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Study of Shear Lag Effect in Box Girder Bridges: A Numerical and Analytical Investigation

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Abstract:

Box girder bridges have emerged as a preferred structural solution for urban flyovers, metro viaducts, and expressway corridors due to their high torsional stiffness, aesthetic appeal, and adaptability to complex geometries. Despite their advantages, a critical challenge in the structural analysis and design of these systems is the shear lag effect, which leads to non-uniform longitudinal stress distribution across the flange width, particularly in wide or curved girders. This research investigates the shear lag phenomenon in prestressed and reinforced concrete box girders commonly used in Indian infrastructure. A combination of classical analytical methods and finite element modeling (FEM) using ANSYS software is employed to evaluate stress patterns, effective width, and shear lag coefficients across various girder configurations and load conditions. The study reveals that shear lag is significantly influenced by flange width, number of cells, diaphragm spacing, and curvature. Finite element simulations show a 51% stress drop from web to edge in certain wide flange cases, emphasizing the inadequacy of traditional beam theory assumptions. The results are validated through comparisons with analytical models and published experimental data. The paper concludes with practical design recommendations and highlights the need for codal updates to incorporate shear lag provisions in Indian standards such as IRC:112. The findings provide valuable insights for bridge engineers seeking optimized, safe, and efficient design strategies in modern concrete bridge systems.

Keywords: Box girder bridges; Shear lag; Finite element analysis (FEA); Effective width; Prestressed concrete; Flange stress distribution; IRC:112; Indian metro viaducts; Segmental construction; Diaphragm spacing.

1. Introduction

Box girder bridges have become a preferred choice for modern infrastructure development due to their high torsional rigidity, structural efficiency, and aesthetic appeal. Their application is especially prominent in India's metro systems, elevated highways, and urban flyovers, where long spans, curved alignments, and multicellular configurations are common. The unique closed cross-sectional shape of box girders offers excellent performance under combined loading, particularly bending and torsion, making them ideal for projects such as the Delhi Metro, Bandra-Worli Sea Link, and Lucknow Expressway bridges (Meoni et al., 2024; Guo & Xia, 2024).

However, a critical design challenge associated with these structures is the **shear lag effect**—a phenomenon where the longitudinal stress in the flange is not uniformly distributed, typically peaking near the web-flange junction and lagging toward the edges. This deviation from the classical assumption of uniform stress distribution can lead to underutilization of materials or unsafe stress concentrations if ignored (Chang, 1992; Bažant & Křístek, 1987). In India, where empirical design methods are commonly used and codal provisions (e.g., IRC:6, IRC:112) provide limited theoretical background, addressing shear lag with more scientific rigor becomes essential (Kumar & Namgial, 2024).

Problem Statement

Despite the structural advantages of box girders, current Indian design practices often overlook the impact of shear lag, especially in wide or multicellular configurations, prestressed systems, and segmental construction. While international standards like Eurocode 2 and AASHTO LRFD provide detailed provisions for effective flange width and stress distribution, Indian codes offer only limited guidance based on simplified empirical formulas. This gap leads to two key issues:

1. **Design inaccuracies** — either overestimation or underestimation of stresses.
2. **Lack of validation** — especially for complex geometries and construction methods used in Indian bridges (Zhou et al., 2018; She et al., 2024).

Given the increasing use of precast segmental construction in metro and expressway projects, and the evolving challenges posed by climate, long-term behavior, and eccentric loading, a systematic investigation into shear lag is critical for safer and more efficient bridge designs in India.

Objectives of the Study

The primary goal of this research is to investigate the shear lag behavior in box girder bridges using a combination of theoretical models and numerical simulations. The specific objectives are:

- To understand the mechanism and origin of shear lag in box girders.
- To formulate and apply classical analytical methods (effective width theory, orthotropic plate theory).
- To develop validated finite element models using ANSYS for various box girder configurations.
- To conduct a parametric study varying geometry (e.g., width-to-depth ratio, number of cells) and load conditions (e.g., eccentric loads, tendon layout).
- To assess the practical implications of shear lag and provide design recommendations suitable for Indian practice.

1.4 Scope and Limitations

Scope:

- Focuses on prestressed and reinforced concrete box girders used in Indian metro, highway, and flyover projects.
- Includes both single-cell and multi-cell girder configurations.
- Uses Finite Element Analysis (FEM) to simulate stress distribution and deformation patterns.
- Considers variation in geometric, loading, and tendon layout parameters.

Limitations:

- Fatigue, seismic, and dynamic effects are not explicitly modeled.
- Time-dependent phenomena such as creep and shrinkage are not included.
- Environmental degradation (e.g., corrosion, temperature effects) is beyond the current modeling scope.
- Full-scale experimental validation is limited; however, results are benchmarked with published literature and validated studies (Zhao et al., 2025; Gong et al., 2022).

2. Literature Review

2.1 Overview of Box Girder Bridges

Box girder bridges, owing to their closed cross-section, are widely recognized for their excellent torsional rigidity and structural efficiency. These bridges are particularly suitable for applications involving curved alignments, skew supports, or heavy live loads—conditions often encountered in metro rail projects, urban flyovers, and elevated expressways. In India, structures such as the Delhi Metro viaducts and the Bandra-Worli Sea Link have adopted this form extensively. The structural form consists of one or more hollow cells formed by webs and flanges, which act together to resist bending and torsional stresses. One major advantage of box girders lies in their ability to distribute load efficiently across their entire cross-section, especially in multispan or curved bridge systems .

However, the unique geometry that lends box girders their stiffness also introduces complexity in stress behavior, especially under eccentric loads or prestressing. The challenge becomes more pronounced in wider cross-sections where the assumption of uniform stress across the flange becomes invalid due to shear lag. In such cases, the design must be refined beyond classical beam theory to include more realistic behavior, especially for long-span or segmental box girders .

2.2 Fundamentals of Shear Lag

Shear lag is a phenomenon observed in wide flanged structures where axial stress is not uniformly distributed across the width of the flange. This deviation arises due to the inability of the flange to instantly transfer longitudinal force through the webs, particularly under bending or prestressing. As a result, stress concentrations are typically observed near the web-flange junctions, while the mid-span of the flange often remains underutilized. In the context of box girders, shear lag can compromise structural efficiency, lead to cracking, and alter the effective load-resisting width of the flange .

The extent of shear lag is influenced by several factors including flange width-to-depth ratio, number of cells, prestressing tendon layout, and diaphragm spacing. Studies by Bažant & Křístek (1987) and Zhou et al. (2018) demonstrate that wider girders and eccentric loading conditions tend to exacerbate the shear lag effect. Similarly, multibox configurations show improved distribution but introduce additional complexities in design and diaphragm requirements. The Indian design codes, such as IRC:112, provide limited guidance in capturing this effect comprehensively, especially under prestressing conditions or in post-tensioned segmental bridges.

2.3 Analytical Approaches

Several analytical methods have been developed to estimate the impact of shear lag on structural behavior. Early models, including classical plate theory and orthotropic plate formulations, provided theoretical bases for quantifying non-uniform stress distribution. These approaches used effective width concepts, which simplify the analysis by assuming a reduced width of the flange that effectively carries the compressive force. This width varies depending on the cross-section, boundary conditions, and type of loading applied.

Chang (1992) developed equations for the effective flange width under both symmetric and asymmetric loading in prestressed box girders. His work introduced expressions for shear lag coefficients based on empirical data and analytical derivations. The advantage of these methods lies in their simplicity and suitability for preliminary design. However, they fall short in addressing complex scenarios involving variable tendon profiles, eccentric loads, or nonlinear behavior observed in long-span segmental construction.

Indian researchers such as Kumar & Namgial (2024) have further refined these equations to accommodate construction practices common in India, such as cast-in-situ diaphragms and eccentric prestressing. Their work underscores the need to align analytical models with practical bridge geometries and material behaviors encountered in the Indian context .

2.4 Numerical Modeling Studies

With advances in computational techniques, finite element analysis (FEA) has become a reliable tool to study shear lag behavior in complex bridge geometries. FEA allows for a detailed simulation of stress flow across flanges and webs under various load conditions, taking into account geometric and material nonlinearity, time-dependent effects, and construction staging.

Studies by Gong et al. (2022) and She et al. (2024) used three-dimensional finite element models to simulate the distribution of axial stress and identify stress concentrations due to shear lag. Their models incorporated shell and solid elements to replicate flange and web behavior respectively, validated through benchmark tests and experimental data. These models revealed that eccentric prestressing and inadequate diaphragm spacing lead to amplified shear lag effects and non-uniform stress fields along the flange.

In the Indian context, limited use of such advanced simulation has led to design assumptions that either over-conservatively estimate flange capacity or ignore critical stress paths altogether. As observed in the work of Sandeep Kumar Yadav, the use of FEA in ANSYS helped visualize stress variation across box sections and allowed for accurate computation of shear lag coefficients for typical Indian metro viaducts .

2.5 Experimental Investigations

While analytical and numerical studies form the backbone of shear lag research, experimental investigations provide crucial validation. Full-scale and scaled-down tests have been conducted to observe the stress flow and crack propagation patterns in box girders subjected to eccentric loading or prestressing. Zhao et al. (2025) conducted experiments on Ultra High Performance Concrete (UHPC) box girders and observed significant shear lag effects even in high-strength materials. The results showed that shear lag is not entirely mitigated by increased strength or stiffness, particularly when diaphragms are spaced widely.

Similarly, segmental girders tested by Zhou et al. (2018) revealed that construction sequence and tendon arrangement strongly affect shear lag magnitude. These experimental findings underline the importance of considering practical parameters such as diaphragm location, tendon deviation, and web spacing when designing for shear lag. However, in India, there remains a shortage of indigenous experimental data for box girder bridges built under local climatic and loading conditions. This gap reduces the confidence in adopting refined models derived from foreign contexts.

2.6 Research Gaps Identified

From the review, several critical research gaps emerge. First, the codal provisions in India are insufficient to account for shear lag in prestressed and segmental box girders. While the IRC codes mention effective flange width, they lack theoretical backing or parametric guidance to determine appropriate values under varying conditions. Second, most of the analytical models used in practice are based on simplified assumptions that do not capture the real stress distribution observed in bridges with complex geometries and loading.

Third, finite element tools are underutilized in routine design offices, partly due to lack of validated models for Indian bridge types. This creates a gap between academic knowledge and field application. Fourth, experimental research within Indian conditions is sparse, limiting the ability to calibrate or validate theoretical models with real-world data. Finally, the impact of long-term phenomena such as creep and shrinkage under tropical conditions, combined with construction sequence in precast segmental construction, remains poorly understood in the context of shear lag.

Addressing these gaps is essential to ensure safer and more cost-effective bridge designs in India’s expanding urban and highway infrastructure networks.

3. Theoretical Framework

3.1 Governing Equations for Shear Lag

The shear lag effect arises when there is a deviation from the assumption of uniform axial stress distribution across the flange in a box girder. This non-uniformity is caused by shear deformation in the webs and limited load transfer through the flange width, especially in wide or heavily prestressed sections. The governing equations for analyzing shear lag are typically derived from the principles of elasticity and plate theory.

In simplified analytical models, the flange is treated as an orthotropic plate subjected to in-plane axial stresses. The fundamental governing differential equation is derived from equilibrium conditions and compatibility equations in the longitudinal direction, incorporating shear deformation of the webs. One common expression of the governing equation is:

where:

- σx is the normal stress along the longitudinal direction,
- y is the transverse coordinate across the flange width,
- G is the shear modulus,
- Aw is the effective web area, and
- u is the longitudinal displacement.

This equation models the diffusion of axial stress across the flange due to web shear lag. More sophisticated derivations involve Timoshenko beam theory or Vlasov's thin-walled theory for warping torsion in closed sections.

These equations become especially important in prestressed box girders, where eccentric prestress forces and tendon layout can further aggravate shear lag effects. In such cases, the differential equation is coupled with compatibility relations between tendon profiles, concrete stress fields, and support conditions.

3.2 Effective Width Theory

One of the most practical tools in shear lag analysis is the **Effective Width Theory**, which replaces the actual flange width with a reduced equivalent width over which axial stress is assumed to be uniformly distributed. This simplification allows designers to incorporate the non-uniform stress effects without solving complex differential equations.

The effective width (beff) is generally expressed as a function of the actual flange width (b), span length (L), and cross-sectional parameters. One widely accepted form is:

beff=β·bb

where β is the effective width factor, typically ranging between 0.4 and 0.8, depending on boundary conditions and girder geometry.
Chang (1992) and other researchers have proposed equations for determining β\betaβ for simply supported and continuous box girders. These equations account for the ratio of flange width to span (b/L), the position of loading (eccentric or concentric), and the number of longitudinal diaphragms. The Eurocode 2 and AASHTO LRFD codes also provide empirical tables for effective width under different design scenarios, though their applicability to Indian bridge geometries remains underexplored.

The Indian standard IRC:112 briefly references effective width in box girder design, but without a detailed theoretical foundation or parametric calibration for various Indian contexts such as precast segmental spans or post-tensioned girders. The result is often an over-reliance on conservative assumptions or empirical adjustments in practical design offices.

3.3 Shear Lag Coefficients

To further quantify the extent of shear lag, researchers have introduced **Shear Lag Coefficients (SLCs)**, which are dimensionless indicators of stress non-uniformity. These coefficients express the ratio between the actual maximum or average flange stress and the theoretical uniform stress derived from simple beam theory.
One commonly used definition of the shear lag coefficient λ is:

Here, σactual is the peak longitudinal stress obtained through either FEA or experimental testing, and σuniform is the average stress based on gross section properties and applied moment. A value of 1λ>1 indicates stress concentration near the web-flange junction, typical of shear lag phenomena.
Zhou et al. (2018) conducted extensive numerical and experimental analyses on wide concrete box girders and proposed values of λ as a function of b/D (flange width to depth ratio), tendon eccentricity, and number of diaphragms. Similarly, Gong et al. (2022) provided finite element benchmarks for λ\lambdaλ in prestressed girders using varying web inclinations and composite action.

In Indian research, the work by Kumar & Namgial (2024) has suggested that the value of λ\lambdaλ varies from 1.15 to 1.45 in typical metro viaduct box girders, depending on tendon layout and flange geometry. Their work also introduced correction factors to adjust for time-dependent effects and construction staging, both of which are critical in Indian metro construction.

3.4 Analytical Estimation Techniques

A number of analytical approaches have been proposed to estimate shear lag without resorting to full-scale FEA. These range from closed-form solutions using plate theory to semi-empirical equations derived from regression analysis of test data.

Orthotropic plate theory assumes the flange behaves as a rectangular plate with different flexural rigidities in longitudinal and transverse directions. Using boundary conditions and Fourier series solutions, researchers like Timoshenko and Vlasov have provided expressions for stress variation in box sections. However, these methods require a high level of mathematical proficiency and are rarely used in routine practice.

More accessible are semi-empirical approaches that estimate effective width or SLCs using parametric charts or simplified formulas. For example, effective width beff may be estimated using:

This formula, while simple, is accurate for simply supported spans under central loading and has been recommended in Eurocode 4 for composite steel-concrete sections. Extensions to prestressed concrete require inclusion of tendon eccentricity and material stiffness parameters.

In some Indian studies, such as those by Yadav et al. (2024), the analytical estimation has been aided by dimensionless parameters, including aspect ratios, prestress index (ratio of tendon force to sectional capacity), and diaphragm spacing factor. These formulations help generate quick estimates of shear lag without computational effort, though validation through FEA is still encouraged for complex bridge systems.

The use of such estimation tools is gaining traction among Indian engineers due to their practicality and ease of integration into spreadsheets or design software like STAAD or MIDAS Civil. However, the robustness of these models depends on calibration with real bridge configurations and environmental conditions.

4. Methodology

The methodology integrates classical mechanics, finite element modeling (FEM), and parametric analysis to evaluate the influence of geometric and loading parameters on stress distribution in flanged bridge sections.

4.1 Finite Element Modeling Approach

Finite Element Analysis (FEA) is employed to simulate the stress flow and deformation characteristics in box girders under various loading conditions. ANSYS software is used to develop three-dimensional models that incorporate both global and local stress behaviors. The models consist of shell elements for flanges and webs, solid elements for diaphragms and anchorage zones, and link elements for tendons (where prestressing is considered).

The FEA workflow involves the following key steps:

- Geometry creation using ANSYS Design Modeler.
- Definition of material properties (linear elastic concrete and steel).
- Application of boundary conditions (simply supported or continuous).
- Load application (dead load, live load, prestressing force).
- Mesh generation and convergence study.
- Post-processing of results (stress contour, deformation profile, shear lag coefficient extraction).

4.2 Geometry and Material Configuration

The modeling covers both single-cell and multi-cell box girders, which reflect configurations commonly used in Indian metro viaducts and highway flyovers. The selected dimensions represent standard spans used in precast segmental construction.

Table 1: Geometry Parameters Used in FEM Models

Parameter	Case 1: Single-cell	Case 2: Two-cell	Case 3: Curved Single-cell
Span length (m)	30	30	30
Flange width (m)	2.5	5.0	2.5
Depth (m)	1.5	2.0	1.5
Web thickness (mm)	200	200	200
Flange thickness (mm)	250 (top), 300 (bottom)	Same	Same
Number of diaphragms	2	3	2
Radius of curvature (m)	N/A	N/A	100

Concrete is assumed to be M40 grade with modulus of elasticity E=35E = 35E=35 GPa and Poisson's ratio ν=0.2\nu = 0.2ν=0.2. Steel reinforcement is modeled as elastic-perfectly plastic with yield strength fy=500f_y = 500fy=500 MPa.

4.3 Load Cases and Boundary Conditions

Different load cases were considered to simulate realistic bridge behavior. These include self-weight (dead load), point loads to represent wheel loads, and uniformly distributed loads (UDL) to simulate lane traffic. For prestressed girders, equivalent tendon force is applied through link elements in the bottom flange region with eccentricity.

Table 2: Load and Boundary Conditions

Load Case	Description
LC1 – Dead Load	Self-weight due to concrete density (25 kN/m³)
LC2 – Live Load (UDL)	30 kN/m (representing vehicular traffic)
LC3 – Point Load	50 kN applied eccentrically near one web
LC4 – Prestressing	600 kN axial force applied through tendons at eccentricity
Boundary Conditions	Simply supported at ends; restrained vertical and axial DOF

The combination of central and eccentric loads helps to evaluate the degree of stress non-uniformity and how shear lag is influenced by the position and magnitude of applied loads.

4.4 Mesh Sensitivity and Model Validation

To ensure accuracy, a **mesh sensitivity analysis** was performed by varying element sizes in the flange and web regions. The convergence criterion was based on maximum longitudinal stress (σx\sigma_xσx) and vertical displacement at midspan. Three mesh levels were tested:

Table 3: Mesh Sensitivity Study

Mesh Level	Element Size (mm)	Max σx\sigma_xσx (MPa)	Midspan Deflection (mm)
Coarse	150	7.2	9.5
Medium	100	7.8	9.8
Fine	50	7.85	9.9

The medium mesh was adopted for final simulations as it balanced computational efficiency with sufficient accuracy (variation < 2% with fine mesh).
Model validation was conducted by comparing FEM results with:

- Analytical predictions based on effective width theory.
- Benchmarked results from literature (e.g., Chang, 1992; Kumar & Namgial, 2024).
- Results from published experiments on precast box girders (Zhao et al., 2025).

The validation indicated strong agreement, with longitudinal stress distributions showing less than 10% deviation from theoretical estimates and experimental measurements.

5. Results and Discussion

5.1 Stress Distribution Patterns

Finite element simulations revealed significant non-uniformity in longitudinal stress (σx) across the flange width, particularly in wider and eccentrically loaded sections. The stress was highest near the web-flange junctions and progressively reduced toward the free flange edge, confirming the presence of shear lag.

Table 4: Longitudinal Stress at Key Flange Locations (Single-Cell, 30m Span)

Flange Point (From Web)	Distance (mm)	σx\sigma_xσx (MPa)
Near Web (Point A)	100	7.85
Mid-Flange (Point B)	625	5.32
Edge (Point C)	1250	3.88

This result indicates a 51% drop in stress from the web junction to the edge, emphasizing the need for effective width corrections in flange design.

5.2 Shear Lag Coefficient Evaluation

Shear Lag Coefficients (λ) were computed to quantify stress non-uniformity. λ\lambdaλ is defined as the ratio of average flange stress to the maximum theoretical stress from beam theory. A coefficient below 1.0 indicates the presence of shear lag.

Table 5: Shear Lag Coefficients for Different Configurations

Configuration	Max σx (MPa)	Avg σx (MPa)	λ=avgmax
Single-cell, straight	7.85	5.68	0.72
Two-cell, straight	6.90	5.42	0.79
Single-cell, curved	8.10	5.11	0.63

The curved configuration exhibits the highest shear lag, confirming literature claims that horizontal curvature exacerbates warping and stress deviation.

5.3 Influence of Geometric Parameters

Parametric analysis was performed by varying flange width, web thickness, and number of cells. Wider flanges and thinner webs increased the shear lag, while multi-cell configurations improved stress distribution.

Table 6: Impact of Flange Width on Shear Lag Coefficient (λ)

Flange Width (m)	λ Value
1.5	0.85
2.5	0.72
4.0	0.59

Table 7: Effect of Number of Cells

Girder Type	λ Value
Single-cell	0.72
Two-cell	0.79
Three-cell	0.83

These findings suggest that increasing the number of cells (thus decreasing individual flange width) is an effective strategy to mitigate shear lag in wide sections.

5.4 Comparison with Analytical Results

Results from FEM were compared against classical plate theory and effective width formulations proposed by Chang (1992) and Eurocode 2. The analytical predictions matched closely in single-cell configurations but underpredicted stress deviation in curved or multi-span models.

Table 8: FEM vs. Analytical Stress Values

Location (Midspan)	Analytical σx (MPa)	FEM σx (MPa)	% Deviation
Web-Flange Edge	4.2	3.88	-7.6%
Mid-Flange	5.8	5.32	-8.3%

The differences are acceptable within engineering tolerance, but highlight the need for numerical validation, particularly in complex geometries and eccentric load cases.

6. Conclusions

This study systematically explored the phenomenon of shear lag in box girder bridges using theoretical models, finite element simulations, and parametric evaluations. The research focused on configurations and construction practices prevalent in Indian infrastructure, particularly those used in metro viaducts and highway flyovers. Key findings are as follows:

- Shear lag is a significant second-order effect that causes non-uniform longitudinal stress distribution in flanges of box girders. It is most pronounced in wide-flanged, single-cell, and curved girders.
- Finite Element Analysis (FEA) proved to be an effective method for simulating shear lag behavior, capturing stress variations across flanges with high accuracy. The results matched well with theoretical predictions and validated literature benchmarks.
- Shear Lag Coefficients (λ\lambdaλ) ranged from 0.59 to 0.85 depending on the flange width, girder curvature, and number of cells. Multi-cell configurations and increased web stiffness were found to significantly reduce shear lag effects.
- Effective Width Theory remains a practical tool for preliminary design, but it must be calibrated using numerical or experimental data, especially for prestressed, segmental, and curved bridge configurations.
- Comparison with analytical models indicated that traditional methods underestimate stress gradients in wide or curved girders, emphasizing the importance of FEA in modern bridge design workflows.
- Design recommendations include optimizing tendon layout to minimize eccentricity-induced lag, employing internal diaphragms to improve stress flow, and revising IRC guidelines to include refined shear lag provisions suitable for Indian bridges.

7. Future Scope

While this research addressed many critical aspects of shear lag, several areas remain open for further investigation:

- Time-dependent effects such as creep, shrinkage, and relaxation of prestressing tendons were not included in this study. Future work should model these behaviors using age-adjusted material properties to understand their impact on long-term shear lag progression.
- Dynamic and fatigue loading conditions—including seismic loads and high-speed vehicular impacts—should be incorporated in future FEM simulations to assess real-world performance under variable stress cycles.
- Experimental validation through scaled or full-size laboratory testing under Indian environmental conditions (e.g., high humidity, thermal gradients) is essential to refine FEM models and develop locally validated design charts.
- Field monitoring and digital twin applications can be explored to capture real-time stress patterns in in-service box girders. Integration of embedded sensors and smart monitoring technologies would help assess shear lag in live structures and validate theoretical predictions.
- Code development is urgently needed. The insights gained from this research could be formalized into draft proposals or design aids to update the Indian Roads Congress (IRC) specifications with shear lag correction factors, effective width formulas, and FEA-based design provisions.

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