

Comparative Structural Behavior and Serviceability Assessment of Post-Tensioned Single-Cell Box Girder and Post-Tensioned Precast Composite I-Girder Railway Bridges Under Arema Loading

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Abstract

Prestressed concrete bridges are widely used in railway projects because it has sufficient strength, durability and serviceability when subjected to heavy rail loading. At present, a comparison was made between two prestressed concrete railway bridge superstructures which include a Post-Tensioned Single-Cell Box Girder and a Post-Tensioned Precast Composite I-Girder. A single track and identical 40 m span was considered for both bridge alternatives. This was then modeled and analyzed in 3-D with the help of MIDAS Civil. The Analysis were carried out in compliance with the AREMA loading requirements, Construction Stage Analysis (CSA) was added to consider the effects of prestressing, long-term factors affecting: operations, construction sequence, creep, shrinkage, etc. The behavior of both bridge systems was compared w.r.t stress requirements, stress development during construction, deflection, material properties, performance to service requirements and consumption of materials. The study indicated that the Precast Composite I-Girder had to use more prestressing steel than the cast in situ post tensioned box girder. Requires more camber in the process too. The Single-Cell Box Girder, however, attained significantly the same structural and serviceability characteristics with fewer use of tendons and materials. The design requirements were met with both options, From the results obtained, it is recommended that the Single-Cell post tensioned Box Girder is more efficient when compared to Precast post tensioned I-Girder & economical.

Keywords: Railway Bridge, Post-Tensioning, Single-Cell Box Girder, Composite I-Girder, Construction Stage Analysis, AREMA Loading, Serviceability.

1. Introduction

Railway bridges are an essential part of the rail transportation network, providing safe and movement of passengers and goods continuously. With the increasing demand for higher train speeds, heavier axle loads and greater traffic volumes, bridge structures are required to operate effectively over the life of their

service. Along with strength, modern railway bridges must satisfy serviceability requirements such as controlled deflections, crack resistance, riding comfort & durability. Prestressed concrete is now a favored construction material as it effectively reduces tensile stress, increases structural performance and improves long term durability. For medium-spans Post-tensioned concrete superstructure is commonly used in railway bridges because of its advantages to carry large loads along with economical construction. Two alternatives were considered, one is Post-Tensioned single-cell Box Girder and the other one is Post-Tensioned precast composite I-girder. Although both systems are capable to meet design requirements for railway bridges, but their behavior varies due to variations in the cross-sectional configuration, load distribution mechanism, construction methodology and prestressing arrangement. The Single-Cell Box Girder is a closed section which provides high torsional rigidity and good load sharing that runs throughout the structure. The characteristics make it suitable for railway bridges, where stiffness and deformation control are important considerations. By contrast, the Precast Composite I-Girder system is made up of composite materials, precast girders with a cast-in-place deck slab, resulting in faster erection, improved quality control for fabrication & reduced activities at the project site. Hence, each system has its own advantages from structural & construction point of view. Parameters like prestressing demand, stress distribution, deformation behavior and material consumption are important in determining the overall efficiency of bridge superstructure. The comparative evaluation of these factors may assist designers to make the right choice in deciding for a particular type of superstructure. In this study, 40m identical span, with identical loadings and single track was taken to produce a comparison of the performance between the both types of PSC systems. Three-dimensional analytical models were developed using MIDAS Civil and Construction Stage Analysis (CSA) was performed to simulate the behavior in every stages. Loadings & load combination parameters were considered as per the AREMA code. The comparison is based on prestressing requirements, behavior during construction stages & material usage. From the above parameters, the study intends to find out which is more efficient PSC Superstructure under same loading & span configuration.

2. Literature Review

Ye et al. (2020) (1) investigated the prestress losses in prestressed railway bridge girders with the help of fiber optic monitoring technologies. Their research uncovered that the change in prestressing force over time can be a major performance factor in bridges. The authors noticed the importance of making reliable predictions of prestress losses to guarantee the satisfactory serviceability throughout the bridge life.

Phani Kumar Ch. et al. (2016) (2) have investigated the behavior of post-tensioned box girder bridge under design loads. The study revealed that prestressing was successful in reducing the tensile stresses and in controlling the deflections. Based on the analysis, the authors concluded that it is structurally reliable to use box girder bridges for medium span bridges.

Sirisonthi et al. (2021) (3) carried out an experimental investigation on a full-scale precast post-tensioned girder system. The bridge was satisfactory to the service loading, cracks were kept to a minimum and deformation was controlled. They found that precast prestressed systems are viable for transportation structures.

Guo et al. (2016) (4) studied the long-term Deflection response of prestressed concrete box girder bridges for a long period. The study focused on creep and shrinkage effects and it was found that the proper prestressing can be a significant factor in reducing excessive deformations in service life.

Tang et al. (2023) (5) studied the structural performance of prestressed composite I-girder bridges. The study found that composite action between the girders and deck slab resulted in a greater level of structural stiffness and enhanced resistance to cracking. This resulted in an overall improvement of serviceability performance of the bridge system.

Kulkarni et al. (2011) (6) compared the response of box girder bridges with that of I-girder bridge structures to loading. They discovered significant variations in stress distribution and load transfer mechanism and in structural response. The study highlighted that the selection of the girder configuration should be dependent on the requirements of the project and the performance expected.

Ramanjaneyulu et al. (2006) (7) discussed about the construction stage analysis in the design of prestressed concrete bridges. The authors pointed out that the order of the construction and prestressing process will directly affect the stress development process of the bridge during the construction. They pointed out that staged construction effects should be taken into account in analysis and design.

Sullivan et al. (2008) (8) studied composite bridge systems consisting of prestressed girders and deck panels. The research showed that the appropriate combination of structural elements can result in improved serviceability response and long-term performance.

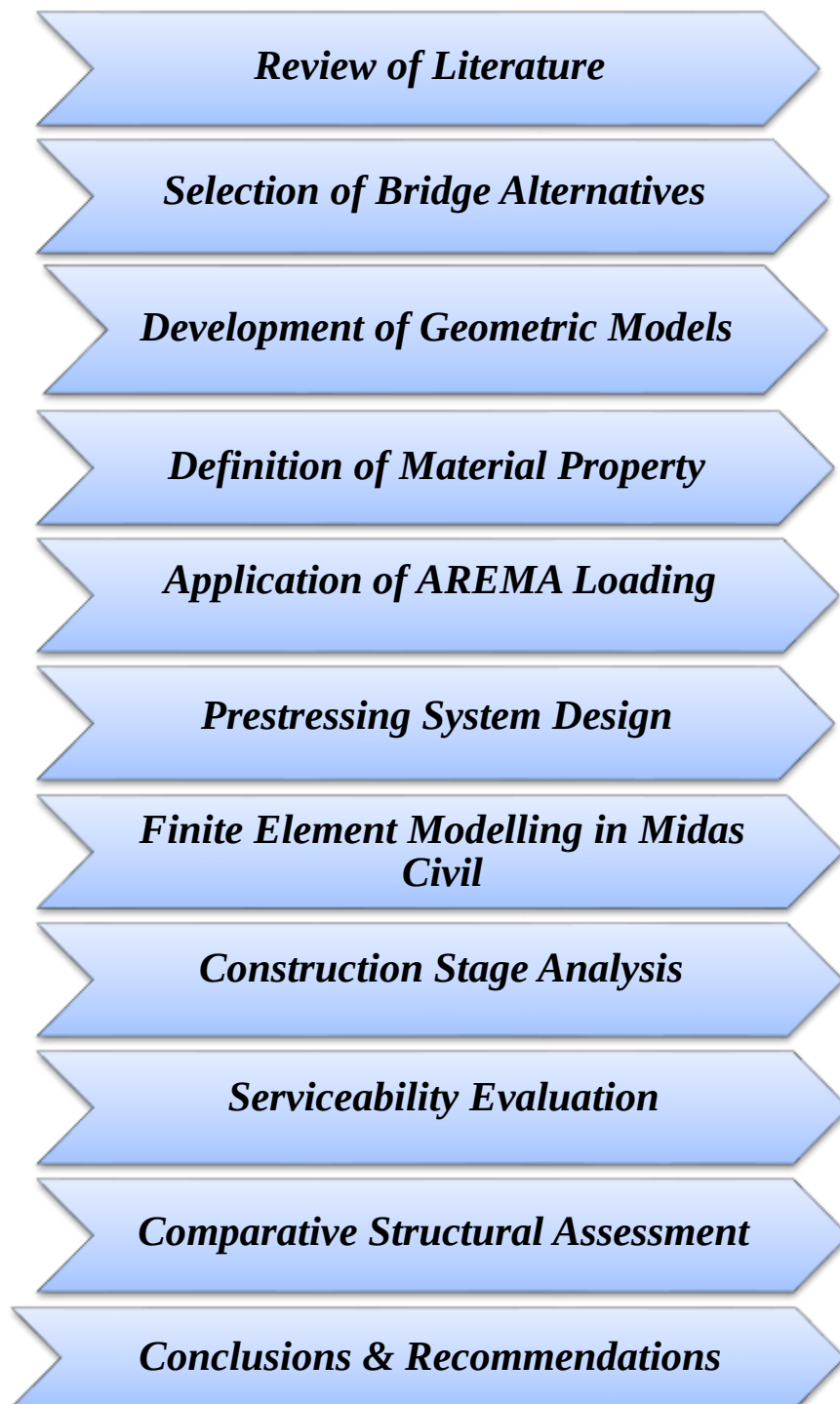
Leiva et al. (2023) (9) assessed different bridge superstructure alternatives using a life-cycle approach. They found that prestressed concrete bridge systems offer a balance between structural efficiency and durability and material consumption, in comparison with other systems.

3. Methodology

A comparative analytical study was undertaken to examine the behavior of two prestressed concrete railway bridge superstructures, namely a Post-Tensioned Single-Cell Box Girder Bridge and a Post-Tensioned Precast Composite I-Girder Bridge. Both bridge alternatives were considered for a 40 m single-track railway span. The study was designed to assess the effect of the structural configuration on the performance of the bridge by keeping the same span and loading condition. The first part of the work consisted of choosing the alternatives for the bridge and creating their geometric models. The span length, deck width and overall depth were the same for both systems to allow for a meaningful comparison. The material properties for concrete, prestressing strands and reinforcing steel were assigned during modelling, which are commonly used in railway bridge construction. The loading conditions were specified as per AREMA recommendations for evaluating the structural response. The effects of dead load, superimposed load, railway live load, impact load, longitudinal load, temperature change, wind load, and derailment load were taken into account in the analysis. To ensure consistency in the comparison, the same loading criteria was applied to both the bridge systems. A series of three-dimensional finite element models were then created using MIDAS Civil. The bridge geometry, support arrangements, tendon profiles and load cases were defined in the modelling process. Because the distribution of stress and the deformation characteristics are greatly influenced by the prestressing, particular importance was placed on the choice of tendon layouts. Several iterations were performed until the stress limits and design requirements were met. As the behavior of prestressed bridges is influenced by the construction sequence, Construction Stage Analysis (CSA) was included in the study. Prestressing operations, permanent loads, casting of the decks, activation of composite action and long-term effects like creep, shrinkage and prestress losses were simulated in the actual construction process. This helped in obtaining a realistic representation of stress development and deformation over the service life of the bridge. The performance of both bridges were then compared and analyzed based on some performance parameters. These parameters included

prestressing demand, stresses during construction stages, camber development, serviceability performance, and material consumption. The comparison provided a clear understanding of the behavior of each bridge system and assisted in identifying the more efficient alternative for the selected railway bridge application.

Flowchart for Comparative Structural Evaluation



4. Bridge Description, Numerical Modelling & Construction Stage Analysis

To evaluate the performance of different railway bridge superstructures, a 40 m single-track railway bridge was selected as the study case. Two commonly adopted prestressed concrete systems were considered: a Post-Tensioned Single-Cell Box Girder and a Post-Tensioned Precast Composite I-Girder. Both alternatives were developed with the same span, width, and overall depth so that any variation in response could be attributed to the structural system itself rather than differences in geometry.

Parameter	Box Girder	Composite I-Girder
Span Length (m)	40	40
Deck Width (m)	8.8	8.8
Overall Depth (m)	3.0	3.0
Cross-sectional Area (m ²)	7.056	7.328
Moment of Inertia (m ⁴)	8.271	7.400

Table-1: -presents the key geometric properties adopted for the study.

Bridge models were created in MIDAS Civil to simulate their behavior under railway loading. The box girder configuration was represented using a single line beam modelling approach, while the composite bridge was modelled by using grillage where the longitudinal elements represents the girders which are basically the load carrying elements & the transverse elements acts as dummy elements just for the load distribution from Deck to girder. Material and sectional properties were assigned based on typical railway bridge construction practices. M45 grade concrete was used for the prestressed structural members, whereas M35 grade concrete was adopted for the deck slab. Prestressing was provided using low-relaxation 15.2 mm diameter strands with an ultimate tensile strength of 1860 MPa. Both bridge alternatives were evaluated under the same loading environment. In addition to their self-weight, the models included ballast loads, rail loads, impact effects, temperature variations, longitudinal forces, wind actions, and derailment loading. Cooper E-80 loading was considered as the governing railway loading model to represent heavy freight traffic conditions. Construction Stage Analysis (CSA) was also introduced to the study because the loads on a bridge do not only affect its behavior, but the sequence of the construction activities also affects its behavior. In the box girder bridge, girder activation and prestressing, application of permanent loads, and the effects of long-term service were taken into account. For the composite bridge, the simulation of the following stages was performed: girder erection, stressing of tendons, casting of the deck, development of composite action, and application of permanent loads. Considering the long-term effects such as creep, shrinkage, and losses of prestress, a realistic understanding of the stresses developed and deformations occurred over the service life of the bridge was obtained.

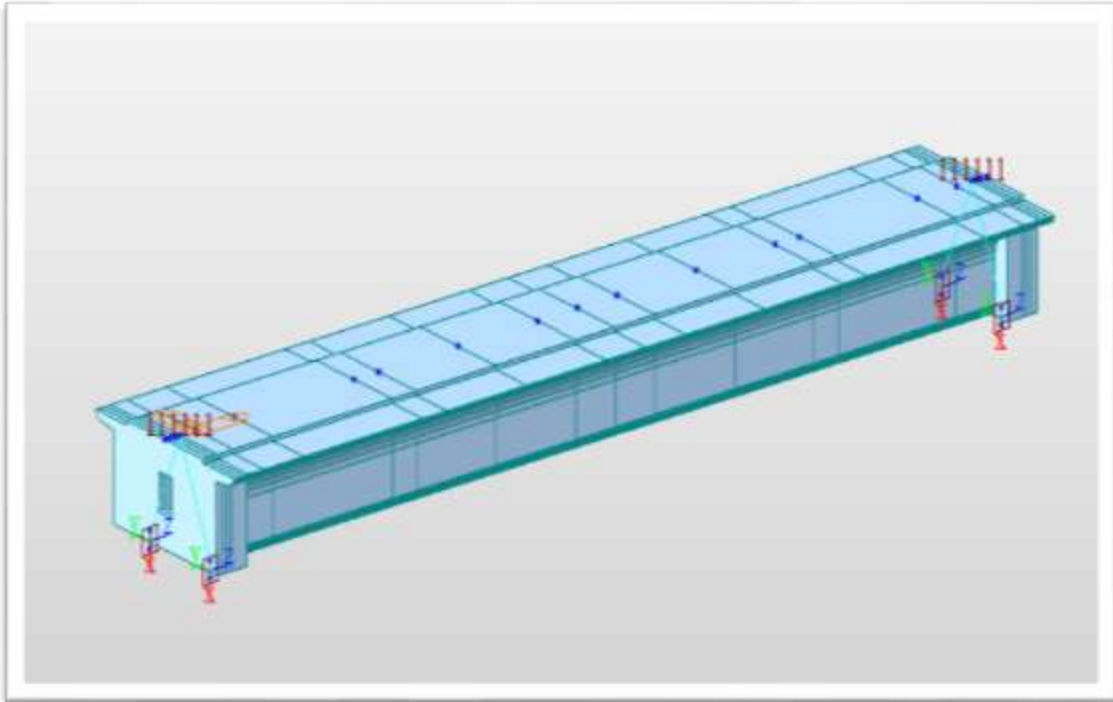


FIG: - ISOMETRIC VIEW OF CAST IN SITU POST TENSIONED BOX-GIRDER

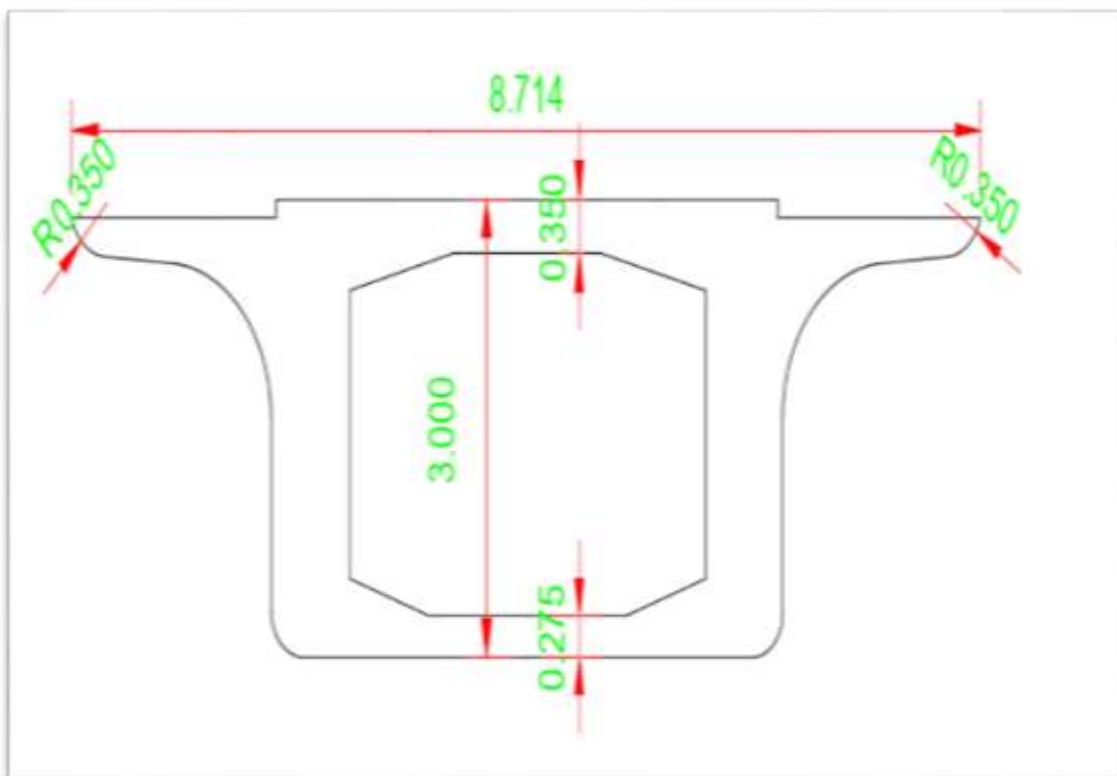


FIG:- TYP BOX GIRDER CROSS-SECTION AT MID SPAN

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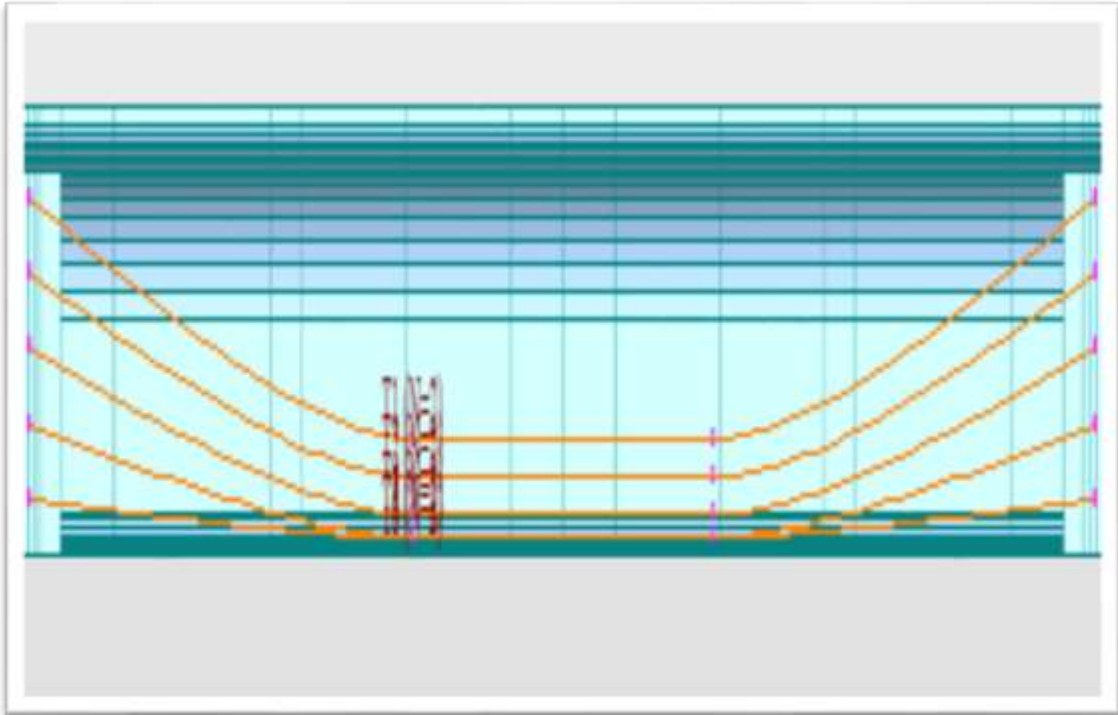


FIG2:- TYP BOX GIRDER TENDON LAYOUT

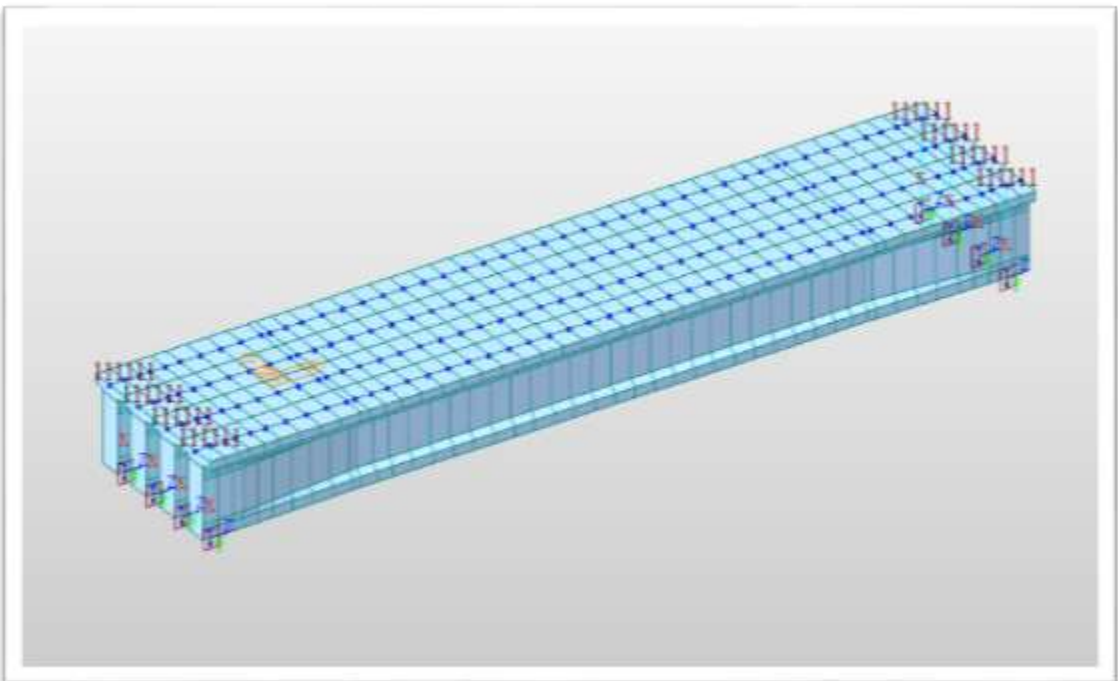


FIG3: - ISOMETRIC VIEW OF PRE-CAST POST TENSIONED COMPOSITE I-GIRDER

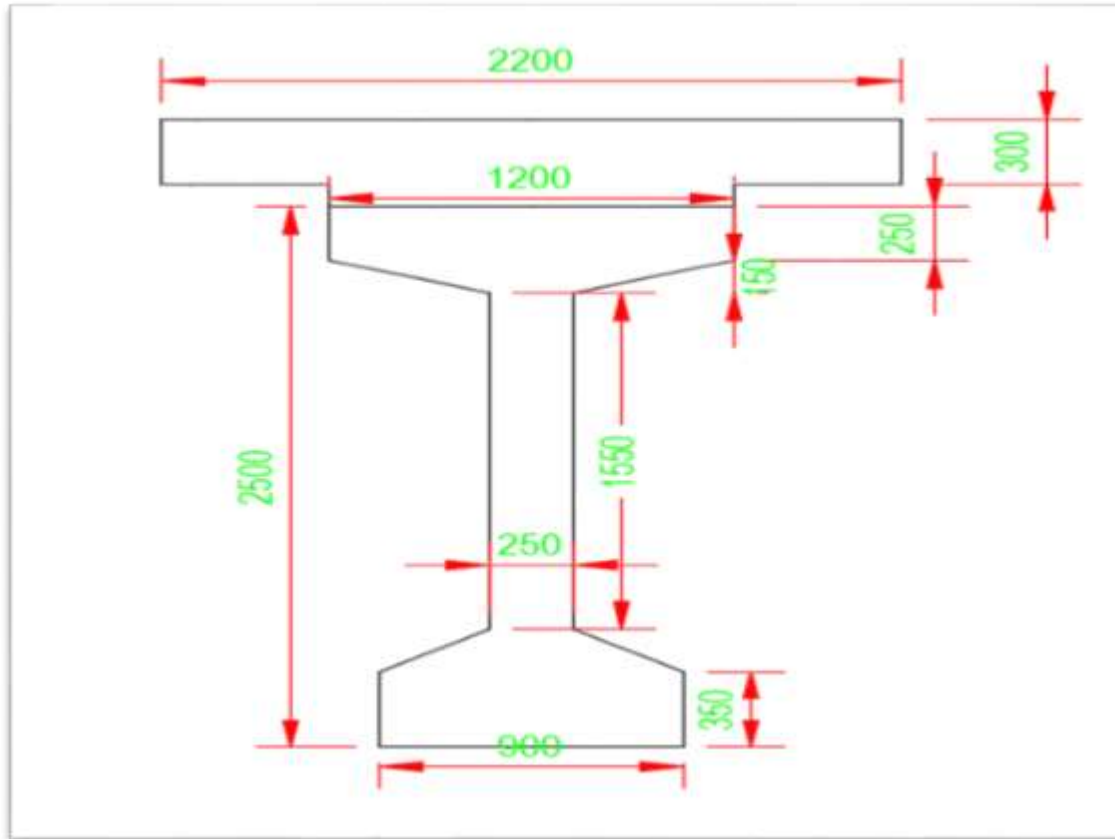


FIG4: - TYP COMPOSITE I-GIRDER CROSS-SECTION AT MID SPAN

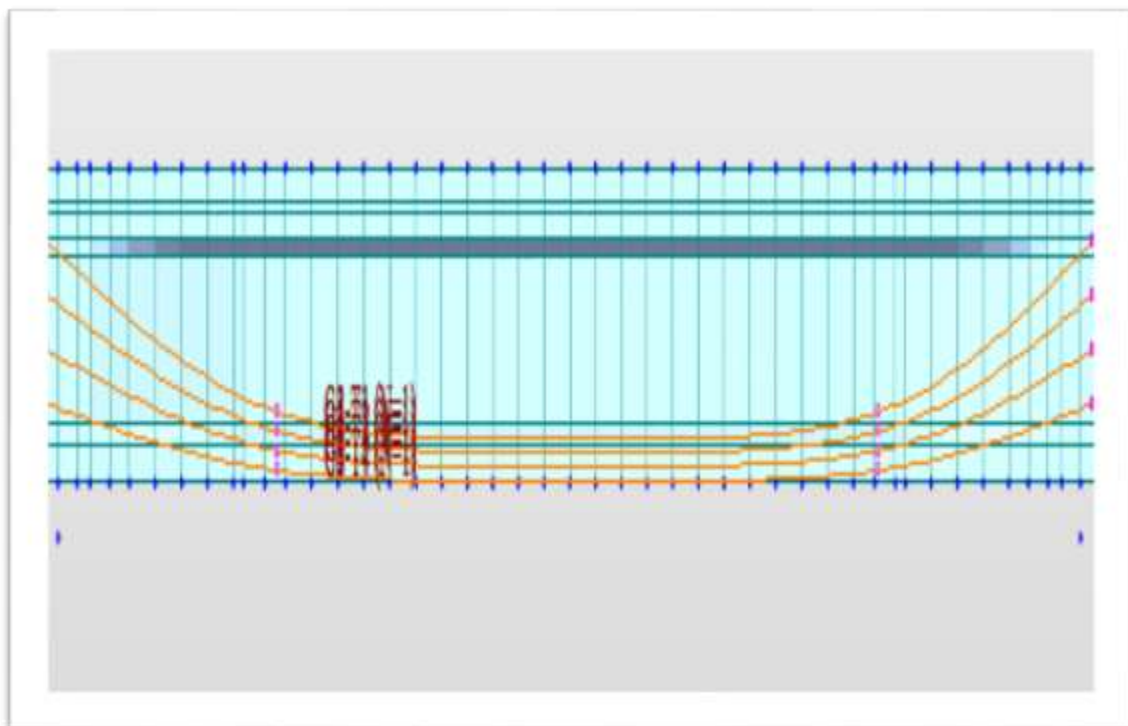


FIG5: - TYP COMPOSITE I-GIRDER TENDON LAYOUT

5. Results & Discussion

Prestressing Requirements

There was a clear difference in the prestressing needs of the two bridge systems. The Post-tensioned Precast Composite I-Girder had a total of 16 tendons, The Post-Tensioned Single-Cell Box Girder met the design requirements with 14 number of tendons. In a similar manner, a rise in the total jacking force was seen. The amount of prestressing steel needed in the Composite I-Girder Bridge uses a higher level of prestressing to obtain the desired Structural and serviceability performance for railway loading conditions.

Table-2: -Comparison of Prestressing Requirements

Parameter	Box Girder Bridge	Composite I-Girder Bridge
No. of 22C15 Tendons	6	8
No. of 27C15 Tendons	8	8
Total Number of Tendons	14	16
Total Jacking Force (kN)	67,964.4	76,557.6
Prestressing Steel Quantity	348	392
Tendon Weight (kN)	154.0	173.2

In the Composite I-Girder Bridge, the higher prestressing demand can be attributed to its Structural arrangement and load carrying mechanism. Since the bridge consists of individual girders combination with a composite deck, additional prestressing is necessary to effectively manage stresses and deformations. The box girder section, on the other hand, offers more continuous and stiffer structure, which enables more efficient distribution of stresses throughout the section. Therefore, the necessary degree of prestressing is relatively lower. The results obtained are compared to the results of the Composite I-Girder Bridge. The Box Girder Bridge required about 12.6% less jacking force than the composite I-Girder. Likewise, this was also due to the higher amount of prestressing steel in the composite system. These observations indicate that the composite alternative is more dependent on prestressing. To meet design and serviceability requirements. Although there are differences, both The systems were satisfactory and met the design requirements. However, the Box Girder Bridge had a similar level of structural performance with lesser amount of prestressing steel. From the viewpoint of prestressing The Box Girder Bridge hence looks to be the more economical and efficient of the two. Structurally efficient solution for the chosen railway bridge span.

Construction Stage Response

Prestressed concrete bridges are not only influenced by service loads, but also by the construction activities are carried. Hence, Construction Stage Analysis (CSA) was carried out to test the stresses and deformations created at various stages, from initial construction to the final service condition.

Parameter	Box Girder Bridge	Composite I-Girder Bridge
Maximum Bottom Fiber Stress (MPa)	20.60	29.05
Maximum Upward Camber (mm)	31.99	70.09
Service Stage Top Fiber Stress (MPa)	6.10	3.28
Service Stage Bottom Fiber Stress (MPa)	9.60	12.08

Service Stage Upward Camber (mm)	28.73	37.63
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Table 3:- Comparison of Construction Stage Response

The results show that both bridge options were within allowable stress levels. During construction and in service. The Composite I-Girder Bridge, however, experienced greater bottom fiber compressive stresses and much greater upward camber, mainly because of its higher prestressing requirement. The Box Girder Bridge, on the other hand, exhibited less stress and less deformations throughout. construction stages. Both bridge systems met the serviceability requirements but the Box Girder Bridge performed at a similar level at a reduced prestressing demand. This suggests that the box girder configuration offers a more efficient structural response under Construct to acceptable behavior in service.

Serviceability Evaluation

Serviceability plays a critical role in railway bridge structures, as excessive stresses or deformations can compromise the structure's long-term performance and durability over service life. To evaluate this behavior, the serviceability responses of both bridge alternatives under the governing loading condition were examined and are presented in Table 4.

Table 4:- Comparison of Serviceability Response

Parameter	Box Girder Bridge	Composite I-Girder Bridge
Top Fibre Stress (MPa)	6.02	0.87
Bottom Fibre Stress (MPa)	0.81	3.20
Maximum Upward Camber (mm)	33.75	44.32

Both bridge systems satisfy the prescribed serviceability requirements. The Composite I-Girder Bridge exhibited lower compressive stress at the top fiber, whereas higher compression was observed at the bottom fiber due to the greater prestressing force adopted in the design. The Box Girder Bridge, on the other hand, showed a more uniform stress distribution and developed lower camber. Overall, both alternatives performed satisfactorily under service conditions, although the Box Girder Bridge achieved comparable performance with a lower prestressing demand.

Material Consumption Comparison

Material usage is a useful indicator for evaluating the efficiency of bridge superstructures, particularly when different alternatives are designed for the same span and loading conditions. The concrete and prestressing steel quantities required for both bridge systems are presented in Table 5

Parameter	Box Girder Bridge	Composite I-Girder Bridge
Concrete Quantity (m ³)	343.42	374.90
Prestressing Steel Quantity (t)	15.67	17.66

Table 5:- Material Consumption Comparison

Composite I-Girder Bridge required a larger quantity of both concrete and prestressing steel compared to the Box Girder Bridge. The higher material requirement of the Composite I-Girder Bridge is mainly due

to the presence of multiple girders, the deck slab, and the increased prestressing needed to satisfy design requirements. In comparison, the Box Girder Bridge performed equally in terms of structural performance, but using less concrete & prestressing steel. Among both the bridges that were considered for the study, we can safely say that Post Tensioned Box girder uses the materials more efficiently in the system, without compromising the required serviceability.

6. Conclusions

This study compared the behavior of a single-cell box girder and composite precast post tensioned I-girder for a 40 m span, single-track railway bridge designed to AREMA loading. Both bridge systems satisfied the strength and serviceability requirements of the design under the investigated loading condition.

The Composite I-Girder Bridge required a higher prestressing force to reach the desired structure performance, which was achieved by providing 16 tendons. This was also manifested during the construction stage through the greater upward camber and higher bottom fiber compressive stresses.

The two alternative bridge structures were found to exhibit satisfactory serviceability performance under the governing loading condition. However, the composite I-girder bridge required a higher prestressing force to achieve this level of performance associated with greater residual deformations. By contrast, the Box Girder Bridge showed acceptable stress and deformation values at a relatively lower level of prestressing.

A similar observation was made in terms of materials consumption as the Box Girder Bridge used 343.42 m³ of concrete and 15.67 t of prestressing steel as against 374.90 m³ of concrete and 17.66 t of prestressing steel required by the Composite I-Girder Bridge.

Overall, it may be concluded that the Post-Tensioned Single Cell Box Girder Bridge makes more efficient use of prestressing and construction materials while exhibiting satisfactory serviceability performance. As such, it was the more efficient choice of superstructure for the span and loading conditions considered in this study.

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