

STRUCTURAL ANALYSIS AND DESIGN OF A PSC FLAT SLAB BRIDGE DECK FOR URBAN OVERPASSES

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Abstract: As modern urban landscapes become increasingly congested, the demand for infrastructure that balances structural integrity with geometric efficiency has never been higher. This thesis explores the structural analysis and design of a Prestressed Concrete (PSC) flat slab bridge deck, a specialized system that supports the concrete deck directly on columns or piers without the aid of intermediate longitudinal or transverse beams. The research highlights the transition toward flat slab bridges driven by several critical engineering factors. By eliminating bulky girders, the construction depth is minimized, which subsequently reduces the required height of approach embankments and overall project costs. Furthermore, the use of pre-stressing technology allows for thinner sections and longer spans, effectively reducing the dead load of the structure while maintaining structural efficiency. From a logistical standpoint, the flat soffit simplifies the formwork and shuttering process, enabling faster construction cycles a necessity for minimizing The core of this study focuses on the complex two-way slab action inherent in these structures, where loads are transferred in multiple directions to support points. This necessitates a sophisticated application of plate theory and an in-depth understanding of shear distribution. This research assesses the structural reliability and serviceability of a bridge under various load conditions. The analysis recorded a maximum deflection of 24.207 mm, satisfying the IRC:112 limit of 25 mm. Findings indicate that utilizing panel drops optimizes load transfer, significantly reducing stress compared to standard flat slabs. While mid-span vehicle positioning governs deflection, support zones dictate shear and negative moment design. High reinforcement needs are met through a 1.07% ratio using 20 mm bundled bars. Finite element modelling confirms the design is safe, stiff, and compliant with all engineering standards

Keywords: Pre-Stressed Concrete, Flat Slab, Bending Moment, Punching Shear, Deflection.

I. INTRODUCTION

The expansion of metropolitan areas has intensified the need for infrastructure systems that can function effectively despite limited space and geometric constraints Urban flyovers and overpasses often have to be constructed in densely populated corridors where maintaining vertical and horizontal clearances is challenging. These conditions have accelerated the search for bridge systems that combine structural reliability with minimal construction depth. Prestressed Concrete (PSC) flat slab bridge decks have gained attention as a solution capable of addressing such demands.

Unlike traditional girder-supported decks, flat slabs distribute loads directly to columns or pier heads without the use of deep longitudinal beams. This configuration reduces overall deck depth, which is particularly advantageous in areas with utilities, underpasses, or heavy traffic flow beneath the structure. The simplified underside also eases formwork preparation and accelerates construction. Prestressing plays a key role in enhancing the performance of flat slab bridges by improving stiffness, reducing cracking, and allowing slender sections capable of spanning longer distances. The structural behaviour of flat slabs, however, is complex due to their inherent two-way action. Load distribution is influenced by slab geometry, support stiffness, and boundary conditions. In addition, punching shear around the supports becomes a critical design consideration.

This thesis focuses on the structural analysis and design of a PSC flat slab bridge deck suited for urban overpasses. The study employs finite element techniques to evaluate stresses, deflections, and shear forces, followed by detailed design checks in accordance with IRC and IS specifications. The goal is to establish an efficient methodology for designing flat slab bridge decks that balance safety, cost-effectiveness, and constructability.

II. PROBLEM CONTEXT

Urban transportation networks are experiencing unprecedented pressure due to rapid urbanization, increased vehicular density, and limited availability of space for new infrastructure. Traditional bridge superstructures, particularly those relying on deep beam-girder systems, often struggle to meet the geometric and functional constraints of modern urban corridors where vertical clearance, architectural integration, and construction speed are critical considerations. As cities expand and mobility demands intensify, engineering solutions must balance structural efficiency, safety, durability, and aesthetic quality while minimizing disruption to existing traffic. Prestressed Concrete (PSC) flat slab bridge systems offer potential advantages in this context due to their shallow depth, efficient load distribution, reduced formwork requirements, and suitability for accelerated construction methods. However, despite their benefits, PSC flat slab bridges remain underexplored for urban overpass applications, especially with regard to their behaviour under concentrated vehicular loads, punching shear near supporting columns or piers, and long-term performance under repetitive urban traffic conditions.

Current design practices rely heavily on conventional girder-type systems, and limited research exists on adapting flat slab prestressed systems for bridge applications in congested city environments. Issues such as stress concentration patterns, slab-column interaction, prestressing tendon configuration, and serviceability requirements are not adequately documented for these scenarios. Moreover, the structural behaviour of PSC flat slab bridge decks under realistic urban loads—including impact factors, dynamic effects, and asymmetrical traffic flow—requires further analytical validation. Without comprehensive analysis and design guidelines, engineers face uncertainty in determining whether PSC flat slabs can safely and economically replace traditional bridge deck systems for urban overpasses. Therefore, a structured investigation is necessary to analyze the feasibility, structural adequacy, and performance characteristics of a PSC flat slab bridge deck specifically tailored for urban overpasses, addressing these critical engineering gaps.

III. PROBLEM DEFINITION

The fundamental problem is the absence of a comprehensive structural analysis and design framework that evaluates whether a PSC flat slab bridge deck can safely, economically, and effectively serve as an alternative to traditional systems for urban overpasses. This thesis seeks to address this gap by analyzing structural behavior using advanced analytical tools, studying load effects, evaluating performance under urban traffic conditions, and proposing a rational design methodology grounded in established code provisions and computational modelling.

The core problem addressed in this thesis arises from the need to develop a structurally efficient, space-optimized, and durable bridge deck system suitable for dense urban areas where conventional girder bridges may not satisfy geometric or functional constraints. A Prestressed

Concrete (PSC) flat slab bridge deck presents a promising alternative; however, its behavior under urban overpass conditions is not yet well established in literature or practice. The lack of well-defined

analytical frameworks and design guidelines for PSC flat slab bridges has created ambiguity regarding their structural performance, safety margins, and long-term reliability when exposed to real-world vehicular loads, environmental conditions, and repetitive stress cycles typical of city traffic systems.

The problem is further compounded by challenges such as predicting two-way load distribution, evaluating punching shear at critical support zones, assessing tendon layout efficiency, and understanding how prestressing modifies the slab's stiffness and cracking behaviour. Without a rigorous structural analysis, engineers cannot accurately determine optimal slab thickness, reinforcement detailing, tendon profiles, or the overall viability of flat slab decks for urban-grade separations. Additionally, modern transportation engineering demands solutions that minimize construction time and traffic disruption—criteria that PSC flat slabs may fulfill but have not been analytically validated for bridge applications.

IV. OBJECTIVES

The primary objective of this research is to analyze and design a Prestressed Concrete (PSC) flat slab bridge deck specifically suited for urban overpass applications, where spatial constraints, structural efficiency, and rapid construction are major priorities. The study aims to evaluate the structural behaviour of a PSC flat slab subjected to realistic urban traffic loads, including dynamic and impact effects, as prescribed by relevant design standards. A key objective is to assess the feasibility of adopting flat slab systems, which are traditionally used in building floors, for bridge scenarios where concentrated wheel loads, punching shear forces, and two-way load distribution pose significant challenges.

To achieve this, the research focuses on several specific goals:

- 1.To perform a comprehensive literature study on the behaviour of two-way flat slabs under heavy vehicular moving loads.
- 2.To determine the design loads (Dead Load, Live Load, and Impact) based on standard codes of practice (IRC:6 or AASHTO).
- 3.To analyze the critical "Punching Shear" at the column-slab interface and design necessary head reinforcements or drop panels.
- 4.To develop 3D Finite Element Model (FEM) of the bridge deck to study the distribution of bending moments and torsion effects.
- 5.To design the cable profile to counteract the maximum sagging and hogging moments.

V. ABOUT THE SOFTWARE

STAAD.Pro (Structural Analysis and Design Program) is the industry-standard software for structural engineers worldwide, developed by Bentley Systems. It serves as a comprehensive solution for analyzing and designing virtually any type of structure, ranging from simple residential buildings and culverts to complex industrial plants, bridges, and offshore platforms. The software's primary strength lies in its versatility and its ability to handle various materials, including steel, concrete, timber, and aluminum, all within a single integrated environment.

At its core, STAAD.Pro utilizes Finite Element Analysis (FEA) to predict how structures will respond to various forces. Engineers can model complex geometries and apply a wide array of loads, such as dead loads, live loads, and environmental factors like wind and seismic forces. One of its most significant advantages is its extensive library of international design codes. This allows engineers to ensure that their designs comply with regional safety standards in over 40 countries, making it indispensable for global engineering firms.

The user interface is designed to streamline the workflow from initial modelling to final documentation. It features an intuitive graphical environment where users can visualize the 3D model, view stress distribution

contours, and identify potential failure points before construction begins. Additionally, its seamless integration with other BIM (Building Information Modeling) software, like Revit or Open Buildings Designer, ensures that data flows smoothly between architects and engineers, reducing errors and saving time.

Beyond basic analysis, STAAD.Pro offers advanced capabilities like dynamic analysis, buckling analysis, and cable-stayed design. By automating tedious manual calculations, it allows engineers to focus on optimizing their designs for safety and cost-efficiency. Whether it's a high-rise skyscraper or a small steel warehouse, STAAD.Pro provides the reliability and precision required to ensure structural integrity in the modern built environment.

VI. METHODOLOGY AND ANALYSIS

Initial Study

Review of applicable Indian standards (IRC/IS) and international references. Study of existing flat slab bridge applications and research findings. Identification of key parameters such as span, clearance requirements, material properties, and urban constraints.

Modelling Approach

A finite element model of the slab is developed using plate elements. Support conditions representing column or pier head stiffness are applied. Prestressing tendons are incorporated using equivalent load or tendon profile modelling techniques.

Load Assessment

Load cases include dead loads, wearing coat, traffic loads per IRC, impact factors, temperature effects, and prestressing forces. Load combinations for ULS and SLS are generated as per code provisions.

A. Dead Load

Self-Weight: Use the Self Weight command to account for the slab's own mass.

B. Live Load

Use the Bridge Deck Processor or Influence Surface Generator to apply moving vehicular loads according to standard codes (e.g., IRC Class 70R or AASHTO).

To check if 6000 kN/m force is sufficient for IRC Class A loading on a 20 m span, you must compare the resulting concrete stresses against the limits in IRC:112-2020.

1. IRC Class A Load Characteristics

- Configuration: A train of 8 wheeled axles totalling 554 kN.
- Axle Weights: Range from 27 kN to 114 kN.
- Impact Factor: For an RCC/PSC bridge with a 20 m span (L), the impact factor is calculated as $4.5/6+L$
- Calculation = $4.5/6+20 = 0.173$ (or 17.3% increase to live load).

2. Stress Analysis Logic

In STAAD.Pro, you must verify that under the Serviceability Limit State (SLS), the concrete remains within these bounds:

- Compression Limit: Typically $0.4 \times f_{ck}$ to $0.45 \times f_{ck}$ for prestressed members.
- Tension (Cracking) Limit: For a "Class 1" structure (fully prestressed), no tension is allowed under service loads. For "Class 2" or "Class 3," limited tension or a specific crack width (e.g., 0.2 mm) is permitted.

3. Verification Steps in STAAD.Pro

1. Define Vehicle: Use the STAAD.Pro Load Generator to define Class A vehicle with its 8 axles.

2. Run Moving Load: Generate a load series to find the maximum bending moment (MLL) at mid-span.

3. Check Combined Stress: Bottom Fibre Stress:

$$f_b = -\frac{P}{A} - \frac{P \cdot e}{Z} + \frac{M_{DL} + M_{LL}}{Z}$$

Fig. 4.1: Bottom Fibre Stress

Provided force of 6000 kN/m

If f_b remains negative (compressive) or stays below the tensile strength of your concrete grade (M50), the design is safe against cracking.

Hence, For a 20 m span, the IRC Class A vehicle adds a dynamic impact of 17.3%. With your 2,500 kN/m force, the slab has a pre-compression of roughly 5 MPa. You must confirm in STAAD's post-processing > Plate Stress that the total tensile stress under this vehicle load does not exceed the limits of IRC:112 (often for critical bridge decks).

C. Generation Of Moving Load

To generate the IRC Class A moving load in STAAD.Pro, you need to first define the vehicle in the Load Definitions and then use the Load Generation command to move it across your 20 m bridge.

1. Define the IRC Class A Vehicle

In the STAAD Editor, under the DEFINE MOVING LOAD block, you must input the axle weights and spacings for the Class A vehicle.

DEFINE MOVING LOAD TYPE 1 IRC-CLASS-A

LOAD 27 27 114 114 68 68 68 68

DIST 1.1 3.2 1.2 4.3 1.2 3.0 1.2

WIDTH 1.8

- LOAD: Specifies the axle weights (kN) for the 8 axles.
- DIST: Specifies the distance (m) between each subsequent axle.
- WIDTH: The wheel spacing (m) of the vehicle.

2. Generate the Moving Load Cases

Under the LOAD CASE DETAILS, use the LOAD GENERATION command to simulate the movement. For a 20 m span, moving the vehicle in 1 m increments requires roughly 21 load cases to cover the full length.

LOAD GENERATION TYPE 1 0.0 0.5 0.0 ZINC 1.0

Use code with caution.

- LOAD GENERATION 90: Tells STAAD to create 21 individual load cases.
- TYPE 1: Refers to the IRC-CLASS-A vehicle defined above.
- 0.0 0.5 0.0: The starting coordinates (X,Y,Z) of the vehicle's reference point.

- XINC 1.0: Moves the vehicle by 1.0 m in the Global Z direction for each of the 90 steps.

3. Review in post-processing

After running the analysis, switch to the Post-Processing Mode. You can view the Envelope of results to see the maximum bending moments and shear forces caused by the vehicle at any point on the bridge deck.

D. Pre Stressing-Forces

Since STAAD.Pro's "Prestress Member Load" is for beams, for a flat slab, you must manually calculate and apply the equivalent loads:

- Calculate Upward Pressure: For a parabolic tendon profile, the equivalent upward load is calculated as **wup = 8Pe/L²**,

where P is the prestressing force, e is the sag, and L is the span.

- Apply Plate Loads: Go to Loading > Load Case Details > Add > Plate Loads. Select Pressure on Full Plate and input the calculated upward pressure as a negative value (to act against gravity) in the Global Y direction.
- End Anchorage Forces: Apply the horizontal compression at the slab ends as Nodal Loads or Edge Pressures.

E. Equivalent Load Calculation

For a prestressed flat slab in STAAD.Pro, you must convert the tendon force into an equivalent upward pressure. This allows you to simulate the "load balancing" effect on the plate elements.

Parameters considered are:

- Span (L) = 20m
- Prestressing Force (P) = 6000 kN (total force across the width)
- Tendon Sag (e) = 0.2m (distance from neutral axis to tendon at mid-span)
- Slab Width (B) = 10m

1. Calculate the Equivalent Line Load Using the load-balancing formula for a parabolic tendon: **wup = 8Pe/L²**

$$\mathbf{wup} = 8 \times 6000 \times 0.2 / 20^2$$

$$\mathbf{wup} = 24 \text{ kN/m}$$

This value represents the upward force exerted by the tendons per metre of the bridge length.

2. Convert to Plate Pressure $q_{up} = w_{up} / B$ $q_{up} = 24/10 = 2.4 \text{ kN/m}^2$

Since STAAD.Pro models the flat slab using plates, you need

to apply this as a pressure load across the surface:

3. STAAD.Pro Input Step

1. Open Load Case Details and create a case named "Prestress".
2. Select Add > Plate Loads > Pressure on Full Plate.

3. Enter 1 in the GY (Global Y) direction
4. Assign this load to all plate elements in your mesh.

F. Exact Pre Stressing Force

1. With a 0.5 m slab depth, your bridge is relatively slender for a 20 m span (a typical span-to-depth ratio for prestressed slabs is 1:20 to 1:25). To calculate the exact Prestressing Force according to Load Balancing Method, Calculate the Dead Load

- Unit Weight of Concrete: 25 kN/m³

Slab Thickness: 1.2 m

$$\text{Dead Load} = 0.5 \times 25 = 30 \text{ kN/m}^2$$

2. Determine Maximum Possible Sag (e)

For a 1.2 m slab, the tendon must stay within the concrete with proper cover (usually 50mm)

- Neutral Axis: 0.25m from the top
- Lower Cover: 0.05m
- Maximum Sag (e): $0.25 - 0.05 = 0.2\text{m}$ (This is the distance from the center to the tendon at mid-span).

TABLE I DISPLACEMENT TABLE

Displacement	Node	L/C	Horizontal	Vertical	Horizontal
			X mm	Y mm	Z mm
Max X	348	2122	2.651	-23.049	9.67
Min X	2933	2170	-2.638	-23.302	9.45
Max Y	80	2121	0.186	13.546	10.494
Min Y	2932	2167	-2.515	-23.458	9.022
Max Z	190	2121	1.236	2.007	10.497
Min Z	232	2031	1.311	1.408	-8.05

1. Calculate Required Force (P)

To balance 80% of the Dead Load (a common design target to limit long-term deflection):

- Load to Balance (w bal): $0.8 \times 30 = 24 \text{ kN/m}^2$
- Span (L): 20m
- Formula: $P = w_{bal} \times L^2 / 8e$
 $P = 24 \times 20^2 / 8 \times 0.2 = 9600 / 1.6 = 6000 \text{ kN per metre}$

G. Analysis Procedure

Extraction of bending moments, shear forces, stresses, and deflections. Detailed review of punching shear forces around supports. Identification of critical design sections.

VII. RESULTS AND DISCUSSION

A. Deflection Check

According to IRC:112 , allowable deflection is 25mm. From, staad results table, we can see that the maximum vertical deflection is 24.207mm < 25 mm(permissible deflection), hence SAFE.

B. Moments and Plate Stress

Table 2 presents a plate center stress summary covering local shear forces, membrane stresses, and bending moments for multiple plate elements. Shear stresses (SQX, SQY) are relatively low in magnitude, indicating no critical shear dominance across the plates.

Membrane stresses (SX, SY, SXY) remain small and balanced, suggesting limited in-plane tensile or compressive demand.

TABLE 2
MOMENTS AND PLATE STRESS

	Plate	L/C	Shear (Local)			Bending Moment (Local)		
			SQX	SQY	SXY	MX	MY	MXY
			N/mm2	N/mm2	N/mm2	kN-m/m	kN-m/m	kN-m/m
Max Qx	1235	2121	0.351	0.293	-0.02	126.123	146.693	66.869
Min Qx	1242	2179	-0.358	0.324	0.017	147.544	150.972	-70.757
Max Qy	1235	2102	0.332	0.345	-0.008	171.05	144.611	66.851
Min Qy	1655	2179	0.276	-0.335	-0.011	152.626	115.59	-58.33
Max Sx	1239	2102	-0.001	0.051	-0.001	60.619	124.799	2.444
Min Sx	1422	2071	-0.042	0.016	0.001	29.644	20.684	15.975
Max Sy	1658	2179	0.001	-0.049	-0.009	40.89	80.21	-23.162
Min Sy	1475	2077	0.112	0.011	0	138.514	51.686	0.288
Max Sxy	1242	2168	-0.333	0.258	0.021	105.896	138.886	-60.252
Min Sxy	1235	2126	0.333	0.259	-0.021	106.174	138.986	60.311
Max Mx	1302	2012	-0.259	0.099	-0.005	202.587	78.559	-44.014
Min Mx	1662	2162	-0.001	0.017	-0.014	-18.621	2.554	-24.28
Max My	1241	2179	-0.094	0.235	0.015	84.985	175.543	-56.515
Min My	1602	2164	0.018	-0.021	-0.011	-11.316	1.266	-19.397
Max Mxy	1235	2121	0.351	0.293	-0.02	126.123	146.693	66.869
Min Mxy	1242	2179	-0.358	0.324	0.017	147.544	150.972	-70.757

Bending moments (MX, MY, MXY) govern the response, with peak values exceeding 200 kN-m/m, identifying bending as the critical design driver.

Overall, the results indicate a bending-controlled plate behavior with no extreme membrane or shear stress concentrations.

C. Shear Stress Contours

From Figure 1, finite-element stress contour plot we can see that,

1. **Highest stress concentration:** The regions shown in red, orange, and yellow ($\approx 18\text{--}21.4 \text{ N/mm}^2$ and above) indicate peak stresses. These occur around the column locations.
2. **Moderate stress bands:** The pink and light blue bands surrounding these hotspots suggest stress gradients—indicating that the load transfers through these zones more heavily than the rest of the structure.
3. **Low-stress regions:** Large areas of the model appear in **dark blue**, corresponding to **very low stress ($\leq 0.134 \text{ N/mm}^2$)**. This implies that much of the structure is **under-utilized** in carrying load.
4. **Symmetry of the stress field:** The pattern is symmetric, indicating that the loading and geometry are likely symmetric as well suggesting the model is behaving as expected under symmetric boundary conditions.

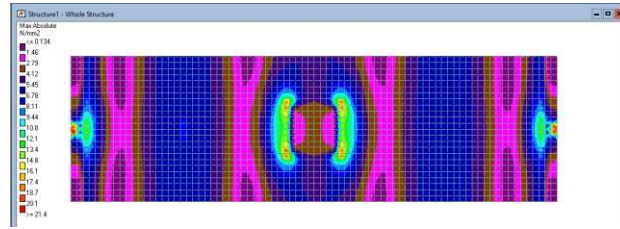


Fig. 1: Shear Stress Contours

D. Tendon Profile

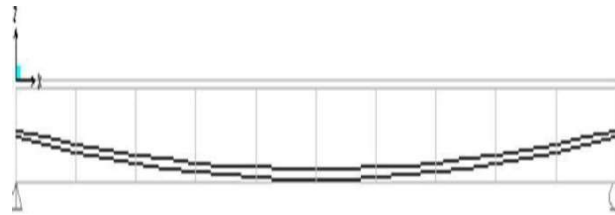


Fig. 2: Tendon Profile

The tendon profile represents the strategic geometric trajectory of prestressing cables within a concrete element, often following a parabolic curve in simply supported structures to optimize performance. This configuration effectively counters downward gravitational forces by generating upward equivalent loads, which significantly minimizes structural deflection through load balancing. By maximizing the cable's eccentricity at mid-span, the point of peak bending moment and reducing it near the supports, engineers can precisely manage internal stresses. This specific alignment ensures the concrete remains under constant compression, thereby preventing structural cracking and enhancing the overall durability of the member under varying service loads.

E. Comparison Of Span/ Deflection Ratio For Different Spans

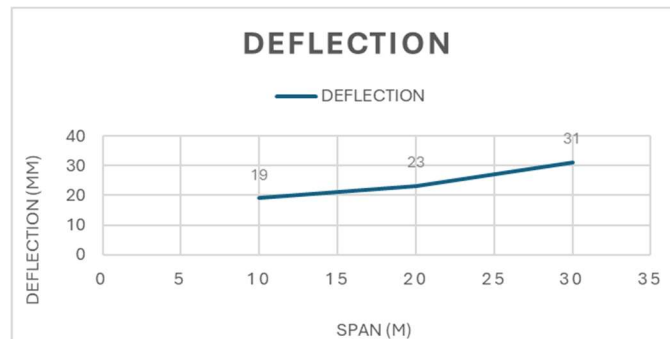


Fig. 3: Deflection Comparison

The presented graph demonstrates the relationship between structural span and deflection, clearly indicating how deflection varies as span length increases. The horizontal axis represents the span, while the vertical axis denotes the observed deflection values. From the graph, it is evident that deflection increases consistently with an increase in span length. Specifically, the deflection value rises from

approximately 19 units at a span of 10 units to about 23 units at a span of 20 units, and further increases to nearly 31 units at a span of 30 units.

This progressive increase highlights the fundamental structural behavior that longer spans tend to be more flexible when subjected to similar loading conditions. As the span increases, the stiffness of the structural member reduces, resulting in higher deflection. Consequently, the span-to-deflection relationship becomes a critical factor in assessing serviceability performance, particularly for long-span elements.

The observed trend emphasizes the need for careful structural design, as excessive deflection can adversely affect usability, aesthetics, and long-term durability. To control deflection in larger spans, designers may adopt measures such as increasing member depth, using higher-strength materials, or providing additional supports. Overall, the graph underscores the importance of optimizing span lengths to ensure acceptable deflection levels within permissible design limits.

F. Behavior Of Bridge Span Under Moving Loads (Class A Vehicle)

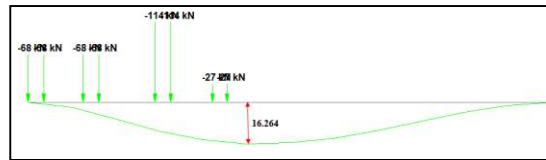


Fig. 4: Deflection For Loads At Starting Span

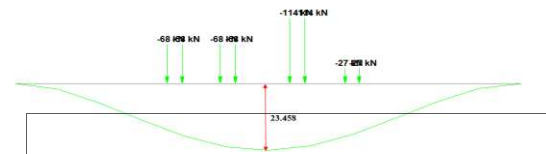


Fig. 5: Deflection For Loads At Mid Span

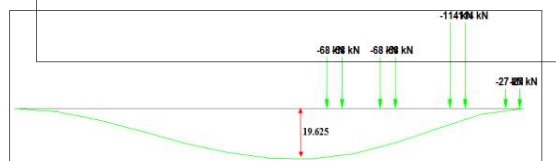


Fig. 6: Deflection For Loads At End Sp

The figures represent the response of a bridge girder subjected to a Class A vehicle moving along the same span, with the vehicle positioned successively at the start of the bridge, at mid-span, and near the end of the bridge. In this study, the span length and structural properties remain unchanged, and only the location of the moving load varies. The applied axle loads are shown as concentrated forces, while the deflected shape of the girder is depicted by the green curve.

When the vehicle is located at the start of the bridge, the resulting deflection is comparatively smaller because the loads act close to the support, where the structure exhibits higher stiffness and lower bending demand. As the vehicle progresses toward the mid-span, the deflection increases significantly and reaches a maximum value. This condition is critical, as loading at mid-span induces the highest bending moment and governs the serviceability performance of

the bridge. When the vehicle moves toward the end of the bridge, the deflection decreases again due to the proximity of the load to the opposite support.

This variation in deflection clearly demonstrates that the position of moving loads has a substantial influence on structural behavior.

The analysis confirms that mid-span loading governs maximum deflection and must be carefully checked during bridge design to ensure compliance with permissible deflection limits and user comfort requirements.

G. Stress Contours For Loads At Different Locations

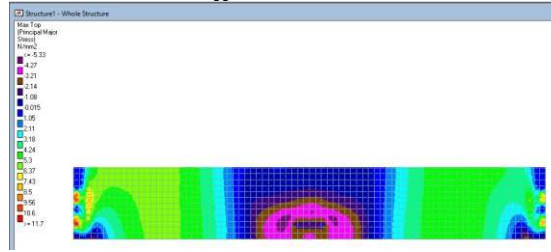


Fig. 7: Stress Contour At End Span

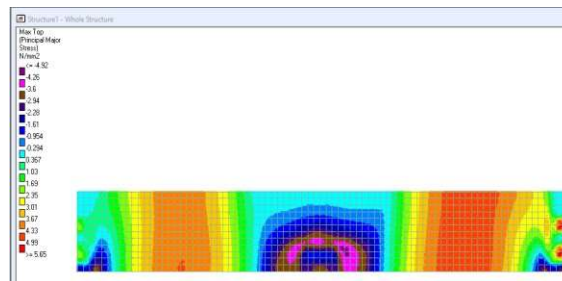


Fig. 8: Stress Contour At Mid Span

The stress contour diagrams illustrate the variation in stress distribution within the bridge due to a Class A vehicle positioned at different locations along the same span. These contours provide a clear representation of how stresses develop and shift within the structural element as the moving load progresses from the start of the bridge to the mid-span and finally toward the end.

When the vehicle is located near the start of the bridge, higher stress concentrations are observed in the region close to the support. In this condition, stresses are predominantly localized, as the load is transferred directly to the support, resulting in comparatively lower bending stresses along the rest of the span. As the vehicle reaches the mid-span, the stress contours indicate a significant increase in stress magnitude, particularly in the extreme fibers of the girder. This position corresponds to the maximum bending moment, making it the most critical case for structural design and serviceability assessment.

As the vehicle moves toward the end of the bridge, the region of higher stress shifts toward the opposite support, and the stress levels at mid-span reduce accordingly. Overall, the stress contour plots clearly demonstrate that load position has a decisive influence on stress distribution. Mid-span loading governs the maximum stress condition and therefore plays a key role in determining the design adequacy and safety of the bridge structure under moving traffic loads.

H. Bending Moment Variation Along Span

TABLE 3
BENDING MOMENT VARIATION ALONG SPAN

SPAN (m)	TOP		BOTTOM	
	MOMENT X (kN-m)	MOMENT Y (kN-m)	MOMENT X (kN-m)	MOMENT Y (kN-m)

1	3287.473	275.473	4635.528	4201.542
2	667.851	118.665	135.056	165.417
3	456.745	104.024	38.507	133.132
4	383.867	72.357	57.133	89.695
5	314.276	46.247	56.966	61.382
6	258.113	28.175	53.299	44.641
7	212.795	16.97	48.267	34.146
8	174.591	9.27	42.792	27.582
9	140.66	4.164	36.704	23.46
10	109.11	0.861	29.855	21.119
11	80.142	0.12	22.119	21.226
12	53.877	10.273	12.91	23.905
13	27.428	0.222	0.821	28.769
14	3.051	0.118	27.752	36.084
15	7.984	10.314	58.16	46.033
16	18.773	1.583	86.783	59.634
17	26.399	2.849	128.98	78.851
18	31.681	3.13	208.665	107.004
19	24.888	4.492	572.545	313.236
20	218.082	219.133	863.035	698.699

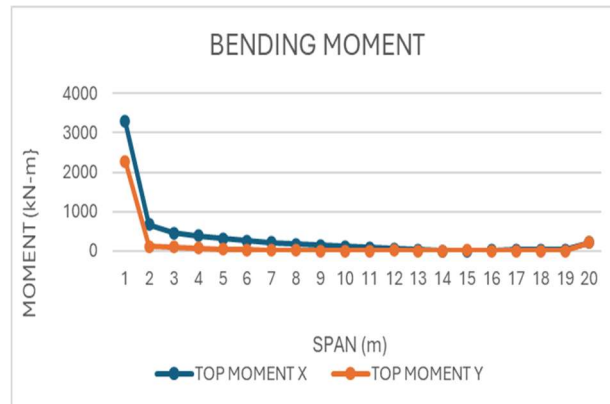


Fig. 9: Bending Moment at Top Along Span

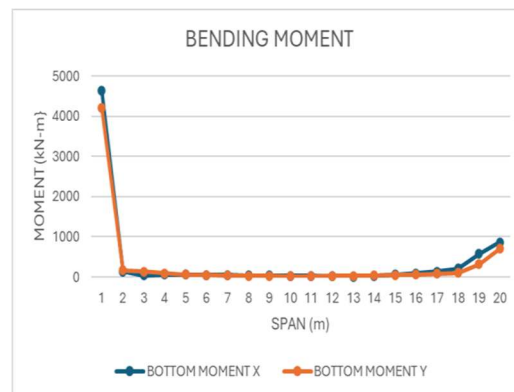


Fig. 10: Bending Moment at Bottom Along Span

The graph illustrates the variation of bending moment along the span, considering bending about two principal directions, referred to as Top and Bottom Moment X and Top and Bottom Moment Y. The horizontal axis represents the span positions, while the vertical axis shows the corresponding bending moment values. The results indicate a clear variation in bending behavior along the length of the span.

At the initial span location, both bending moments exhibit their highest magnitude, with Top Moment X showing a substantially larger value compared to Top Moment Y. This indicates that bending about the X-direction is dominant at this critical location and governs the flexural demand. As the span length increases, a sharp reduction in bending moment is observed for both directions, signifying a decrease in bending influence as the effect of loading diminishes along the span.

Beyond the initial portion of the span, the bending moments gradually reduce and approach relatively low and stable values, suggesting that these regions are less critical from a flexural design perspective. Toward the end of the span, a slight increase in Top Moment Y is noticeable, which may result from localized boundary effects or load redistribution near the support.

Overall, the graph highlights that maximum bending moments occur near critical load regions and primarily control structural design. Identifying such peak values is essential to ensure adequate member sizing and structural safety under applied loading conditions.

I. Shear Variation Along Span

TABLE 4
SHEAR VARIATION ALONG SPAN

	SHEAR X (N/mm²)	SHEAR Y (N/mm²)
1	2.377	2.738
2	0.923	2.395
3	0.222	0.306
4	0.079	0.145
5	0.024	0.081
6	0.006	0.049
7	0.013	0.031
8	0.023	0.02
9	0.032	0.013
10	0.04	0.009
11	0.047	0.006
12	0.053	0.005
13	0.057	0.006
14	0.06	0.011
15	0.062	0.017
16	0.062	0.029
17	0.062	0.05
18	0.06	0.146
19	0.132	0.437
20	2.117	2.505

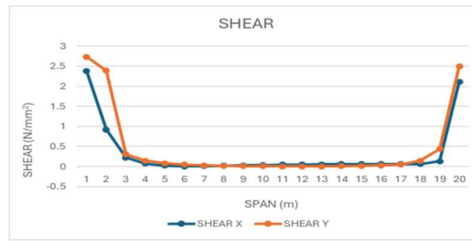


Fig. 11: Shear Variation Along Span

The shear force diagram illustrates the distribution of shear forces along the span of the structural element for two mutually perpendicular directions, identified as Shear X and Shear Y. The horizontal axis denotes the span locations, while the vertical axis represents the magnitude of shear force. The overall trend observed in the plot highlights the variation of shear demand from the supports toward the central region of the span.

At locations close to the supports, both shear components exhibit higher magnitudes, indicating that maximum shear forces develop in these regions. This behavior is characteristic of beam action, as loads are directly transferred to the supports, resulting in elevated shear effects near the ends.

Moving away from the supports toward the mid-span, the shear values decrease rapidly and approach minimal levels, almost zero in some regions. This indicates that shear effects are least critical at the center of the span, where bending action becomes more dominant.

Near the opposite end of the span, the shear forces increase again, reflecting a symmetric response with respect to the supports. Minor variations between Shear X and Shear Y suggest directional differences in load transfer or stiffness characteristics.

Overall, the diagram emphasizes that shear forces govern design near support regions, and these zones require careful detailing and adequate strength provisions to ensure structural safety and performance under applied loading conditions.

J. Comparison Of Shear And Bending Moment/ Span For Different Flatslabs (Flat slab, Flat Slab + Panel Drop, Flat Slab + Column Head, Flat Slab + Panel Drop + Column Head).

1. Shear

The presented shear diagrams compare the variation of shear forces along the span for four flat slab configurations: flat slab (FS), flat slab with panel drop (FS + DP), flat slab with column head (FS + CH), and flat slab with both panel drop and column head (FS + DP + CH). The shear response is evaluated separately in the X and Y directions to understand directional behavior and load transfer characteristics.

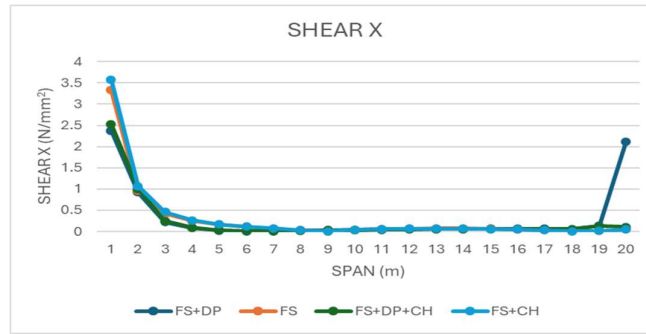


Fig. 12: Comparision of Shear X for different Flat slab Systems

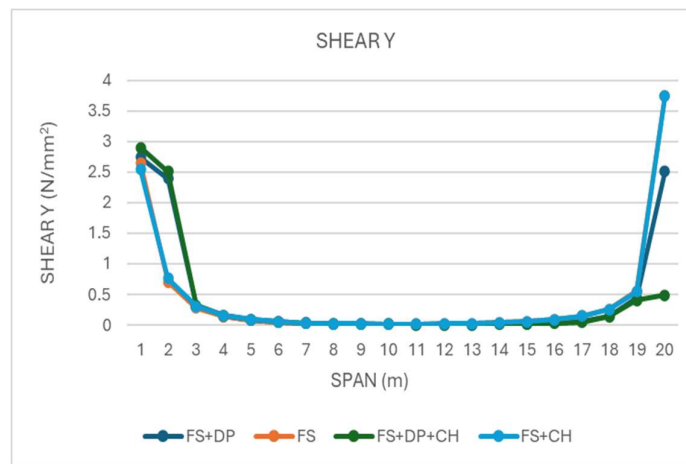


Fig. 13: Comparision of Shear X for different Flat slab Systems

The presented shear diagrams compare the variation of shear forces along the span for four flat slab configurations: flat slab (FS), flat slab with panel drop (FS + DP), flat slab with column head (FS + CH), and flat slab with both panel drop and column head (FS + DP + CH). The shear response is evaluated separately in the X and Y directions to understand directional behavior and load transfer characteristics.

In all configurations, shear forces are observed to be highest near the supports and reduce significantly toward the mid-span. This pattern reflects the fundamental behavior of slab systems, where shear demand is concentrated around column regions due to direct load transfer. The conventional flat slab system exhibits comparatively higher shear values near the supports, indicating greater shear concentration and higher demand on the slab-column connection.

The inclusion of panel drops and column heads leads to a noticeable reduction in peak shear values. Panel drops increase the effective depth of the slab, thereby improving shear resistance, while column heads enhance load dispersion over a larger area. Among the systems considered, the flat slab with both panel drop and column head consistently shows the lowest shear demands in both directions, demonstrating superior structural performance.

Overall, the comparison highlights that the provision of panel drops and column heads is highly effective in controlling shear forces, improving safety, and enhancing the structural efficiency of flat slab systems.

2. Moment

The bending moment behavior along the span has been examined for four flat slab configurations: conventional flat slab (FS), flat slab with panel drop (FS + DP), flat slab with column head (FS + CH), and flat slab with both panel drop and column head (FS + DP + CH).

The comparison is carried out by evaluating top and bottom bending moments in both X and Y directions, allowing a comprehensive assessment of flexural performance under identical loading conditions.

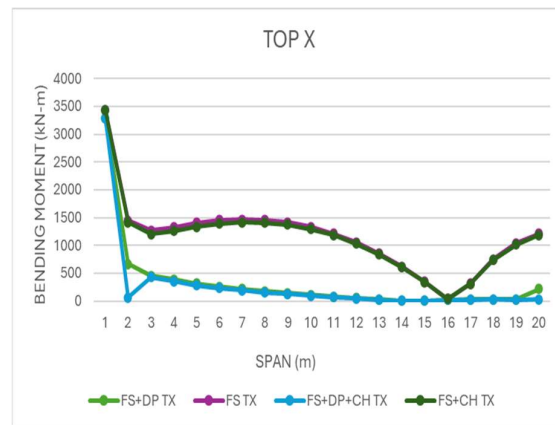
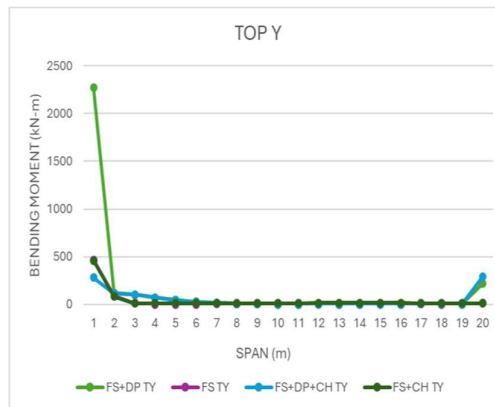


Fig. 14: Comparison Of Top Bending Moment (X) For Different Flat Slab Systems

Fig. 15: Comparison Of Top Bending Moment (Y) For Different Flat Slab Systems



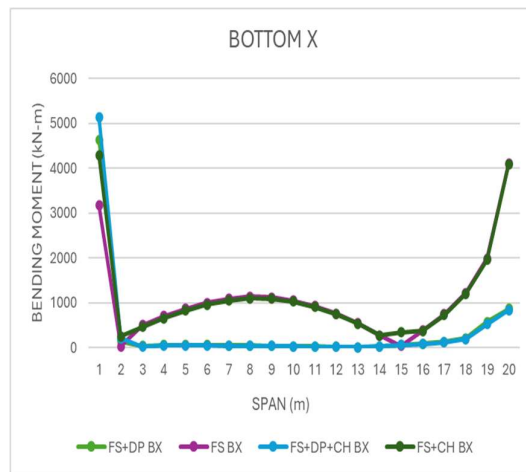


Fig. 16: Comparison Of Bottom Bending Moment (X) For Different Flat Slab Systems

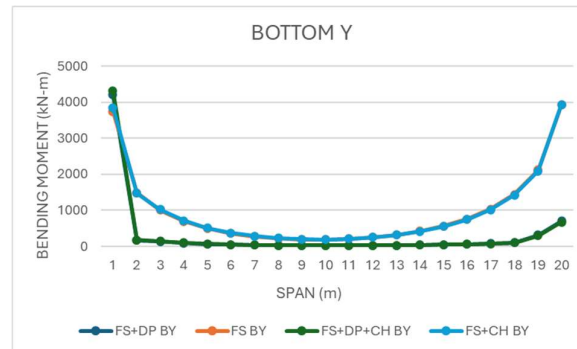


Fig. 17: Comparison Of Bottom Bending Moment (Y) For Different Flat Slab Systems

From the **top moment** distributions, it is evident that negative bending moments are significantly higher near the slab-column junctions for all configurations. The conventional flat slab exhibits comparatively larger peak moments, indicating higher flexural demand due to the absence of local stiffness enhancement. The introduction of a panel drop results in a noticeable reduction in these moments, as the increased slab thickness improves flexural rigidity near the supports. Similarly, the presence of a column head helps in spreading the load over a wider area, leading to a smoother and more uniform moment distribution. The combined system (FS + DP

+ CH) consistently demonstrates the lowest top moments, confirming its effectiveness in controlling negative bending stresses.

The bottom moment plots reveal that positive bending moments dominate the mid-span regions. Once again, the conventional flat slab shows higher moment values when compared to the modified systems. Flat slabs with panel drops and column heads exhibit reduced mid-span moments owing to improved load transfer and enhanced stiffness. The configuration incorporating both panel drop and column head shows the most favorable performance, with reduced peak moments and balanced moment variation along the span. Overall, the results indicate that structural enhancements such as panel drops and column heads significantly improve bending moment distribution. Their combined application is particularly effective in

reducing both negative and positive bending moments, leading to safer, more efficient, and structurally optimized flat slab systems.

VIII. CONCLUSION

This study focused on the structural analysis and performance evaluation of the bridge superstructure under static and moving loads, along with a comparative investigation of different flat slab systems. Finite element analysis was carried out to assess deflection behavior, stress distribution, bending moments, shear forces, and reinforcement adequacy. Based on the results obtained from the analysis, the following conclusions are drawn.

- The maximum vertical deflection obtained from the structural analysis is **24.207 mm**, which is within the permissible limit of **25 mm** as specified by **IRC:112**, confirming satisfactory serviceability performance. The structure demonstrates adequate global stiffness under the applied loading conditions, indicating that serviceability criteria are safely met.
- Bending moments and plate stresses remain within allowable limits for all considered load combinations, ensuring structural safety. Higher bending moments are concentrated near the support regions, while reduced values are observed toward the mid-span, reflecting expected flexural behavior.
- The stress distribution across slab and girder elements indicates efficient load transfer and satisfactory overall structural performance. Maximum stress concentrations occur at slab-column junctions, identifying these regions as critical zones requiring careful design consideration.
- Large regions exhibiting low stress levels indicate a conservatively designed structure operating well within safe limits. Symmetric stress contour patterns confirm the accuracy of the analytical model, loading conditions, and boundary constraints.
- Deflection increases consistently with an increase in span length, highlighting the influence of span on structural flexibility. Longer spans exhibit reduced stiffness and increased deflection, emphasizing the need for span optimization in design.
- Under moving load conditions, maximum deflection occurs when the Class A vehicle is positioned at mid-span, making it the governing load case. Deflections reduce as the vehicle approaches the supports due to higher stiffness near support zones.
 - The analysis confirms that the position of moving loads has a significant influence on structural response and design requirements.
- Stress concentration zones shift along the span as the vehicle moves, indicating realistic and consistent load transfer behavior.
- Stress levels reduce considerably away from critical zones, ensuring overall structural safety.
- Maximum negative bending moments occur near the supports, while positive bending moments dominate the mid-span region. Bending moments in the **X-direction** are generally higher than those in the **Y-direction**, indicating directional dominance in structural demand.
- Critical flexural design sections are clearly identified near the support locations.

- Shear forces attain maximum values near the supports and decrease significantly toward the mid-span region. Symmetric shear force distribution confirms proper structural behavior and uniform load transfer. Support regions govern shear design and require careful detailing to ensure safety.
- The required steel area of 24,120.59 mm² is satisfactorily provided using 120 bars of 20 mm diameter, resulting in a reinforcement ratio of 1.07%. Bundled reinforcement, consisting of three-bar bundles at corners and two-bar bundles elsewhere, effectively accommodates high reinforcement demand.
- The reinforcement detailing ensures adequate strength, constructability, and compliance with design standards.
- Conventional flat slab systems exhibit higher shear forces and bending moments near column locations.
- The introduction of panel drops significantly reduces shear demand by increasing effective slab depth. Column heads further enhance load dispersion and reduce flexural demand. The flat slab system incorporating both **panel drop and column head** demonstrates the best structural performance with minimum shear forces and bending moments.
- Finite element analysis effectively captures structural behavior under both static and moving load conditions. The structural responses obtained are consistent with established theoretical principles of structural engineering.
- Overall, the bridge structure is found to be **safe, serviceable, and structurally efficient** under the considered loading conditions.

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