# Lightweight Foam Concrete and Prestressed Decks for Girder Bridges: A Review of Materials, Finite Element Modelling, Code-Based Loading and Cost

Atul Kori*[1], Murlidhar Chourasia*[2], Dr. Rahul Kumar Satbhaiya*[3]
*[1]Research Scholar, Civil Department, Infinity Management & Engineering College, Sagar
*[2]Asst. Prof. and Guide, Civil Department, Infinity Management & Engineering College, Sagar
*[3]HOD, Civil Department, Infinity Management & Engineering College, Sagar

***Abstract—***

Girder bridges with reinforced cement concrete (RCC) decks remain the most widely built highway crossings for short and medium spans, yet the self-weight of the deck consumes a large share of their load-carrying capacity and drives the size of piers and foundations. Two complementary strategies are now being explored to relieve this burden: prestressing the deck so that internal stresses counteract service loads, and replacing normal-weight concrete with lightweight foam concrete or lightweight aggregate concrete. This paper reviews 29 peer-reviewed studies and two Indian bridge codes published between 2001 and 2026, grouped into four themes: lightweight deck materials, prestressed girder systems and their finite element (FE) modelling, live-load distribution under code vehicles, and cost optimisation. The review finds that foam concrete is now well characterised as a material, with densities of about 400–1,850 kg/m³ and favourable strength-to-weight ratios, but that structural design guidance remains thin and largely borrowed from lightweight aggregate concrete. Three-dimensional shell–beam FE models in SAP2000 or CSiBridge are the accepted tool for comparing deck alternatives under Indian Roads Congress (IRC) loading, while nonlinear models are reserved for extreme events. Cost studies consistently show that optimised prestressed girders save material, but almost none couple a lightweight deck material with prestressing in one techno-economic comparison. The paper closes with a five-step framework to fill this gap and with priorities for future research.

***Keywords—*** *girder bridge; prestressed concrete deck; foam concrete; lightweight concrete; finite element analysis; SAP2000; IRC loading; cost optimisation*

## 1. INTRODUCTION

A girder bridge carries its deck on longitudinal girders that act as the main load-carrying members. Structurally it is divided into a foundation, a substructure of piers and abutments, and a superstructure of girders and deck slab above the bearings. The superstructure receives the traffic load and is the most critical part of the structure, while the substructure transmits that load to the ground. Because the concept is simple, adaptable and economical over spans of roughly 10–50 m, the reinforced-concrete T-girder and box-girder bridge is the default choice for highway and river crossings across South Asia [1]–[3].

The weakness of the conventional RCC deck is its self-weight. In a short or medium span, dead load forms a large fraction of the design moment, so every kilonewton of deck weight adds reinforcement in the girders, axial force in the piers and area in the foundations. Two remedies are available. The first is prestressing, which introduces internal compressive stresses that offset tensile stresses from external load, allowing shallower and crack-free members [4], [5]. The second is the use of lightweight concretes, either cellular foam concrete or lightweight aggregate concrete (LWAC), which reduce density while retaining useful strength [6], [7].

Each remedy has its own literature, but the two are rarely examined together, and Indian studies seldom evaluate the cost consequences of the choice. This review therefore brings the material, modelling, loading and economic strands into one place. Its objectives are to (i) summarise what is known about foam concrete and LWAC as deck materials, (ii) review how prestressed and conventional girder decks are modelled and compared using FE software under code loading, (iii) collate the evidence on cost and optimisation, and (iv) identify gaps that a combined techno-economic study should address. Section 2 describes the review method; Sections 3–7 discuss each theme; Section 8 synthesises the findings; Section 9 sets out research gaps; and Section 10 concludes.

## 2. REVIEW METHODOLOGY

### *2.1 Scope and Source Selection*

The review focused on journal articles and code documents dealing with (a) the properties of foam and lightweight concrete relevant to structural use, (b) analysis of RCC and prestressed concrete girder bridges, (c) live-load distribution among girders, and (d)

cost optimisation of concrete bridge superstructures. Only sources with a verifiable digital object identifier (DOI) were retained for the journal literature, so that every claim can be traced; the two IRC codes that govern Indian highway bridge loading and concrete design [8], [9] were added as normative references. Studies on culverts, cable-supported bridges and railway track were excluded because their load paths differ from deck-on-girder systems.

### *2.2 Classification Framework*

The retained studies were classified into four themes that together determine whether a lightweight prestressed deck is technically and economically viable (Fig. 1). The temporal distribution of the studies (Fig. 2) shows that research on deck materials and on FE modelling of prestressed girders has grown sharply since 2016, whereas cost studies are concentrated in the period before 2015. This imbalance is itself an indication that recent material advances have not yet been translated into updated economic comparisons.

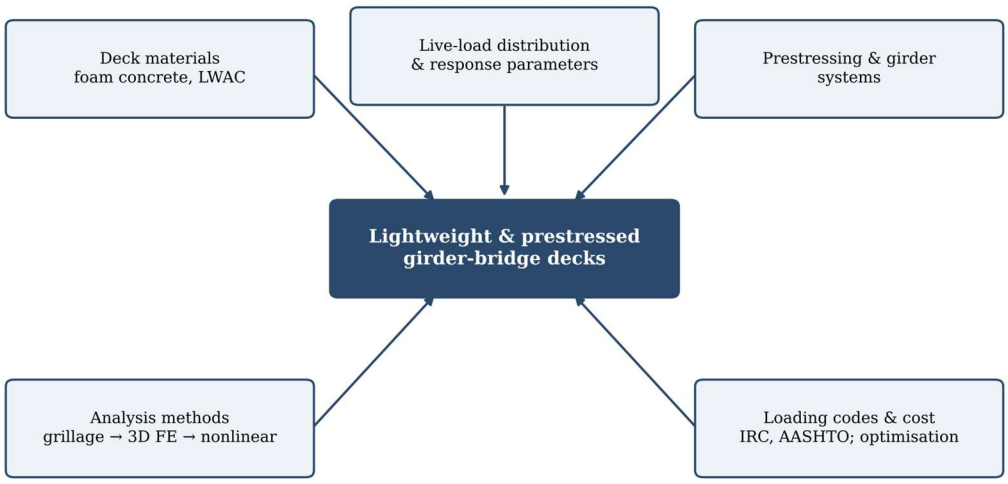


**Fig. 1.** Classification framework adopted for the review: four themes converging on lightweight and prestressed girder-bridge decks.

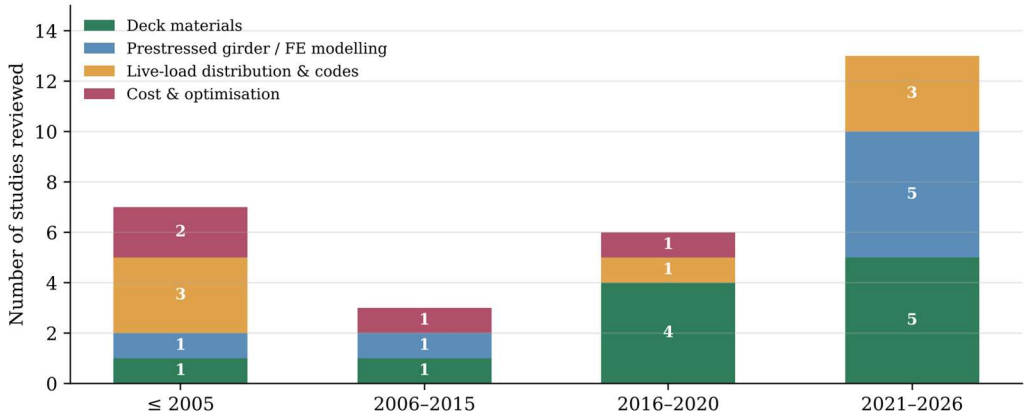


**Fig. 2.** Distribution of the reviewed journal studies by theme and period of publication.

## 3. GIRDER BRIDGE SUPERSTRUCTURES AND PRESTRESSING

### *3.1 Load Path in a Deck-on-Girder System*

Wheel loads disperse through the wearing coat and deck slab at roughly 45° in both the longitudinal and transverse directions before reaching the longitudinal girders and cross girders. The girders carry the load to the bearings, which transfer it to pier caps and then to the piers, piles or footings. Whether the slab and girder act compositely depends on shear connection; composite action increases stiffness and changes the share of load carried by each girder [10], [11]. Because the deck slab is both the first element to receive load and a significant contributor to dead load, its material and thickness affect every member below it.

### *3.2 Benefits of Prestressed Concrete Decks*

Prestressing exploits the tensile strength of high-strength steel to compensate for the low tensile strength of concrete. The practical benefits for bridges are well documented: longer spans with shallower members, smaller deflections because dead-load effects are partly

balanced, reduced cracking and corrosion, and lower self-weight, which in turn reduces substructure and foundation cost [5], [12]. Parametric FE studies of prestressed box girders designed to IRC:6, IRC:18 and IRC:21 show that span, span-to-depth ratio and skew angle all govern bending moment, shear, torsion and deflection, and that the ratios between these responses can be captured by simple design equations [4].

### *3.3 Precast and Segmental Construction*

Precast pre-tensioned girders and post-tensioned cast-in-place decks dominate current practice. Precasting moves concrete work off the critical path and improves quality control, while segmental methods avoid extensive falsework over deep gorges or navigable waterways. These construction modes introduce stage-dependent stresses that must be checked separately from the final service state; models that ignore construction sequence or the composite behaviour of the girder–deck system can misjudge both capacity and damage [13], [14].

## 4. LIGHTWEIGHT DECK MATERIALS

### *4.1 Foam Concrete: Production and Properties*

Foam concrete is a cement or cement–fly ash slurry into which a stable preformed foam is mixed, so that air voids replace coarse aggregate. Classification studies place its dry density between about 400 and 1,600 kg/m³, with strength falling steeply as density decreases [15]. A recent systematic review extends the working range to roughly 400–1,850 kg/m³ and notes growing use of the material in semi-structural and non-structural lightweight elements, owing to its low self-weight and low cost [6]. Its thermal and acoustic insulation, fire resistance, flowability and self-levelling behaviour are consistently reported as advantages, while drying shrinkage, low tensile strength and sensitivity to foam stability are the main drawbacks [16]–[18].

Mix design, foaming agent type and the use of fly ash or other fillers control the void structure and therefore the mechanical response [17], [19]. Fibre reinforcement—synthetic or natural—has been shown to improve flexural and splitting tensile strength and to reduce shrinkage cracking, which partly addresses the brittleness that limits structural use [20].

### *4.2 Structural Potential and Design Guidance*

Early laboratory work demonstrated that foam concrete can reach strengths and durability suitable for structural members, although its wider adoption had been held back by unfamiliarity and the perceived difficulty of exceeding about 25 N/mm² [21]. For reinforced foamed concrete (RFC), a review of code provisions concluded that flexural–shear behaviour is more complex than pure flexure and, borrowing from lightweight aggregate concrete design, suggested strength reduction factors of 0.75 for shear, torsion and compression and 0.6 for flexure [22]. The same review noted that data on RFC compression members such as columns and load-bearing walls are scarce, so safe design rules remain to be validated [22].

### *4.3 Lightweight Aggregate Concrete in Bridges*

LWAC made with expanded clay, shale or sintered aggregates offers an alternative route to weight reduction with strengths closer to normal concrete. A 2025 state-of-the-art review traced its use in existing and planned bridges and concluded that, although promising, further research is needed before lightweight aggregates can be adopted widely in bridge decks [7]. Complementary testing of LWAC with sintered aggregate has quantified the short- and long-term properties—creep and shrinkage in particular—that are essential for designing prestressed members, where time-dependent prestress losses depend directly on these parameters [23].

### *4.4 Implications for Deck Self-Weight*

Because dead load scales linearly with density, the potential benefit can be illustrated directly. Fig. 3 compares the self-weight of a 250 mm deck slab for normal-weight concrete and for representative lightweight densities: a 1,600 kg/m³ foam concrete reduces slab dead load by one third. Table 1 summarises the main attributes of the three material options as reported in the literature.

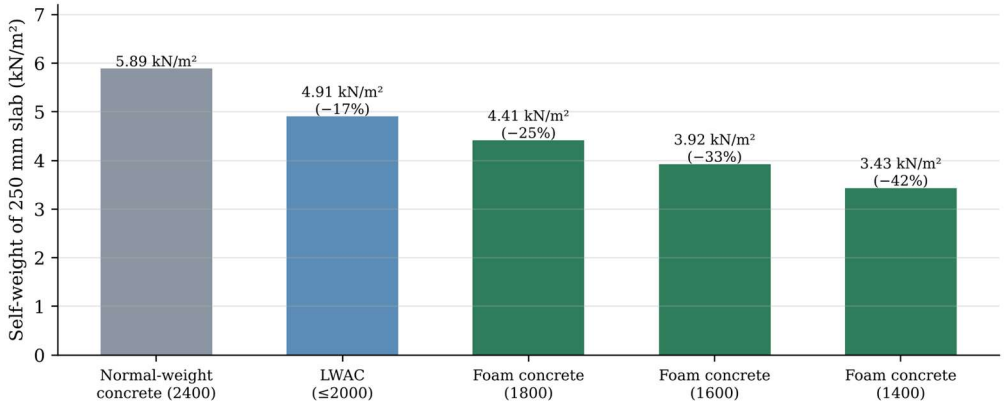


**Fig. 3.** Self-weight of a 250 mm deck slab for normal-weight concrete and lightweight alternatives (computed as density × g × thickness; densities in kg/m³).

**Table 1.** Comparison of deck material options for girder bridges.

| Attribute | Normal-weight RCC | LWAC | Foam concrete |
|---|---|---|---|
| Typical density (kg/m³) | ≈ 2,400 | ≤ 2,000 | ≈ 400–1,850 [6], [15] |
| Structural track record in bridges | Extensive | Growing; case studies exist [7] | Limited; mainly fill and non-structural [6] |
| Key advantages | Familiar, codified | Lower dead load, durability [7] | Very low weight, insulation, low cost [16], [18] |
| Main limitations | High self-weight | Creep/shrinkage data needed [23] | Low tensile strength, shrinkage, few design rules [21], [22] |
| Design guidance | IRC:112 [9] | Adapted from NWC with factors | Reduction factors 0.6–0.75 proposed [22] |

## 5. ANALYSIS AND MODELLING APPROACHES

### *5.1 Classical and Grillage Methods*

Hand methods such as Courbon's method and moment distribution, and grillage analogy, remain the basis of preliminary design in India. A review of box-girder analysis traced the evolution from these elastic approaches to folded-plate, finite-strip and finite element methods, and pointed out that distortion and warping in box sections are not captured by simple beam theory [24]. Similar conclusions were drawn for Indian practice, where grillage and FE results are compared for straight, skew and curved box girders under IRC loading [3].

### *5.2 Linear Three-Dimensional FE Models*

Three-dimensional models in which the deck is meshed with shell elements and the girders with frame or eccentric beam elements are now the accepted standard for comparative studies. A study of four modelling techniques for composite girder bridges found that the eccentric-beam model is economical yet accurate for predicting overall flexural behaviour when compared with a detailed solid model [10]. In Indian research, SAP2000 and CSiBridge have been used to analyse skew and curved box girders, with convergence studies to fix mesh size and validation against published results before parametric runs [4], [25]. Curve angles up to about 12° were found to have a negligible effect, allowing such bridges to be analysed as straight ones [25].

### *5.3 Nonlinear and Extreme-Event Modelling*

Where ultimate or extreme-event behaviour matters, nonlinear models are required. An LS-DYNA model validated against tests captured the response of prestressed girder bridges to lateral low-velocity impact, compared four ways of introducing prestress and four concrete constitutive models, and showed that the bridge must be modelled as a composite system rather than as isolated girders [13]. The improved applied element method has been used to trace progressive collapse of a prestressed girder bridge under blast and sudden pier loss, including both material and geometric nonlinearity [14]. Fig. 4 places these methods on a spectrum of fidelity and effort.

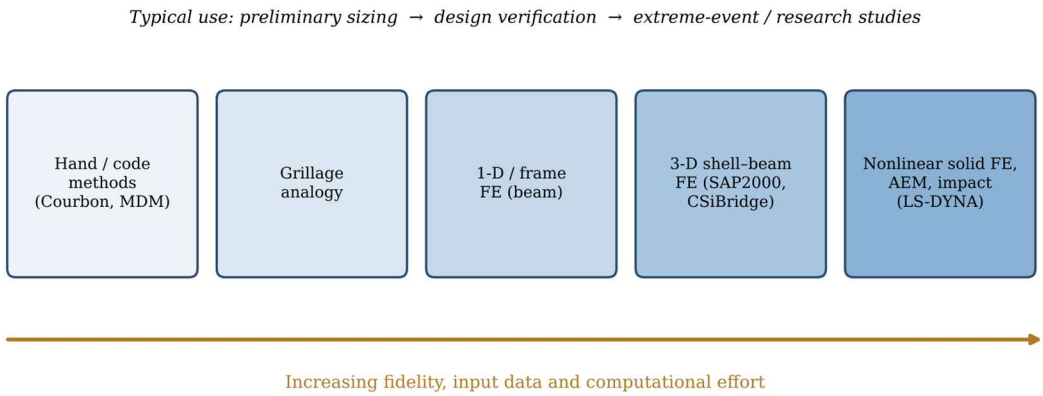


**Fig. 4.** Spectrum of analysis methods for girder-bridge decks, from hand methods to nonlinear solid models.

### *5.4 Live-Load Distribution among Girders*

The share of vehicle load carried by each girder governs girder design. FE studies of prestressed girder bridges showed that code distribution factors can be conservative and that features such as diaphragms, skew and continuity alter distribution noticeably [11]. For steel girder bridges, unintended composite action and partial support fixity were identified as the reasons why measured distribution factors fall below code values [26]. Box-girder studies questioned the restrictive applicability limits of the AASHTO LRFD factors [27], and field tests of prestressed girder bridges with continuous connections confirmed that measured factors were generally lower than the code equivalents [28]. These findings imply that a well-calibrated FE model can recover reserve capacity that simplified methods leave unused.

## 6. CODE-BASED VEHICULAR LOADING

Indian highway bridges are designed for the standard vehicles of IRC:6 [8]. The loading classes differ markedly in magnitude and contact pattern (Table 2), so the governing class must be identified for each span and carriageway width. A T-girder bridge analysed in CSiBridge under IRC, AASHTO and Chinese vehicle patterns produced noticeably different responses although the three codes share the same principles, which underlines the need to state the code basis explicitly when comparing alternatives [29]. Recent parametric work on RCC T-girders in the 10–25 m span range has also examined dynamic amplification and showed that girder configuration and span length jointly govern stress and deflection [2]. Assessment of an in-service T-girder bridge under vehicular loads likewise demonstrated the value of combining inspection, testing and FE analysis [1].

**Table 2.** Principal IRC:6 vehicle loading classes for highway bridges [8].

| IRC loading class | Vehicle type | Gross load (approx.) | Typical application |
|---|---|---|---|
| Class 70R | Tracked / wheeled | 700 kN / 1,000 kN | Permanent bridges on national and state highways (checked with Class A) |
| Class AA | Tracked / wheeled | 700 kN / 400 kN | Bridges in specified industrial and defence areas |
| Class A | Wheeled train | 554 kN (train) | Normal loading for all permanent bridges |
| Class B | Wheeled train | Lighter than Class A | Temporary structures and timber bridges |

## 7. ECONOMIC AND OPTIMISATION STUDIES

A review of cost optimisation for concrete bridge infrastructure noted that 30–40% of North American bridges were deteriorating and argued that advanced analysis and life-cycle costing should replace first-cost comparisons [30]. Total-cost optimisation of precast prestressed I-beam bridges, accounting for girder and deck concrete, prestressing steel, deck reinforcement and formwork, was formulated as a mixed-integer problem and solved with a neural dynamics model [5].

Genetic algorithms have been applied to optimise span number and cross-section of multi-span prestressed bridges under working-stress, ultimate-strength, ductility and deflection constraints [12], and to minimise the material cost of single prestressed I-girders [31]. Cost optimisation of RCC T-girders has also been included in recent parametric studies [2].

Two features stand out. First, almost every study optimises within one material system—either RCC or normal-weight prestressed concrete. Second, the

substructure saving that a lighter deck brings is rarely carried through to the cost function. For lightweight decks, where much of the benefit appears in piers and foundations, this omission understates the economic case.

## 8. SYNTHESIS OF KEY FINDINGS

Table 3 condenses the most relevant studies by theme, structure, tool and principal finding. Read together, they show a mature body of FE practice for conventional and prestressed girders under code loading, an increasingly detailed picture of foam concrete and LWAC as materials, and a separate optimisation literature focused on prestressed girders. The connecting study—one that applies the same FE model and the same loading to RCC, lightweight, prestressed and lightweight-prestressed decks and then prices each option—is largely missing.

**Table 3.** Summary of representative studies reviewed.

| Study | Theme | Structure / material | Tool / method | Principal finding |
|---|---|---|---|---|
| [4] | FE modelling | PSC skew box girder | CSiBridge, IRC | Design ratios for BM, SF, torsion vs. skew and span |
| [13] | FE modelling | PSC girder bridge | LS-DYNA | Composite system behaviour governs impact response |
| [14] | FE modelling | PSC girder bridge | Improved AEM | Collapse mechanism under blast and pier loss |
| [10] | FE modelling | Composite girders | 3-D FE | Eccentric beam model accurate and economical |
| [11] | Load distribution | PSC girders | FE vs. code | Code factors often conservative |
| [29] | Codes | RCC T-girder | CSiBridge | IRC, AASHTO and Chinese loads give different responses |
| [6] | Materials | Foam concrete | Systematic review | 400–1,850 kg/m³; semi-structural use growing |
| [22] | Materials | Reinforced foamed concrete | Review of codes | Reduction factors 0.75 (shear) and 0.6 (flexure) |
| [7] | Materials | LWAC bridges | State of the art | More research needed before wide deck use |
| [5] | Cost | PSC I-beam bridge | Neural dynamics | Total-cost optimisation incl. deck and formwork |
| [12] | Cost | Multi-span PSC bridge | Genetic algorithm | Optimum span number and sections |

## 9. RESEARCH GAPS AND FUTURE DIRECTIONS

The review identifies the following gaps, each of which points to a concrete research need:

1) **Combined material–prestress comparisons.** No reviewed study evaluates a lightweight deck and a prestressed deck—and their combination—under identical geometry, loading and modelling assumptions.
2) **Structural design rules for foam concrete.** Reduction factors are proposed by analogy with LWAC [22]; experimental validation for bridge-deck slabs, punching shear and fatigue under repeated wheel loads is lacking.
3) **Time-dependent behaviour.** Creep, shrinkage and prestress loss of lightweight concretes need quantification for bridge service lives [7], [23].
4) **Whole-structure economics.** Cost studies should include pier and foundation savings and life-cycle maintenance, not only superstructure quantities [30].
5) **Code harmonisation and dynamic effects.** Comparisons across IRC, AASHTO and Eurocode loading, and seismic and impact checks, should accompany static IRC analysis [13], [29].

A five-step framework is proposed to address these gaps in an integrated way (Fig. 5): characterise the candidate deck materials; apply code-based loading for the governing IRC class; build and validate one 3-D FE model with a mesh-convergence study; compare bending moment, shear, axial force and deflection for every deck alternative; and estimate quantities and life-cycle cost to select the preferred option, feeding back to material or prestress choices where needed.

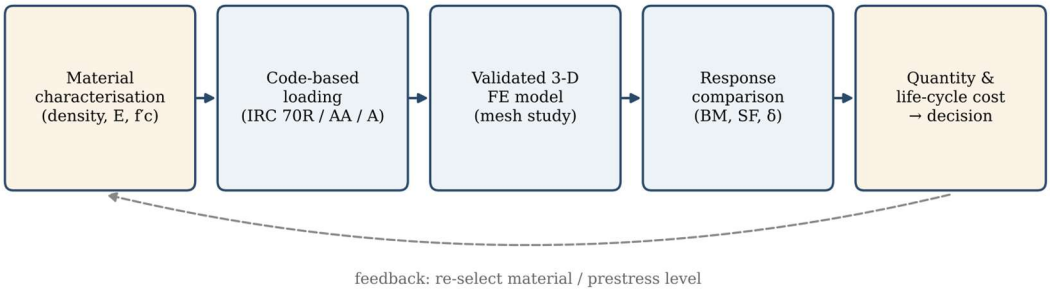


**Fig. 5.** Proposed integrated techno-economic framework for selecting girder-bridge deck materials and prestressing.

## 10. CONCLUSIONS

This review examined 29 journal studies and two IRC codes on lightweight deck materials, prestressed girder modelling, live-load distribution and bridge cost optimisation. The main conclusions are:

- Foam concrete is well characterised as a material (≈400–1,850 kg/m³) and can reduce deck slab dead load by a third or more, but structural design guidance for bridge decks remains provisional.
- LWAC offers a more proven path to lighter decks; its creep and shrinkage behaviour must be established for prestressed applications.
- Validated 3-D shell–beam FE models in SAP2000 or CSiBridge are adequate for comparing deck alternatives under IRC loading; nonlinear models are needed only for impact, blast or collapse studies.
- Code live-load distribution factors are often conservative, so calibrated FE models can reveal reserve capacity.
- Optimisation studies confirm the economy of prestressed girders, but none couples lightweight materials with prestressing or carries substructure savings into the cost function.

A combined techno-economic comparison of RCC, foam concrete, prestressed and prestressed-foam-concrete decks under the same IRC loading is therefore the logical next step, and the framework in Fig. 5 provides a basis for such work.

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