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Comparative Structural Performance of Cable-Stayed Bridges with Concrete, Steel, and Prestressed Concrete Deck Systems: A Review

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Abstract — The deck girder is one of the most influential components governing the structural response, stiffness, weight, durability, and overall economy of a cable-stayed bridge, and the choice between reinforced concrete (RC), structural steel, and prestressed concrete (PSC) remains a central design decision. This paper presents a structured literature review of published research relevant to this choice, covering material-specific behaviour of RC, steel, and PSC deck girders; design practice and analytical studies on tower geometry, dynamic/seismic response, and finite element modelling; direct comparative studies between deck materials and hybrid/composite systems; economic and life-cycle cost studies; construction-stage and composite-action behaviour; and studies conducted under Indian IRC loading provisions. The review finds general agreement that RC decks are economical and durable under normal service but suffer from higher self-weight and tensile cracking over longer spans; steel decks offer a superior strength-to-weight ratio and rapid erection but require sustained corrosion protection and careful fatigue design; and PSC decks combine improved stiffness and crack control with the durability of concrete, at the cost of higher initial complexity. The review further finds that although each material has been studied extensively in isolation or in pairwise comparison, very few investigations evaluate reinforced concrete, structural steel, and prestressed concrete decks together under identical bridge geometry, loading, and analytical procedure, and fewer still combine such a structural comparison with a consistent life-cycle economic evaluation. This gap is identified as the principal motivation for a unified, controlled-variable comparative investigation of the three deck systems.

Keywords— Cable-Stayed Bridge, Deck Girder, Reinforced Concrete, Structural Steel, Prestressed Concrete, Literature Review, Finite Element Analysis, Life-Cycle Cost, Composite Constructio.

I. INTRODUCTION

Cable-stayed bridges are widely adopted for medium- to long-span crossings on account of their high structural efficiency, aesthetic appearance, and ability to carry heavy traffic loads with relatively slender structural members. Among the principal components of a cable-stayed bridge, the deck girder is one of the most important, since its material significantly influences the bridge's stiffness, self-weight, load distribution, durability, construction methodology, and overall economy. Three deck girder materials — reinforced concrete (RC), structural steel, and prestressed concrete (PSC) — are most commonly adopted in practice, each offering a distinct combination of advantages and limitations.

This paper presents a structured, critical review of the published literature relevant to the selection and performance of RC, steel, and PSC deck girders in cable-stayed bridges. Rather than describing individual studies chronologically, the review is organized thematically to examine the major findings, areas of agreement and disagreement, and limitations of existing research, with particular attention to studies investigating the influence of deck material on structural response. Based on this synthesis, the paper identifies the principal research gap that motivates a unified, controlled-variable comparative investigation of the three deck systems.

The remainder of the paper is organized as follows. Section II reviews material-specific behaviour of RC, steel, and PSC deck girders. Section III reviews design practice and analytical studies concerning tower geometry, dynamic/seismic response, and finite element modelling.

Section IV reviews direct comparative and hybrid/composite deck studies. Section V reviews economic and life-cycle cost studies. Section VI reviews construction-stage and composite-action behaviour. Section VII reviews studies relevant to Indian design practice and IRC loading. Section VIII synthesises the research gaps identified, and Section IX concludes the paper.

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II. DECK GIRDER SYSTEMS AND MATERIAL BEHAVIOUR

The selection of deck material is one of the most critical decisions in cable-stayed bridge design because it directly influences dead load, stiffness, serviceability, durability, construction methodology, and maintenance requirements. Table I summarises the qualitative characteristics generally reported for the three deck systems in the literature.

Table 1. Qualitative Comparison of Deck Materials for Cable-Stayed Bridges

Attribute	RC	Steel	PSC
Self-weight	High	Low	Moderate
Tensile capacity	Low (needs reinf.)	High	High (via tendons)
Initial material cost	Low	High	Moderate
Construction speed	Moderate	Fast (prefab.)	Moderate
Durability / maintenance	Moderate; crack-prone	Corrosion-sensitive	High; crack-resistant
Damping characteristics	Good	Comparatively low	Good
Typical suitability	Short–moderate spans	Long spans, fast erection	Medium–long spans

1. Reinforced Concrete Decks

Reinforced concrete remains one of the most widely used deck materials because of its high compressive strength, economy, and ease of construction. Its relatively low tensile strength, however, necessitates steel reinforcement to control cracking, and this cracking tendency is repeatedly identified as a limiting factor for longer spans and heavier service loading [25]. Studies on high-strength concrete report improved durability and load-carrying capacity together with a reduction in achievable deck thickness, lowering long-term maintenance cost [11]. Overall, the literature agrees that RC decks are economical and durable under normal service but are constrained by higher self-weight — which increases cable, tower, and foundation demand — and by comparatively greater susceptibility to tensile cracking.

2. Structural Steel Decks

Structural steel decks are consistently reported to offer a markedly higher strength-to-weight ratio than concrete alternatives, enabling longer spans, reduced cable and tower forces, and faster, prefabricated erection [6]. This advantage, however, is offset by the need for rigorous and recurring corrosion protection, particularly in coastal or industrial environments, and by fatigue-sensitive welded connections that require careful detailing [6]. The literature is consistent in finding that steel decks minimize structural demand on the supporting system but shift the economic burden toward long-term maintenance rather than initial construction.

3. Prestressed Concrete Decks

Prestressed concrete decks combine the compressive strength of concrete with the tensile capacity provided by prestressing tendons, enabling longer spans, improved crack resistance, and enhanced structural efficiency [1], [14]. Prestressing is reported to reduce deflection, permit more slender sections, and retain the durability, corrosion resistance, and vibration-damping characteristics of conventional concrete, while requiring specialised equipment and quality control during tendon stressing and anchorage installation. Because of this balance between performance, durability, and economy, PSC has become one of the most widely adopted deck materials for medium- and long-span cable-stayed bridges [14].

III. DESIGN PRACTICE AND ANALYTICAL STUDIES

1. Tower Geometry and Structural Behaviour

Tower geometry governs cable inclination, force distribution, structural stiffness, and overall bridge stability. Numerical investigations comparing tapered, inclined, H-type, A-type, and diamond-shaped pylons report that stiffer and more optimally shaped towers reduce deck displacement, improve the distribution of cable forces, and lower bending moments within the tower, though at the cost of more complex construction and higher fabrication cost [20]. Such studies consistently note that the effectiveness of tower geometry depends on deck stiffness and weight, implying that evaluating deck materials within an identical tower configuration provides the most reliable basis for isolating the deck's independent contribution to overall bridge performance.

2. Dynamic and Seismic Behaviour

Because of their long spans and relative flexibility, cable-stayed bridges are susceptible to seismic, wind, and traffic-induced dynamic actions. Nonlinear seismic studies report that deck stiffness has a considerable influence on dynamic performance:

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stiffer decks reduce lateral displacement but increase seismic force demand in the towers, while lighter decks move more but generate lower inertial forces; supplemental damping devices are reported to be effective in reducing vibration amplitude in either case [1]. These findings, although focused on dynamic rather than static response, reinforce that deck material and mass materially affect overall bridge behaviour and that comparative studies should ideally consider more than static structural response alone.

3. Finite Element Modelling

The availability of advanced finite element software has transformed cable-stayed bridge analysis, allowing realistic representation of geometric nonlinearity, cable sag, staged construction, and complex loading combinations. Comparative numerical studies demonstrate that finite element analysis accurately predicts deck deflection, cable tension, internal forces, and stress distribution while capturing interaction between structural components, and that simplified linear approaches tend to underestimate cable forces and overestimate stiffness, particularly for longer spans [12]. These studies establish finite element modelling as the most appropriate tool for comparative investigations in which deck material is varied while all other geometric and loading parameters are held constant.

IV. COMPARATIVE STUDIES OF DECK MATERIALS

Comparative evaluation of deck materials is an important but comparatively under-populated area of cable-stayed bridge research. Although RC, steel, and PSC have each been studied extensively in isolation, relatively few investigations compare them directly under identical structural and loading conditions, and most available comparative studies examine only two of the three materials at a time.

1. Reinforced Concrete versus Structural Steel

Comparative finite element studies of RC and steel decks under identical bridge geometry report that steel decks substantially reduce dead load, cable forces, tower compression, and foundation reactions, and permit longer unsupported construction segments during cantilever erection, but require comprehensive and continuing corrosion protection [17]. RC decks, by contrast, exhibit greater stiffness and higher inherent damping — reducing traffic-induced vibration — and lower initial cost and construction complexity, making them attractive for short- and medium-span bridges, at the expense of larger internal forces in cables and towers for longer spans [17]. Because such studies typically exclude PSC, they cannot determine whether prestressing can overcome the tensile limitations of RC while retaining its economic advantage.

2. Prestressed Concrete versus Structural Steel

Comparative studies of PSC and steel decks report that steel offers reduced self-weight, rapid prefabrication, and faster cantilever erection, making it attractive for spans exceeding roughly 300 m, whereas PSC decks demonstrate superior long-term serviceability through effective tensile stress control, reduced cracking, and smaller deflection under traffic loading [3]. Although PSC construction periods are often longer than for steel, overall life-cycle cost is frequently found to be lower due to reduced maintenance. These studies generally conclude that neither material is universally superior, with the optimum choice depending on span, environment, and construction and maintenance strategy — but again, ordinary RC is typically excluded from the comparison, leaving an incomplete three-way evaluation [3].

3. Hybrid and Composite Deck Systems

Hybrid and steel–concrete composite decks, designed so that steel primarily resists tension while concrete carries compression, are reported to achieve lower dead load than RC while providing greater stiffness than conventional steel decks, with improved composite action reducing deck deflection, enhancing fatigue resistance, and improving the distribution of internal forces between deck and stay cables [5], [24]. Composite construction is also reported to reduce material consumption and construction time relative to conventional RC [5]. However, widespread application remains constrained by more complex detailing, higher fabrication requirements, and increased quality-control demands, and most published composite studies compare the hybrid system with only one conventional material rather than against RC, steel, and PSC simultaneously.

V. ECONOMIC AND LIFE-CYCLE COST STUDIES

Initial construction cost alone is increasingly regarded as insufficient for evaluating bridge deck alternatives; durability, maintenance, rehabilitation, and overall life-cycle performance are now considered equally important. Comparative cost studies of RC T-beam and box-girder bridges find that the most economical structural form is span-dependent — T-beams more economical for shorter spans, box girders for longer spans — establishing the general principle that bridge economics depend on span and configuration rather than material cost alone [21]. Similar span-dependent trends are reported between prestressed I-girders and box girders [15].

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Life-cycle cost analyses comparing prestressed concrete with painted and galvanized steel bridges consistently find that, although steel bridges may have competitive initial cost, recurring painting, corrosion protection, inspection, and rehabilitation make their total life-cycle cost higher than that of prestressed concrete, which requires comparatively little maintenance because prestressing limits cracking and reinforcement corrosion [8]. Studies on high-strength steel (e.g., Fe 590 versus Fe 410) report reduced material consumption and improved flexural capacity, translating into economic savings for longer spans, but also note that the resulting slenderness can increase service-load deflection, requiring additional stiffening or serviceability verification [10]. Collectively, these studies indicate that deck material selection should be based on total ownership (life-cycle) cost rather than initial construction expenditure alone.

VI. CONSTRUCTION-STAGE BEHAVIOUR AND COMPOSITE ACTION

Cable-stayed bridges pass through several temporary loading configurations before reaching their final state, particularly during cantilever construction, so construction-stage behaviour materially affects deck performance. Early classification of composite steel-deck shear-transfer mechanisms established that the efficiency of composite action depends primarily on shear-connector effectiveness [22], while experimental studies of composite girders under combined bending and torsion showed that torsional stiffness becomes increasingly important as span increases and that composite sections outperform conventional RC under combined loading [19].

Time-dependent effects — creep, shrinkage, and prestress loss — are widely reported as critical to long-term performance: delaying full composite action during construction reduces creep/shrinkage-induced bending moments [4], while restrained shrinkage and thermal effects are identified as primary drivers of early-age transverse cracking in concrete decks, underscoring the importance of curing practice and reinforcement detailing [7]. Improved precast connection details and composite dowel connectors have been shown, respectively, to increase stiffness and reduce differential displacement between deck panels [23], and to provide higher shear capacity and improved fatigue performance than conventional shear studs [9]. Comparative studies of composite versus conventional RC bridges report reduced dead load, improved flexural stiffness, and increased span capability for composite systems, particularly where self-weight governs design [16], [18].

VII. STUDIES RELEVANT TO INDIAN DESIGN PRACTICE AND IRC LOADING

Bridge design in India is governed principally by IRC:6 loading provisions and IRC:112 for concrete bridge design, making studies conducted under these provisions directly relevant to Indian cable-stayed bridge practice. Comparisons of RC and steel–concrete composite bridges under Indian conditions report that composite construction offers lower dead load, faster construction, and improved cost efficiency relative to conventional RC [18]. Similarly, composite steel–concrete girders are reported to show improved flexural behaviour and reduced deflection compared with RC alternatives, supporting the case for composite or lightweight systems in medium- and long-span applications where self-weight reduction is a priority [16]. More broadly, three-dimensional finite element modelling under IRC Class AA loading is reported to provide more accurate predictions of bending moment, shear force, and deflection than conventional analytical methods, reinforcing the case for finite-element-based comparative evaluation in the Indian design context [12].

VIII. CRITICAL SYNTHESIS AND RESEARCH GAPS

The reviewed literature demonstrates considerable progress in understanding the material behaviour, analytical modelling, construction-stage response, and economic performance of RC, steel, and PSC deck girders for cable-stayed bridges. RC decks are consistently found to be economical and durable under normal service but prone to cracking and higher self-weight over longer spans; steel decks offer superior strength-to-weight ratio and construction speed at the cost of corrosion-related maintenance; and PSC decks are consistently reported to provide an effective balance of stiffness, crack control, and durability.

Notwithstanding this progress, several gaps remain evident. First, most comparative studies evaluate only one pair of materials at a time (typically RC–steel or PSC–steel); comprehensive three-way comparisons of RC, steel, and PSC decks under identical bridge geometry and loading remain very limited. Second, existing investigations often differ in bridge geometry, material property assumptions, loading standards, or analytical procedure, making direct comparison across published results difficult. Third, many studies focus on a single structural parameter (deflection, stress, or bending moment alone) rather than a comprehensive set covering joint reactions, displacements, internal forces, and stress distribution together. Fourth, although construction-stage behaviour has

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been studied independently, few studies evaluate both the completed-bridge condition and free-cantilever construction stages for different deck materials within one consistent analytical framework. Finally, in the Indian context specifically, studies combining IRC-loading-based structural analysis with a consistent life-cycle economic evaluation across all three deck materials remain scarce.

These gaps collectively indicate the need for a controlled-variable, finite-element-based comparative investigation in which reinforced concrete, structural steel, and prestressed concrete deck girders are evaluated using identical bridge geometry, material modelling procedures, and loading conditions, combined with a consistent life-cycle economic assessment, to provide a more reliable basis for deck material selection in cable-stayed bridge design.

IX. CONCLUSION

This paper has presented a structured review of the literature relevant to reinforced concrete, structural steel, and prestressed concrete deck girders in cable-stayed bridges, covering material behaviour, design and analytical practice, direct comparative and hybrid/composite studies, economic and life-cycle cost evaluation, construction-stage and composite-action behaviour, and studies relevant to Indian IRC loading practice. The review confirms that each deck material offers a distinct and well-documented combination of structural and economic advantages and limitations, and that material selection is properly a span-, loading-, and context-dependent decision rather than a matter of universal preference. At the same time, the review identifies a clear and consistent gap in the literature: the scarcity of studies that evaluate reinforced concrete, structural steel, and prestressed concrete deck girders together, under identical bridge geometry and loading, using a common finite element framework and a consistent life-cycle economic assessment. Addressing this gap through a controlled, unified comparative investigation is identified as a valuable and necessary direction for future research in cable-stayed bridge deck design.

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