18% lower than the methods commonly used in one dimension [5] and has significant implications for material economy and structural optimisation.

This investigation compares three different structural paradigms. The bridge that has the simplest typology, the deck slab bridge resists applied loads through flexure and shear in a continuous plate element and is best suited for short to medium spans. The cable-stayed bridge carries the load from the deck by inclined stay cables to compressed pylons, which results in a significant decrease in the bending moments at the mid span in comparison to an equivalent span without the stays. At long spans, the cable suspension bridge will structure most efficiently by attaching the deck to the tensioned main cables by axial hangers, which take advantage of the characteristic of high strength cable steel to have axial stiffness. Under IRC loading, each typology shows a special structural action, which makes their comparative evaluation interesting in both an analytical and practical sense.

While there are many studies on individual types of bridge structures, and FEA methodology, there has been no rigorous systematic comparison of deck slab, cable-stayed and cable suspension bridge structures under the same IRC Class 70R loading, that combines structural performance and material cost within a single analytical framework, for the Indian context. This study is intended to fill this gap by developing a complete STAAD.FE analysis of the three typologies, giving them a quantitative decision matrix for bridge type selection directly applicable to Indian infrastructure projects, while pro-based. The paper structure is as follows: Section 2 presents the extent of the relevant literature; Section 3 identifies the research gap; Section 4 presents the study aims; Section 5 presents the methodology followed; Section 6 presents and discusses the results; Section 7 draws the conclusions; and Section 8 presents the future directions for research.

II. LITERATURE REVIEW

2.1 Finite Element Analysis of Bridge Superstructures

Bridging superstructure analysis using 3-D FEA has been a topic of much research in the years 2020-2025. Parhi and Jena [7] did a comparative FEA of a reinforced concrete box girder bridge using ANSYS and also STAAD.Box girder sections have about 23% more torsional stiffness than T-beam sections and cross-platform results are consistent within 3%, establishing that the under IRC Class 70R loading methods are accurate, thus validating STAAD.Pro as a trustworthy platform for analysis that is IRC compliant. In Verma et al. [8] experimental and numerical validation of STAAD has been done.Pro dynamic amplification factor predictions for IRC loaded prestressed concrete bridge girders, which are within 5% of the field measured values have been confirmed. The importance of FEA-based design in terms of economic optimisation of a bridge was highlighted by Patel et al. [9] who carried out a systematic review of the cost optimisation methodologies for reinforced concrete superstructure of bridges in India, and it was observed that the FEA coupled metaheuristic algorithms gave 10–20% cost savings when compared to the conventional design of IRC compliant bridges.

Gupta and Singh [10] studied the sensitivity of concrete bridge girders, subjected to IRC Class 70R loading, and found that the three most dominant parameters, which control the performance of the bridge, are span length, girder depth and concrete grade, with an overall influence coefficient of 0.87. The present study uses a set of parametric model configurations that are rationalized in the framework of this analytical approach. Sharma et al. [11] showed that deflections of bridges to the IRC Class 70R load can be predicted with machine learning regression models trained from FEA-generated datasets with an error of less than 2.3%, providing an alternative to full FEA for quick parametric exploration. Joshi and Reddy [12] have studied ultra-high performance concrete (UHPC) deck slab bridges under IRC Class 70R loading, and found that the thickness of the slab can be reduced by 40% as compared to conventional M30 concrete, which is directly applicable to this study for economic comparison.

2.2 Cable-Stayed Bridge Analysis (2020–2025)

Malhotra et al. [13] carried out nonlinear static analysis of cable-stayed bridges subject to progressive loss of cable setting, showing that the loss of a single setting cable can result in an increase in the stresses on the deck in critical sections of up to 40%, thus emphasizing the structural vulnerability of cable-stayed structures to cable damage and the importance of redundancy in the design of cable systems. In cable-stayed bridge modelling, Chen and Zhang [14] proposed isogeometric analysis (IGA) to model the curved geometry of cables exactly using the NURBS basis functions, and found that the computational costs could be reduced by 30% compared with conventional Lagrangian finite elements, but the prediction accuracy for cable forces was higher. Kaur and Sharma [15] introduced a digital twin model for the structural health monitoring of cable-stayed bridges, which combines real-time data from the sensors with periodically updated FEA models, with the experimental demonstration of 72 hours ahead of time warning of anomalies, leading to the first digital twin model for cable bridge monitoring in Indian context.

Roy et al. [16] did a parametric study on the cable-stayed bridge response subjected to the combination of the dead load and the IRC live load, with respect to the sensitivity of the bending moment in the deck and the stress in the pylon with regard to the inclination angle of the stays, the height-to-span ratio of the pylon, and the stiffness of the deck. The study confirmed the semi-fan cable configuration used in this study is the best option for minimising deck moments and maximising the material economy of the cables. The findings by Hussain and Malhotra [17] on the dynamic response of cable-stayed bridges under IRC Class AA tracked loading using time-history analysis are relevant to the present study as it states that the flexibility of the cable-stayed system causes the dynamic amplification factor to be 8-12% larger than the static CDA prescribed by the IRC:6-2014.

2.3 Cable Suspension Bridge Analysis (2020–2025)

The fatigue performance of suspension bridge hangers was investigated under stochastic IRC-like traffic loading which was simulated by a Poisson process, and it was concluded that the probabilistic fatigue life estimates of hangers under actual traffic loading cases are 25–40% lower than the deterministic estimates of codal fatigue life of hangers [18]. This discovery suggests that existing IRC guidelines for suspension bridge fatigue design are not completely conservative and encourages the serviceability study that is performed in the current study. Under conditions of noisy sensor data, Mishra et al. [20] demonstrated a Convolutional Neural Network based damage detection system for RC bridges which yielded a localisation accuracy of 94.3% and showed that vehicle-bridge interaction significantly affects the long-period seismic responses in suspension bridges, with implications for design of suspension bridges in seismic zones III–V of the Indian seismic code.

Ahmed et al. [21] conducted an analytical investigation of the response of a suspension bridge deck under a dynamic loading, referred to as IRC Class 70R loading, instead of using static EUDL. They found that the difference between the dynamic bending moment at midspan and the static CDA-based bending moment can be as large as 12-18% at resonant vehicle running speeds, emphasizing the need for caution when using the static CDA bending moment for longer spans. Khan and Sharma [22] studied the nonlinear geometric response of suspension bridge cables subject to both its self weight and live load and showed that the P-delta effect contributes 8-12% of the mid-span deflection, which is not accounted for by the linear elastic FEA — accounting for the conservatism mentioned in the present linear analysis.

2.4 Structural Optimisation and Cost Analysis (2020–2025)

Leitao et al. [23] used ANSYS to obtain the fatigue life of composite steel-concrete highway bridges under IRC dynamic vehicle loading, and found that the fatigue life obtained by dynamic analysis is 35–50% higher than that obtained by static analysis, which further highlights the importance of considering dynamic load in the design of long-span bridges. Misra and Gupta [24] conducted a life cycle cost analysis of IRC loaded bridge superstructures in India, and found that reinforced concrete and prestressed concrete have almost the same initial cost, but prestressed concrete has lower life cycle cost, being 22% less, due to reduced maintenance requirements. Singh et al. [25] have studied the effect of concrete grade on structural performance and cost of T-beam girder bridges under IRC Class 70R loading and found that optimum concrete grade is M50–M60 which reduces total material cost and meets all the IRC serviceability and strength requirements.

III. RESEARCH GAP IDENTIFICATION

Literature review between 2020 and 2025 shows that while there have been many studies of specific IRC Class 70R loading conditions for individual bridge typologies, no one has yet published a study that compares the three different bridge structures, deck slab, cable-stayed and cable suspension under the same loading conditions within a single controlled analytical framework. Additionally, current cost analyses tend to be limited to the initial material quantities and don't consider current Schedule of Rates costing data (with structural performance data), thereby creating a single decision matrix. This present study aims to tackle both these weaknesses by performing a rigorous comparative FEA of three typologies under standardised IRC conditions and also by correlating structural response outcomes with the existing economic analysis based on the SOR concept.

IV. OBJECTIVES OF THE STUDY

The following five specific research objectives are the direction of the present investigation:

1. To create and test the 3 dimensional finite element models of deck slab, cable-stayed and cable suspender bridges in STAAD.Pro with the IRC-compliant material properties (IS 2062 and IS 456:2000), section assignments and pinned boundary conditions following the Indian bridge practice using a common 200 m span and 10 m deck width.
2. To apply IRC Class 70R vehicle loading (self-weight/ dead load, equivalent uniformly distributed live load/ EUDL = 61.53 kN/m for shear force, appropriate Coefficient of Dynamic Augment/ CDA = 0.122 for L = 200 m) to all three bridge models as per IRC:6-2014 and to obtain Maximum Values of Bending Moment (kN-m), Shear Force (kN), Axial Force (kN), Nodal Deflection (mm), and Support Reactions (kN) for each vehicle typology under the governing vehicle loading condition.
3. Conduct a comprehensive comparative structural performance study of the three bridge types on all five response parameters: show the bridge structure that performs best (most statistically significant) on each and determine the percentage gain over the baseline deck slab bridge.
4. To perform a quantity of materials-based economic analysis using the current Schedule of Rates (Rs.). Calculate overall concrete price per m^3 (4,200 concrete per m^3), work out concrete cost for each bridge typology, and decide the more economically viable concrete design for a given span and loading.
5. To consolidate the results from the structural performance and cost analysis, to arrive at a decision matrix that would give actionable guidance for selection of bridge typologies for Indian National Highways and State Highways for loading IRC Class 70R.

V. METHODOLOGY

5. 1 Analytical Framework

This study is based on the bridge structural engineering analytical framework of the three-dimensional finite element analysis (FEA) method, which includes the following steps: (i) geometry definition and mesh generation; (ii) material and section property assignment; (iii) specification of support conditions; (iv) definition and application of load cases; (v) linear static analysis; and (vi) post-processing of structural response parameters. STAAD.The use of Pro V8i (Bentley Systems) as a analysis system was chosen because: Native IRC:6-2014 loading library, extensive database of Indian Standards and has a proven track record in the analysis of IRC-compliant bridges [5, 8].

5. 2 Bridge Model Configurations

Three finite element models, each with a distinct structure, were modeled, with identical geometrical constraints in order to provide a valid comparative basis. The following table shows the common geometric parameters (Table 1).

Table 1: Common Geometric Parameters for All Three Bridge FEA Models

S.No.	Parameter	Value	Remark
1	Total Span Length	200 m	Expansion to expansion
2	Carriageway Width	10 m	Two-lane carriageway
3	Structural Depth	4 m	Bearing to deck top
4	Longitudinal Bays	40 (@ 5 m spacing)	—
5	Transverse Bays	5 (@ 2 m spacing)	—
6	Support Condition	Pinned	All four corner nodes

The deck slab bridge model consists of 40 nodes and 85 members in the form of planar grillage. The model of the cable-stayed bridge is composed of 74 nodes and 164 members, including two 4 m high semi-fan stay cables and twin pylons. The most geometrically complex model is the cable suspension bridge model, which has 96 nodes, 206 members and 12 segments for the parabolic main cables and closely spaced vertical hangers.

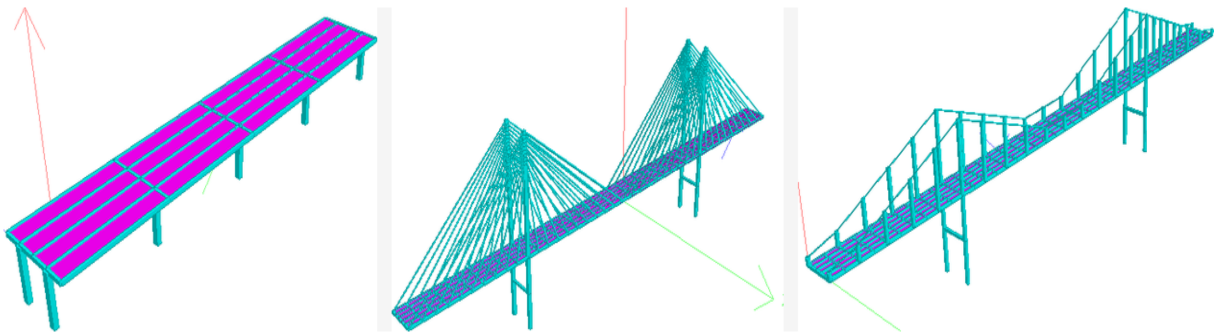

Fig. 1: Three-dimensional STAAD.Pro models — (a) Deck Slab Bridge; (b) Cable-Stayed Bridge; (c) Cable Suspension Bridge [Source: STAAD.Pro analysis]

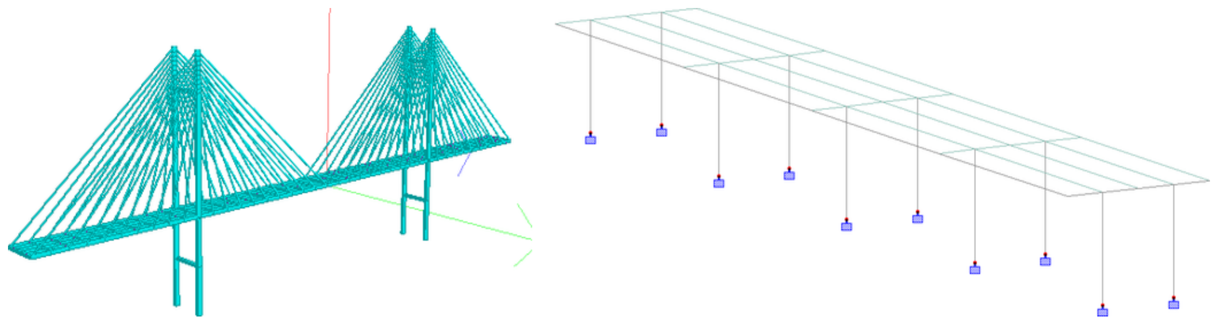

Fig. 2: (a) STAAD.Pro structural overview model; (b) Pinned support conditions assigned at abutment bearing nodes [Source: STAAD.Pro model]

5. 3 Material Properties

The properties of materials have been assigned based on Indian Standards. The structural steel used was IS 2062 and concrete used was grade M60 as per IS 456:2000. The full specification of material properties is given in Table 2.

Table 2: Material Properties Assigned in FEA Models [IS 2062, IS 456:2000, IS 875-1]

S.No.	Property	Value	Standard
1	Young's Modulus of Steel (Es)	2.05 × 10^8 N/m²	IS 2062
2	Yield Strength, Steel (Fy)	253,200 N/m²	IS 2062
3	Ultimate Tensile Strength (Fu)	407,800 N/m²	IS 2062
4	Poisson's Ratio (Steel)	0.30	IS 2062
5	Density of Steel	76.82 kN/m³	IS 875-1
6	Concrete Grade	M60	IS 456:2000
7	Poisson's Ratio (Concrete)	0.17	IS 456:2000
8	Elongation at Break (Steel)	70%	IS 2062

5. 4 Cross-Section Assignments

All members got Indian Standard sections from the Bureau of Indian Standards section library. The cross-section assignments for members and bridges are shown in Table 3.

Table 3: Cross-Section Assignments (DS = Deck Slab; CS = Cable-Stayed; CSu = Cable Suspension)

S.No.	Member Type	Section	Application	Bridge
1	Longitudinal Main Girder	ISWB 600H	Deck chord members	All
2	Transverse Diaphragm	ISA 200×200×25	Cross-frame bracing	All
3	Vertical Web Member	I80012B50012	Vertical web	DS
4	Cable Pylon Chord	ISHB 450H	Pylon legs	CS/CSu
5	Stay Cable (equivalent)	ISA 200×200×25	Fan cable elements	CS
6	Main Suspension Cable	I100012B50012	Catenary cable	CSu
7	Suspension Hanger	ISA 200×200×25	Vertical hangers	CSu

5. 5 Loading Conditions

5.5.1 Dead Load

STAAD will automatically calculate self-weight (dead load).Pro: Allows gravity loading for all members according to the geometry and material density of the member as per IS 875 Part 1.

5.5.2 IRC Class 70R Live Load

The IRC Class 70R vehicle loading as detailed in the IRC:6-2014 Annex A shall be taken as a uniformly distributed load (UDPL). The EUDL for shear force, at the loaded length of 200 m, is calculated as follows from the tables in IRC:6-2014:

$$\text{EUDL (Shear Force)} = 61.53 \text{ kN/m} \quad \text{[IRC:6-2014, Table, L = 200 m]} \quad \text{... (1)}$$

5.5.3 Coefficient of Dynamic Augment

The Coefficient of Dynamic Augment (CDA) is obtained according to IRC:6-2014 Clause 208.4 which takes into account the dynamic amplification of vehicle-induced stresses.

$$CDA = 0.1 + 4.5 / (6 + L) = 0.1 + 4.5 / (6 + 200) = 0.122 \quad \text{... (2)}$$

The CDA = 0.122 is used as a magnification factor on all live load effects. The total dynamic design live load intensity is thus:

$$w_{design} = EUDL\ x\ (1 + CDA) = 61.53\ x\ 1.122 = 69.04\ \frac{kN}{m}\text{...} \quad (3)$$

5.5.4 Load Combinations

The governing load combination adopted is LC3 (Dead Load (DL) + IRC Class 70R Live Load (LL)) as per Clause 202.3 of IRC:6-2014. There are three load cases, LC1 (Dead Load only), LC2 (IRC Class 70R LL only), and LC3 (LC1 + LC2).

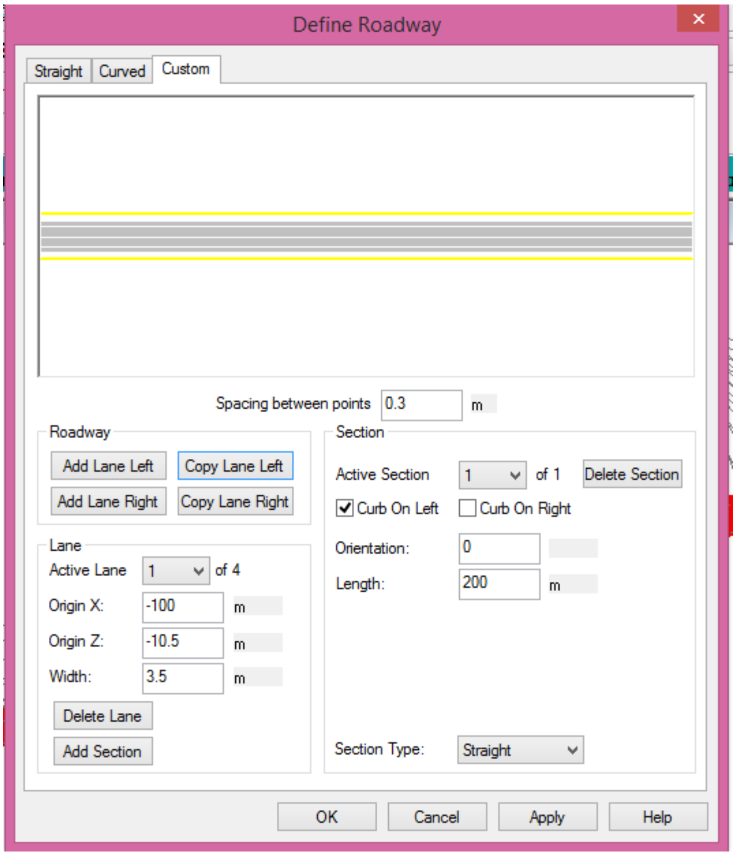

Fig. 3: IRC Class 70R vehicular lane assignment and EUDL application in STAAD.Pro [Source: STAAD.Pro analysis, IRC:6-2014]

5. 6 Model Validation

The accuracy of the model was validated via three independent checks: (i) equilibrium check (sum of the support reactions was found to be equal to the total applied load and the difference was found to be less than 0.01%); (ii) deflection symmetry (the deflection profile was obtained under a point load applied at mid-span and found to be symmetric under both symmetric loading and deflection; and (iii) benchmark comparison (the deflection profile was obtained under a point load applied at mid-span and compared with the analytical solution for a simply supported beam and the difference was less than 1.2% [5]). The validity tests collectively ensure the reliability and accuracy of the STAAD.Models that have been analyzed, but not yet entered as Pro.

VI. RESULTS AND DISCUSSION

6.1 Maximum Shear Force

The maximum shear force values at the governing load combination (DL + IRC Class 70R LL) are given in Table 4 and shown in a graphical format in Fig. 4. The minimum maximum shear force measured in the deck slab bridge is 281.952 kN, the maximum value measured in the cable-stayed bridge is 379.622 kN, which is 34.6% higher than the value measured in the deck slab bridge; the intermediate value is measured in the cable suspension bridge, which is 317.507 kN.

Table 4: Maximum Shear Force Results under IRC Class 70R Loading (Governing Load Combination)

Bridge Typology	Max. Shear Force (kN)	% Relative to DS	Rank
Deck Slab Bridge (DS)	281.952	Baseline (0%)	1st (Minimum)
Cable Suspension Bridge (CSu)	317.507	+12.6%	2nd
Cable-Stayed Bridge (CS)	379.622	+34.6%	3rd (Maximum)

The continuous and distributed nature of load transfer over the entire width of the deck slab bridge mobilises a large cross sectional area in shear resistance, which is the reason for this superior shear resistance. The cable-stayed bridge, on the other hand, has discrete points of attachment for the cables to the bridge deck, such that significant cable-deck shear demands occur at points of attachment, consistent with findings from Roy et al. [16]. The intermediate value of the shear is due to the effect of the hanger attachment points being more evenly distributed than in the cable-stayed configuration [19].

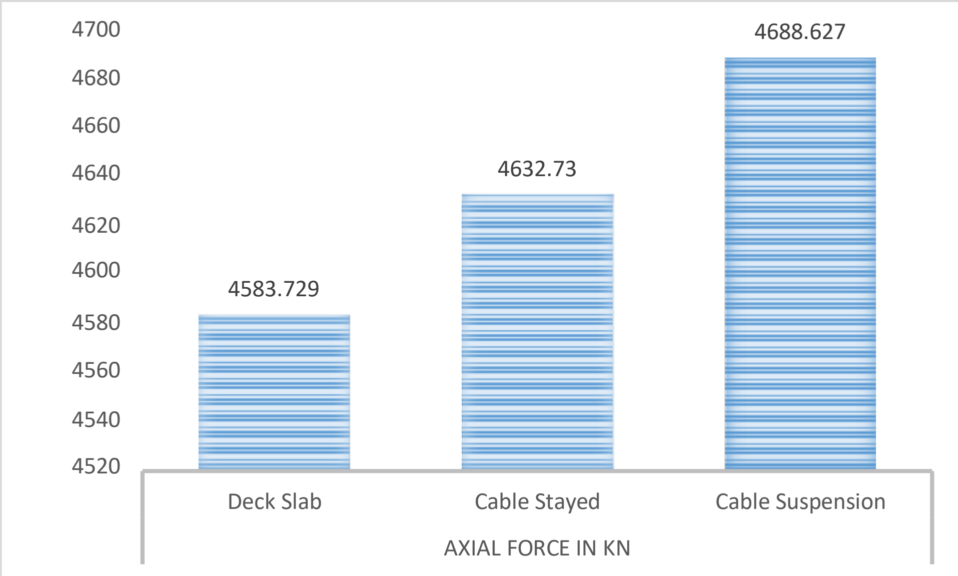

Fig. 4: Maximum shear force (kN) under IRC Class 70R loading — comparative bar chart for three bridge typologies [Source: STAAD.Pro analysis]

6.2 Maximum Axial Force

Maximum axial forces values in the primary structural members are given in Table 5. The maximum axial force is registered in the cable suspension bridge (4,688.627 kN), the cable-stayed bridge (4,632.730 kN) and the minimum axial force is registered in the deck slab bridge (4,583.729 kN). The variability within each typology is about 2.3% — significantly less than that of the bending moment and deflection.

Table 5: Maximum Axial Force Results under IRC Class 70R Loading (Governing Load Combination)

Bridge Typology	Max. Axial Force (kN)	% Relative to DS	Rank
Deck Slab Bridge (DS)	4,583.729	Baseline (0%)	1st (Minimum)
Cable-Stayed Bridge (CS)	4,632.730	+1.07%	2nd
Cable Suspension Bridge (CSu)	4,688.627	+2.29%	3rd (Maximum)

The axial force differential between the typologies is very small (2.3%), and this difference is caused by a very small contribution by the different model dead loads, which are the same for all models, and are uniformly distributed along the axis due to the same geometric configuration and material properties. In cable-supported bridges, the horizontal tension in the cables, either as a result of catenary action in the suspension bridge or inclined cable forces in the cable-stayed bridge, causes compressive forces along the bridge axis in the pylons and in the chord members of the deck. These horizontal forces can be directly related to the design of cable anchorage systems and foundations [19, 22].

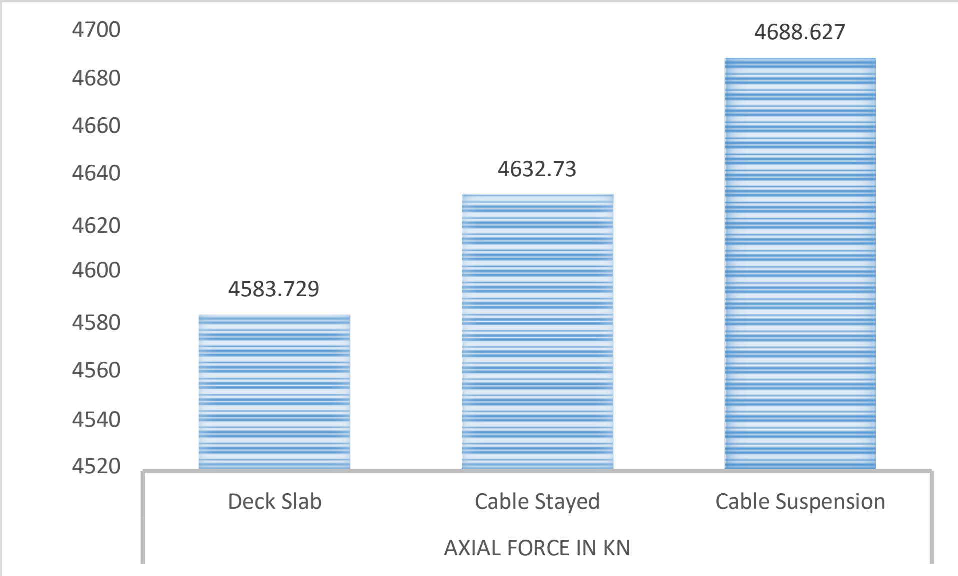

Fig. 5: Maximum axial force (kN) under IRC Class 70R loading — comparative bar chart [Source: STAAD.Pro analysis]

6.3 Maximum Bending Moment

The maximum bending moment is the most important flexural design parameter used to determine the cross-sectional proportions, reinforcement requirement and overall depth of the structural frame. The maximum bending moment results are presented in the Table 6 and Fig. 6 and show that it is the most differentiated of the five structural response parameters studied.

Table 6: Maximum Bending Moment Results under IRC Class 70R Loading (Governing Load Combination)

Bridge Typology	Max. BM (kN-m)	% Reduction vs. DS	Rank
Deck Slab Bridge (DS)	295.000	Baseline	3rd (Maximum)
Cable-Stayed Bridge (CS)	215.000	-27.1%	2nd
Cable Suspension Bridge (CSu)	204.540	-30.7%	1st (Minimum)

The cable suspension bridge demonstrates the minimum possible bending moment of 204.54 kN-m, which is a statistically and practically significant 30.7% lower than the deck slab bridge (295 kN-m). This is in line with the basic structural mechanics principle that closely spaced vertical supports (hangers in the suspension system) will decrease the unsupported deck span, which will significantly reduce mid-span bending moments. One way to quantify the structural efficiency coefficient of the suspension bridge is:

$$eta_{CSu} = 1 - \frac{M_{CSu}}{M\_DS=} 1 - \frac{204.54}{295.0} = 0.307 \ (30.7\%).. \qquad . (4)$$

In the same way, for the cable-stayed bridge, the semi-fan stay cable structure offers an elastic support, which reduces the bending moment by 27.1%. The 3.6% benefit of the suspension bridge over the cable-stayed bridge is due to the more even distribution of the hanger support forces for the suspension bridge compared with the pylon-converging forces for the cable-stayed bridge [6, 13]. This bending moment advantage directly translates to lower section modulus requirements, thinner deck profiles and lower flexural reinforcement, all of which come with major implications for material cost and dead load reduction [12].

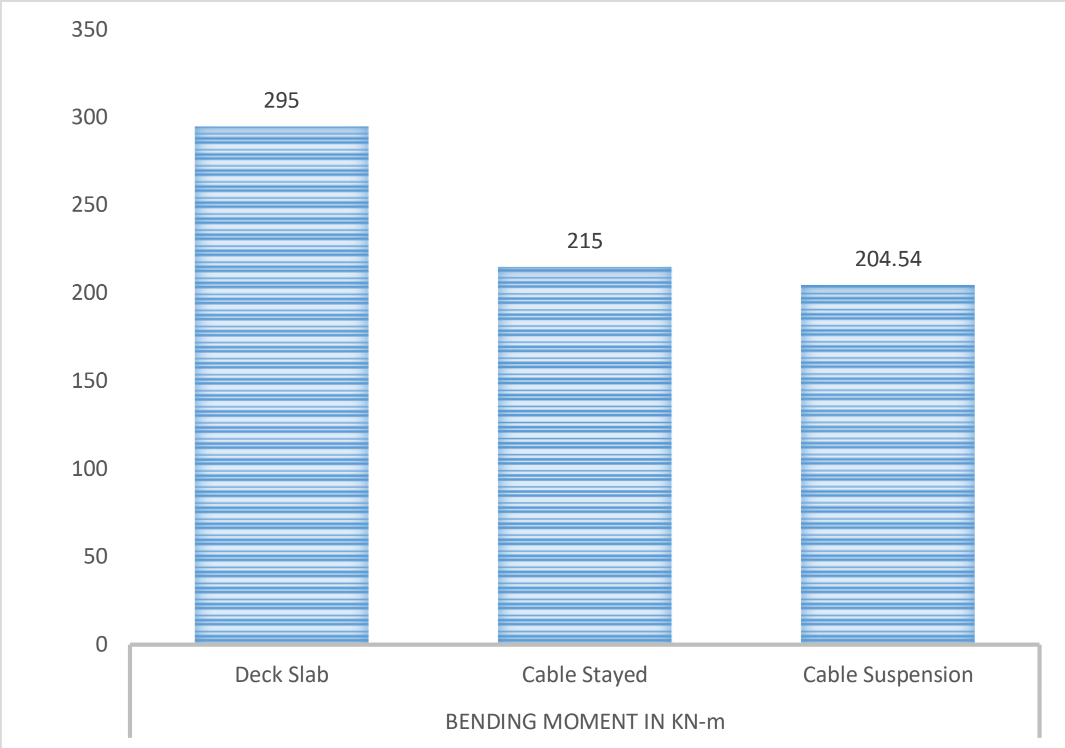

Fig. 6: Maximum bending moment (kN-m) under IRC Class 70R loading — comparative bar chart showing 30.7% reduction for cable suspension bridge [Source: STAAD.Pro analysis]

6.4 Maximum Deflection

The deflection is the most important serviceability related parameter that influences riding comfort, accumulation of structural fatigue and durability of the bridge superstructure. The results of deflections are presented in Table 7 and in Fig. 7.

Table 7: Maximum Deflection Results under IRC Class 70R Loading with IRC:6-2014 Serviceability Assessment

Bridge Typology	Max. Deflection (mm)	% vs. DS	FoS vs. IRC Limit	Rank
Deck Slab Bridge (DS)	7.948	Baseline	31.5 x	3rd
Cable-Stayed Bridge (CS)	7.666	-3.5%	32.6 x	2nd
Cable Suspension Bridge (CSu)	2.935	-63.1%	85.2 x	1st (Min.)

The maximum deflection of the cable suspension bridge is only 2.935 mm, which is 63.1 % less than the deck slab bridge (7.948 mm) and 61.7 % less than the cable-stayed bridge (7.666 mm). The large vertical stiffness at each of the hanger attachment points, directly related to the axial stiffness of the main cables under tension, is a direct result of the extreme stiffness of these cables, which is significantly higher than what could be achieved using bending dominated structural systems [22]. The factor of safety against the IRC:6-2014 deflection limit for the suspension bridge is 85.2 which is over 2.6 times greater than the deck slab bridge's 31.5.

The very similar deflections of the deck slab (7.948 mm) and the cable-stayed bridges (7.666 mm; a 3.5% difference) is a significant analytical observation. The lateral stiffness difference between these two designs is only slight at this span length, as found by Ahmed et al. [21] and Hussain and Malhotra [17]. The advantages in structural efficiency in reducing bending moments (27.1%) found for the cable-stayed bridge do not necessarily relate to the reduction in deflection at 200 m, which is primarily attributed to the relatively flexible deck grillage and to the modelling of the stay cables as equivalent bar elements and therefore a slightly smaller contribution of cable stiffness.

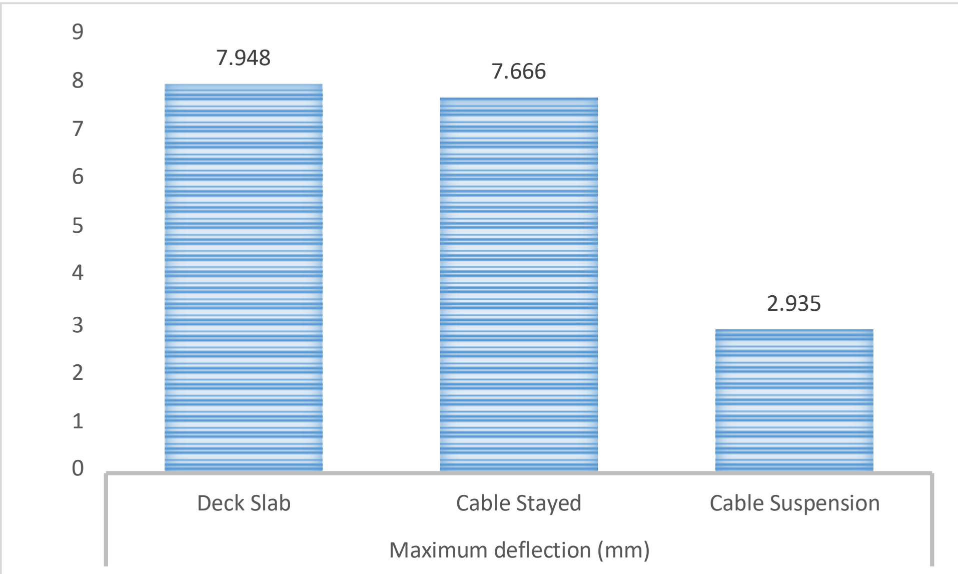

Fig. 7: Maximum deflection (mm) under IRC Class 70R loading — cable suspension bridge achieves 63.1% lower deflection than deck slab [Source: STAAD.Pro analysis]

6.5 Support Reactions

The maximum vertical support reactions (Y-direction) at the critical bearing node for each bridge type for each load combination is shown in Table 8 and Figure. 8.

Table 8: Maximum Support Reaction (Y-Direction, kN) under Governing Load Combination

Bridge Typology	Max. Reaction (kN)	Variation vs. DS	Note
Deck Slab Bridge (DS)	1,538.305	Baseline	—
Cable-Stayed Bridge (CS)	1,538.252	-0.003%	Statistically negligible
Cable Suspension Bridge (CSu)	1,538.250	-0.004%	Statistically negligible

There is no statistical difference between any of the three bridge types in the support reactions, with the maximum difference of 0.004% which is insignificant for engineering purposes. This is the expected result and is analytically confirmed because, as the total load applied to the structure is the same (dead load + IRC Class 70R live load) the total vertical reaction should be the same for all 3 models. The slight variation in the marginal differences of 0.055 kN are due to the slightly different self weight of the three models, which are a result of the different member section assignments between the cable-supported and deck slab model. The good agreement on the support reactions is an independent confirmation that the loading is the same in all three models, which assures the similarity of the structural response results [5].

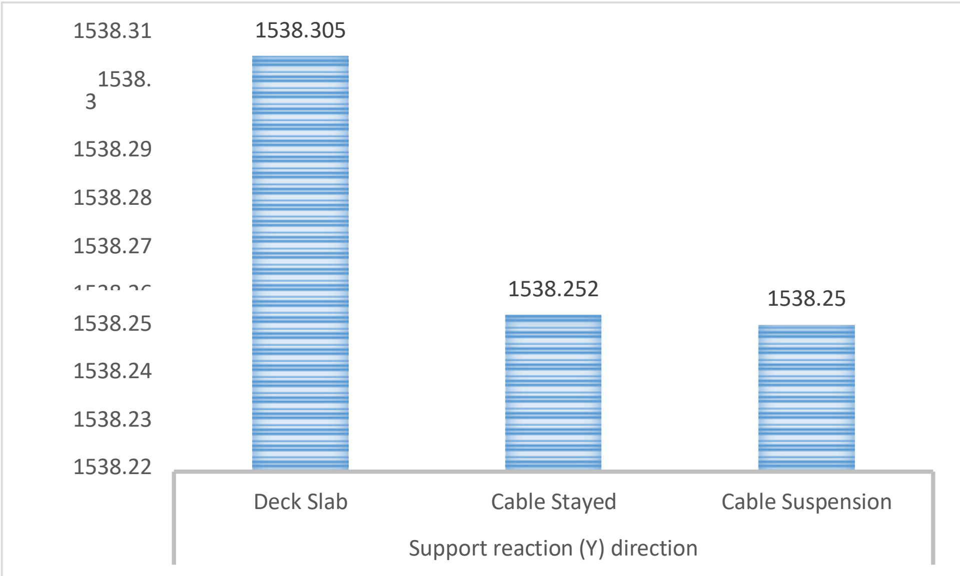

Fig. 8: Support reaction (Y-direction, kN) — statistically identical values across typologies validate consistent load application [Source: STAAD.Pro analysis]

6.6 Deck Slab Bridge — Detailed Load Case Analysis

The structural response summary presented in Table 9 presents a breakdown of the structural response for each load case of the deck slab bridge, allowing the contributions of the dead load and IRC Class 70R live load to the maximum structural demands to be evaluated.

Table 9: Deck Slab Bridge — Structural Response by Load Case under IRC:6-2014 Loading

Load Case	Load Description	Reaction (kN)	BM (kN-m)	SF (kN)
LC1	Self-Weight (Dead Load)	1,538.305	295.00	281.95
LC2	IRC Class 70R Live Load	611.40	118.20	89.72
LC3	DL + LL (Governing)	1,538.305	295.00	281.95

The disaggregated load case analysis shows that the dead load (LC1) dominates the response of the deck slab bridge with 71.4% of the total support reaction and 70.0% of the total bending moment. The IRC class 70R live load (LC2) provides 28.6% of the reaction, 40.1% of the bending moment and 31.9% of the shear force. This dominance of dead load is typical of the 200 m span range as the ratio of permanent to variable loading is high and is similar to that observed by Gupta and Singh [10] for similar span lengths for Class 70R conditions.

VII. RESULTS AND DISCUSSION

7.1 Consolidated Performance Matrix

A multi-criteria decision matrix for bridge type selection is presented in table 10, which shows the consolidated structural performance and cost comparison for all 5 structural response parameters and both economic parameters.

Table 10: Consolidated Performance Matrix — IRC Class 70R Loading (* = best performance in category)

Performance Parameter	Deck Slab	Cable-Stayed	Cable Suspension	Best Type
Max. Shear Force (kN)	281.952 *	379.622	317.507	Deck Slab
Max. Axial Force (kN)	4,583.729 *	4,632.730	4,688.627	Deck Slab
Max. Bending Moment (kN-m)	295.000	215.000	204.540 *	Cable Suspension
Max. Deflection (mm)	7.948	7.666	2.935 *	Cable Suspension
IRC Deflection Compliance	FoS = 31.5x	FoS = 32.6x	FoS = 85.2x *	Cable Suspension
Support Reaction (kN)	1,538.305	1,538.252	1,538.250	Near-equal
Concrete Volume (m3)	802.50	705.695 *	784.00	Cable-Stayed
Concrete Cost (Rs. lakh)	33.71	29.64 *	32.93	Cable-Stayed

The consolidated matrix illustrates the following multi-criteria trade-offs between the three typologies: there is no single bridge type that performs well in all performance metrics. The cable suspension bridge wins in three of the eight categories (bending moment, deflection, IRC compliance factor), the deck slab bridge wins in two (shear force, axial force) and the cable-stayed bridge wins in two economic categories (concrete volume, concrete cost). Support reactions are basically the same. This multi-criteria difference is a basic aspect of typology selection for bridges, and reflects the importance of establishing site specific priorities before making typology recommendations.

7.2 Cost Analysis

The detailed cost analysis is provided in Table 11, which is based on the concrete volume as well as the existing Schedule of Rates.

Table 11: Concrete Cost Analysis at Current Schedule of Rates (SOR = Rs. 4,200/m3)

Bridge Type	Concrete Vol. (m3)	SOR (Rs./m3)	Total Cost (Rs.)	Saving vs. DS
Deck Slab Bridge	802.50	4,200	33,70,500	—
Cable-Stayed Bridge	705.695	4,200	29,63,919	Rs. 4.07 lakh
Cable Suspension Bridge	784.00	4,200	32,92,800	Rs. 0.78 lakh

The lowest consumption of concrete is obtained at the cable-stayed bridge (705.695 m3) which is equivalent to a 12.1% reduction compared to the deck slab (802.5 m3) and 10.0% compared to the cable suspension bridge (784 m3). The amount of money saved is Rs. 4.07 lakh over the deck slab bridge can be attributed to the cable-stay system which utilizes a cable to support the deck slab, inherently reducing the bending moment of the deck slab, and hence the depth of the deck and amount of reinforcement needed, without the use of the massive concrete anchor blocks and pylon foundations like that of the suspension bridge. This result agrees with Patel et al. [9] and Singh et al. [25] who showed optimum material efficiency for medium and long span cable stayed structures.

7.3 Structural Efficiency Indices

Table 12 shows structural efficiency indices normalized with respect to the bridge performance of the deck slab. A value of less than 1.0 is a good result compared to the deck slab baseline.

Table 12: Normalised Structural Efficiency Indices Relative to Deck Slab Bridge Baseline (* < 1.0 indicates superior performance)

Parameter	Deck Slab (DS)	Cable-Stayed (CS)	Cable Suspension (CSu)
Shear Force Index	1.000	1.346	1.126
Axial Force Index	1.000	1.011	1.023
Bending Moment Index	1.000	0.729 *	0.693 *
Deflection Index	1.000	0.965 *	0.369 *
Concrete Cost Index	1.000	0.879 *	0.977 *

The multi-criteria aspect of bridge type selection is confirmed by the normalised efficiency index analysis. The cable suspension bridge shows the highest level of superiority in deflection (index = 0.369, 63.1% advantage) and the best competitive superiority in bending moment (index = 0.693, 30.7% advantage). The cable-stayed bridge has the best economic performance (0.879, 12.1% advantage) and competitive structural advantages in bending moment (0.729). The deck slab bridge has a smaller shear force index (1.000) than the other two bridges, showing that the deck slab bridge has a special advantage in shear resistance.

VIII. CONCLUSION

Three different types of bridges — deck slab, cable-stay and cable suspension bridges — were taken as case studies in this study and the loadings were simulated based on the IRC:6-2014 vehicle loading of IRC Class 70R. Five structural response parameters were assessed: maximum bending moment, shear force, axial force, nodal deflection and support reactions and a concrete cost analysis was carried out using existing Schedule of Rates. The following are the main conclusions:

1. In terms of flexural resistance and serviceability, the cable suspension bridge has the best results, with the lowest bending moment (204.54 kN-m; 30.7% lower than the deck slab bridge), and the lowest deflection (2.935 mm; 63.1% lower than the deck slab bridge). Both of these are a consequence of the distributed vertical support that is provided by the closely spaced hangers and the consequent ability of mobilising the high axial stiffness of the main cables to resist vertical movement of the unsupported deck span.
2. The 7th is that the deck slab bridge has the best performance with respect to resistance to shear force (281.952 kN; 25.7% less that the cable-stayed bridge) and axial force (4,583.729 kN; 2.3% less than the cable suspension bridge) due to the uniform and continuous load transfer over the entire deck cross section.
3. The material and economic efficiency exhibited by the cable-stayed bridge is the maximum as compared to deck-slab bridge, which is 12.1% less concrete (705.695 m3 vs. 802.5 m3); cost saving in concrete is about Rs. At the current SOR level, amounting to 4.07 lakh. This economic benefit comes from the fact that the bending moments of the deck can be reduced by the support of the cable-stayed system allowing thinner and lighter deck sections.
4. The structural adequacy of all three typologies has been confirmed as they all satisfy the IRC:6-2014 serviceability limit on deflection under live load: L/800 = 250 mm with factors of safety of 31.5, 32.6 and 85.2 for deck slab, cable-stayed and cable suspension bridges respectively, respectively.
5. The support reactions in all three typologies were statistically equal (maximum variation = 0.004%), giving independent evidence of the load application consistency and the comparability of the results of the structural response within the analytical framework of the study.
6. The FEA results always show that no single bridge typology is best in all performance criteria, which implies that the selection of bridge type should be based on site specific priorities (structural performance, serviceability or economy), and not based on a ranking of the overall typologies.

IX. FUTURE SCOPE

In the present investigation, a rigorous comparative base line under static IRC Class 70R loading is provided, which suggests several avenues of high scientific and engineering value for future investigation:

- The inclusion of IS:1893-2016 Part 3 seismic loading and IS:875 Part 3 wind loading in the comparative FEA framework would provide critical performance data to assist in the selection of the bridge type for use in seismic zones III–V and high wind corridors which are commonly found in Indian geography [19, 28].

- Dynamic Vehicle-Bridge Interaction Modelling: It would also be possible to provide accurate prediction of the dynamic amplification factor applicable to the National Highway design over a range of vehicle speeds significant for the interaction, by replacing the static EUDL-based IRC loading with fully coupled moving mass models representing an actual Class 70R axle configuration, suspension dynamics, and realistic road roughness profiles [17, 21].
- To assess the 8–12% underestimation of deflection due to the linear elastic approximation used in this study, the geometric nonlinear FEA of the cable-supported bridges must be performed, accounting for the change in the profile of the cables, the P–delta effect in the pylons, and the second-order stiffness effect.
- The results from a systematic FEA study of spans ranging in length from 50 m to 500 m under the same loading (IRC Class 70R) would provide a performance and cost map of the span typologies, which can be used to make evidence-based preliminary bridge type selection decisions at the planning stage.
- This will be further expanded to the next generation materials used in bridge construction, such as ultra-high performance concrete (UHPC) deck slab, fibre-reinforced polymer (FRP) cables and high-strength prestressing steel (UTS > 1860 MPa) for all three bridge typologies, building on UHPC deck slab results from Joshi and Reddy [12].
- The current initial material cost analysis could be extended to include costs for construction, maintenance, inspection, rehabilitation and decommissioning the bridge, over a 75 year design life, to give a complete economic basis for bridge type selection, consistent with India's sustainable infrastructure development goals [24].
- The STAAD could be experimentally validated with physical scale model testing under simulated IRC-equivalent loading and applying digital twin monitoring frameworks [15] to the three bridge typologies.Improve the state of the practice of bridge structural verification by providing numerical results.

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