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Structural Analysis and Optimization of Long-Span Curved PSC Girder Bridges Using STAAD Pro

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Abstract: *Prestressed Concrete (PSC) girder bridges are widely used in modern infrastructure due to their high strength, durability, and economic feasibility, especially for long-span and curved alignments. This study focuses on the structural behavior of PSC girders with 25m and 30m span lengths, analyzing key parameters such as displacements, shear forces, bending moments, support reactions, and prestress losses.*

A detailed computational analysis was performed using STAAD Pro, complemented by manual calculations to evaluate the effects of span length on structural efficiency and performance. The results indicate that longer spans experience significantly higher bending moments, shear forces, and vertical support reactions, necessitating enhanced reinforcement and optimized prestressing techniques. Prestress losses were found to be notably higher in the 30m span (278.3 - 294.9 t) compared to the 25m span (96.1 - 99.3 t), emphasizing the need for advanced prestress compensation methods to maintain long-term structural integrity.

The study also highlights the critical role of expansion joints, bearings, and lateral stability measures in accommodating increased longitudinal and transverse forces in longer spans. Optimized tendon layouts, high-strength concrete, and multi-stage prestressing techniques are recommended to enhance durability, minimize deflections, and improve load-bearing capacity.

This research provides valuable insights into the design and performance optimization of curved PSC girder bridges, offering practical recommendations for bridge engineers to improve safety, serviceability, and cost-effectiveness. Future studies should focus on dynamic loading, seismic effects, and innovative materials to further enhance the performance of PSC girder bridges.

Keywords: *Prestressed Concrete (PSC) Girder, Bending Moment, Shear Force, Prestress Losses, Structural Analysis, STAAD Pro, Bridge Design, Long-Span Bridges.*

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I. Introduction

Prestressed concrete (PSC) girder bridges have become a cornerstone in bridge engineering due to their excellent structural performance, economic feasibility, and adaptability to diverse conditions. Their ability to resist high tensile stresses and minimize cracking makes them a preferred choice for long-span structures. The application of PSC girders in curved bridge designs is particularly advantageous in urban environments and challenging terrains, where geometric constraints necessitate non-linear alignments.

Curved PSC girder bridges provide a seamless solution for accommodating sharp turns, intersecting roadways, and constrained rights-of-way. Despite these advantages, the introduction of curvature into PSC girder bridges brings about complex structural challenges. The curved geometry inherently results in a non-uniform distribution of forces, leading to combined bending and torsional stresses, shear lag effects, and differential deflections across the girder span. These effects are magnified with increasing span lengths and variations in curvature, making span-specific analysis a critical requirement.

Additionally, curved PSC girder bridges require careful consideration of prestressing forces to counteract the increased torsional demands and warping effects caused by curvature. The interplay between span length, curvature radius, and load conditions necessitates detailed modeling and analysis to ensure structural stability, serviceability, and economic viability.

This study aims to investigate the behavior of curved PSC girder bridges across different spans, focusing on critical parameters such as bending moments, torsional responses, deflections, and shear forces. By conducting a comprehensive parametric analysis, the research seeks to fill gaps in understanding the span-dependent performance of these structures, providing valuable insights for design optimization and the development of robust guidelines for curved PSC girder bridge construction.

There are several types of bridges, each with its own unique design and structural characteristics. These include:

a. Cantilever bridges: These bridges use cantilevered beams or structures projecting from fixed supports to create an overhang. They are commonly used for long-span bridges.

b. Arch bridges: These bridges have a curved design and rely on the load-bearing capability of the arch shape to distribute forces. They are known for their strength and aesthetic appeal.
c. Suspension bridges: Suspension bridges utilize a series of cables suspended from tall towers to support the bridge deck. The cables transfer the load to the towers and anchorages, allowing for longer spans.
d. Truss bridges: Truss bridges are constructed using interconnected triangular units (trusses) that provide strength and stability. They are often used for medium-span bridges.
e. Cable-stayed bridges: Cable-stayed bridges feature cables that extend directly from the towers to support the bridge deck. This design offers a balance between the arch and suspension bridge types.

PSC Girder Bridges are a preferred choice in modern bridge engineering due to their strength, efficiency, and cost-effectiveness. With advancements in precasting, post-tensioning, and segmental construction, they continue to play a crucial role in infrastructure development worldwide.

Flyovers play a crucial role in modern transportation infrastructure by improving traffic flow and reducing congestion in urban and highway networks. The design of flyover superstructures, particularly the prestressed concrete (PSC) girders, is a critical aspect that influences the overall structural efficiency, durability, and cost-effectiveness of the bridge. One of the key challenges in PSC girder design is accommodating different span lengths and curvature radii, which significantly affect the structural behavior, load distribution, and stress variations within the girders.

This study focuses on the analysis of PSC girders for a flyover with span lengths of 25 meters and 30 meters, considering different bridge curvature radii of 100 meters and 500 meters, respectively. The influence of these varying curvature conditions on the structural performance of PSC girders is examined through detailed analytical modeling. The analysis aims to evaluate key parameters such as bending moments, shear forces, deflections, and prestressing losses under different curvature conditions.

By comparing the structural responses of PSC girders under different radius of curvature conditions, this study provides valuable insights into the optimal design considerations for curved flyover structures. The findings will contribute to improved design methodologies, ensuring enhanced structural stability, safety, and longevity of flyover bridges.

II. Objective

The primary objective of this study is to analyze and evaluate the performance of Prestressed Concrete (PSC) girder bridges with varying span lengths, particularly focusing on curved bridge designs. This analysis aims to:

1. To understand how the curvature and span length influence the stress distribution, bending moments, shear forces, and deflections of PSC girder bridges.
2. To assess the impact of different span lengths on the design parameters such as the number of girders, prestressing forces, and overall structural efficiency.
3. To compare the performance of curved PSC girder bridges with different span lengths under static and dynamic loads, including vehicular loads and seismic forces.
4. To propose optimized solutions for curved PSC girder bridge designs in terms of material usage, span length, and cost-effectiveness without compromising safety or performance.
5. To offer practical design recommendations for engineers involved in the design and construction of curved PSC girder bridges, ensuring safe, cost-efficient, and durable bridge solutions.

III. Methodology

The superstructure of the curved PSC (Prestressed Concrete) girder bridge is designed to withstand all loads encountered during both construction and service conditions. The design approach involves a comprehensive understanding of the load distribution and the interaction between different structural components. The methodology is outlined as follows:

1. Load Consideration:

- Dead Load: The dead load, which includes the self-weight of the girder and the deck slab, is resisted by the girder section. The weight of the girder itself is calculated to ensure it does not exceed permissible limits.
- SIDL (Standard Immovable Dead Load) and Live Load: These loads are resisted by the composite action of the deck slab and the PSC I-beam. The deck slab and girder system work together to distribute and resist these loads effectively.

2. Grillage Analysis:

o The Grillage Analysis for the superstructure is performed using STAAD Pro to calculate the bending moments and shear forces resulting from the SIDL and live loads. This tool provides a detailed simulation of how the bridge will behave under load and helps in designing for the internal stresses.

o The dead load due to the self-weight and the deck slab is calculated manually using an Excel sheet for simplicity and quick estimation. These loads are applied separately to understand their contribution to overall stress.

3. Loss Calculation:

o Losses in prestressing due to creep, shrinkage, and relaxation are calculated in stages, accounting for different phases of prestress transfer during construction and over the life of the bridge.

4. Ultimate Load Checks:

o Bending and shear checks are performed in accordance with IRC 112 (Indian Roads Congress guidelines), which set the standards for design checks for concrete structures. The design follows the ultimate limit state (ULS) to ensure the safety and stability of the bridge under extreme load conditions.

5. Cable Profile:

o The cable profile is kept the same for both the inner and outer girder. This simplifies the construction process and ensures uniform distribution of prestressing forces, making the design easier to execute.

6. Critical Girder Design:

o The design of the most critical girder (the one under maximum stress) is presented in the design note. This includes a detailed analysis of the maximum bending and shear forces experienced by the girder.

7. Transverse Analysis of Deck Slab:

o The deck slab is analyzed using STAAD Pro for its transverse behavior, considering the unit width of the deck slab spanning over the PSC girders. This helps in determining the distribution of forces across the slab and its capacity to resist applied loads.

o The live load is applied after considering dispersion perpendicular to the span using the effective width method to account for the load distribution across the deck slab.

8. Serviceability Limit State (SLS) and Ultimate Limit State (ULS) Combinations:

o The deck slab is designed for both SLS (Serviceability Limit State) and ULS (Ultimate Limit State) combinations. SLS ensures that the deflections, cracks, and stresses are within acceptable limits for comfort and safety during normal service, while ULS checks the strength of the bridge under extreme conditions.

This methodology ensures that all critical aspects of the design, including load distribution, material properties, and safety checks, are thoroughly evaluated to achieve a safe and durable curved PSC girder bridge.

Flyovers are essential components of modern transportation infrastructure, enabling efficient traffic movement and reducing congestion. The structural design of flyover superstructures, particularly pre-stressed concrete (PSC) I-girders, plays a crucial role in ensuring stability, durability, and cost-effectiveness. Curved flyovers introduce additional complexities in design due to the influence of curvature on load distribution, stress variations, and overall structural behavior.

This study focuses on the design and analysis of PSC I-girders with 25m and 30m span lengths, considering different curvature radii of 100m and 500m, respectively. The impact of curvature on bending moments, shear forces, deflections, and prestressing losses is analyzed using advanced computational tools such as STAAD Pro and verified through manual calculations. The objective is to optimize girder design while ensuring compliance with IRC 112 guidelines for ultimate limit state (ULS) and serviceability limit state (SLS) conditions.

Figure 01. Plan of the curve Prestressed Bridge

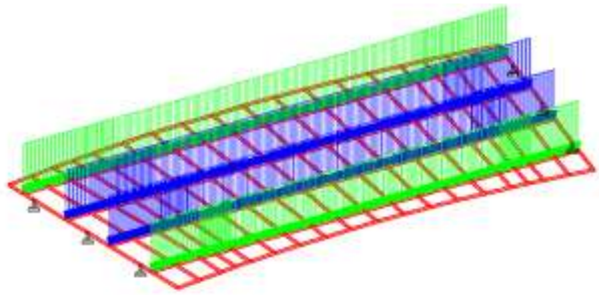

Figure 02. Vehicle load on Curve Prestressed Bridge

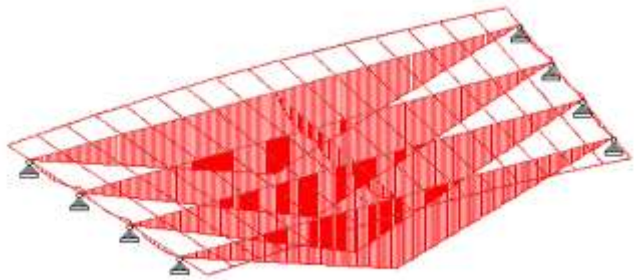

Figure 03. Shear force on Curve Prestressed Bridge

IV. Results and Discussion

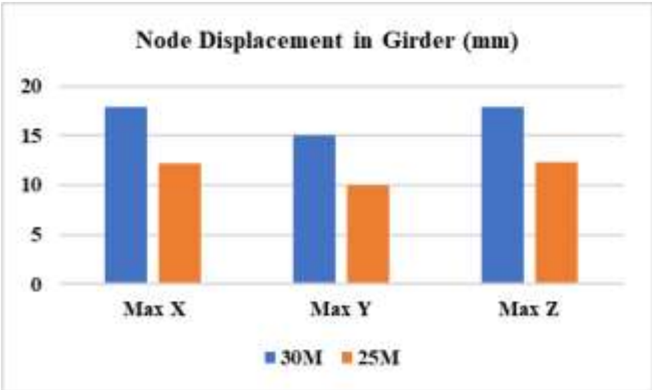

Figure. 4 Node Displacement at Different length Span

Figure. 5 Shear force on Different Span

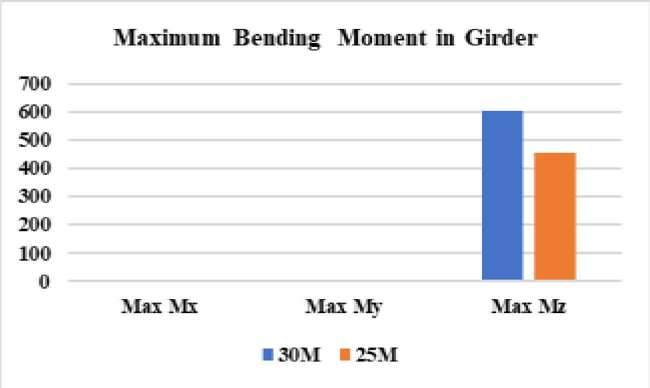

Figure. 5 Bending Moment at Different Span

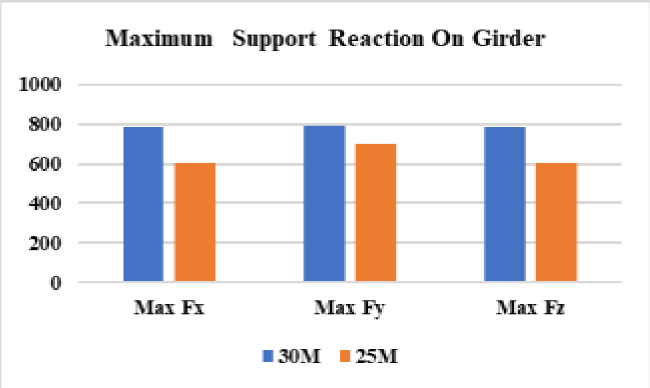

Figure. 6 Maximum Support Reaction for Different Span

Table 1 Combined Total (Short-Term + Long-Term Losses)

Stage	Total Loss (t)	% Loss in Terms of Jacking Force
1st Stage (25m Span)	46.8 - 51.2	18.8% - 20.6%
1st Stage (30m Span)	93.8 - 108.2	19.4% - 22.4%
2nd Stage (25m Span)	48.1 - 49.3	11.7% - 12.0%
2nd Stage (30m Span)	186.8 - 184.5	35.4% - 34.9%
Overall Total (25m Span)	96.1 - 99.3	14.0% - 15.1%
Overall Total (30m Span)	278.3 - 294.9	27.5% - 29.2%

V. Conclusions

This study has provided a comprehensive analysis of the structural behavior of Prestressed Concrete (PSC) girders with varying span lengths (25m and 30m), focusing on key parameters such as displacements, shear forces, bending moments, support reactions, and prestress losses. The findings highlight the significant impact of span length on the load distribution, prestress efficiency, and overall performance of curved PSC girder bridges.

1. Displacement Behavior

- The 30m span girder exhibited significantly higher displacements compared to the 25m span.
- The maximum displacement in the X and Z directions was 17.931mm for the 30m span, whereas the 25m span showed lower values of 12.2mm and 12.3mm, respectively.
- Vertical displacement (Y-axis) also increased from 10mm (25m) to 15mm (30m), indicating greater flexibility in longer spans.
- These results emphasize the need for increased prestressing forces and optimized tendon layouts to control deflections in longer spans.

2. Shear Force Analysis

- The maximum vertical shear force (Fy) was significantly higher for the 30m span (751.237 kN) compared to the 25m span (617.352 kN).
- The longitudinal (Fx) and transverse shear (Fz) components remained relatively low, suggesting that shear stress due to torsion and lateral loading is minimal.
- Adequate shear reinforcement near supports is crucial to prevent shear failure in longer spans with higher vertical shear demands.

3. Bending Moment Distribution

- Major axis bending moment (Mz) was 605.279 kN·m in the 30m span, compared to 454.956 kN·m in the 25m span, reflecting a significant increase in flexural demand due to increased span length.
- Torsional moment (Mx) was slightly lower in the 30m span (6.206 kN·m) than in the 25m span (7.158 kN·m), indicating torsion is less of a concern for longer spans but could increase for curved alignments.
- The weak axis bending moment (My) remained low for both spans, suggesting that lateral stiffness is sufficient under normal loading conditions.

4. Support Reactions and Load Transfer

- Vertical reaction (Fy) increased from 698.52 kN (25m) to 793.993 kN (30m), emphasizing the need for stronger foundations and well-designed bearings to withstand higher loads.
- Longitudinal reaction (Fx) was significantly higher in the 30m span (781.567 kN) than in the 25m span (605.553 kN), requiring proper expansion joints and sliding bearings to accommodate thermal movements.
- Transverse reaction (Fz) also increased in the 30m span, necessitating additional lateral stability measures such as bracing systems and diaphragms.

5. Prestress Losses and Structural Durability

- Total prestress losses were significantly higher in the 30m span (278.3 - 294.9 t) compared to the 25m span (96.1 - 99.3 t), requiring higher initial prestressing forces to compensate for long-term losses.
- First-stage prestress losses were dominated by friction and elastic shortening, while second-stage losses were primarily due to creep, shrinkage, and steel relaxation.
- The percentage loss in jacking force was significantly greater in the 30m span (27.5% - 29.2%) compared to the 25m span (14.0% - 15.1%), confirming the need for enhanced loss mitigation strategies in longer spans.
- Optimized tendon layouts, high-strength concrete, and multi-stage prestressing methods should be employed to minimize long-term losses and maintain structural integrity.

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