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Nonlinear Time-Dependent Analysis of Segmentally Constructed Structures Using CSI Bridge

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Abstract

The study discusses the significance of nonlinear time-dependent analysis in evaluating segmentally constructed bridges, crucial for ensuring their safety and long-term performance. Prestressed concrete structures face challenges due to long-term effects like creep and steel relaxation, leading to inaccuracies in current bridge standards. Addressing this, a master's thesis aims to develop a comprehensive model within a Finite Element Analysis (FEA) program to accurately predict these effects, providing a reliable tool for future research. The thesis investigates existing creep models and their practical implementation, evaluating methods within the FEA program for their efficacy. A study involves analyzing bridge models using the CSI Bridge application, incorporating time hardening, strain hardening, and viscoelastic models. These models are assessed against prevailing bridge codes to determine their effectiveness in capturing the structure's behavior over time. The research seeks to enhance understanding and prediction capabilities in segmentally constructed prestressed concrete bridges, essential for improving design standards and ensuring infrastructure integrity.

Keywords: Finite element analysis, CSI Bridge, Pre-Tensioning, Segmental Construction, Time-Dependent Analysis, Construction Stages, Analysis, investigation.

INTRODUCTION

In the realm of modern civil engineering, the construction of segmental bridges stands as a testament to innovative engineering practices, facilitating the development of complex infrastructure with both efficiency and precision. Yet, as these monumental structures rise incrementally, they are subject to an intricate interplay of time-dependent factors and nonlinear behaviours that challenge conventional engineering wisdom. In the pursuit of sustainable, resilient, and cost-effective infrastructure, the nonlinear time-dependent analysis of segmental constructed bridges emerges as a critical frontier, where the integration of cutting-edge computational tools and advanced structural modelling techniques seeks to unravel the complexities inherent in these engineering marvels. This research work embarks on a journey into this intricate domain, aiming to shed light on the nuanced interactions of material properties, construction sequences, environmental conditions, and dynamic loading effects. Through an in-depth exploration of these multifaceted aspects, we endeavour to equip engineers and researchers with the insights and methodologies necessary to ensure the longevity, safety, and performance of segmental constructed bridges in the face of ever-evolving challenges.

This study's goal was to better our understanding of prestressed modular segmental bridges' time-dependent behaviour. By accurately modelling the Bridge and comparing for creep, shrinkage loads, the study aimed to identify the most suitable approach for predicting structural displacements and capturing the real-life behaviour of such bridges. This knowledge can then be applied to optimize future bridge designs and inform maintenance practices, ensuring the long-term durability and performance of segmental box girder bridges.

FE modelling results are using in the different creep models were compared to each other, revealing notable differences, particularly in terms of long-term deformations. This study aimed to evaluate the advantages and limitations of prestressed box girders when using the conventional theory of bending when creep occurs, specifically in the context of segmental bridges that undergo multiple construction stages. FE models utilizing beam elements were employed to analyse the impact of unbalanced static schemes in the end span cantilevers and the central span. The lateral ends of the cantilevers and the central mid-span were found to have considerable long-term deflections as a result of these unbalanced systems. To learn more about this phenomena, two independent creep models with distinct long-term trends in their creep functions were combined in FE analyses.

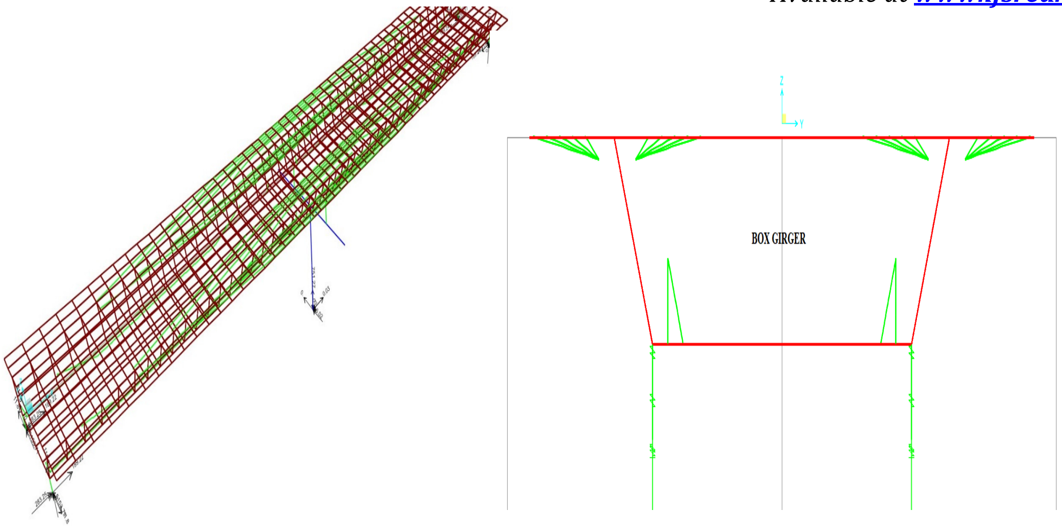


Figure 1: Isometric Representation of box girder bridges in CSI bridge software.

On the context of segmental bridges with several construction stages, our work clarified the impacts of creep on prestressed box girders. By utilizing FE models and implementing the different creep models, the study aimed to investigate the factors contributing to high long-term deflections. The results provided valuable insights into the behaviour of such bridges and the significance of considering creep effects when evaluating their long-term performance. The first section provides a comprehensive review of the balanced cantilever construction method, considering its applicability to both cast-in-place and precast bridges. It explores the fundamental principles and techniques involved in this construction method.

I. METHODOLOGY

In contemporary civil engineering, the demand for robust and efficient structural analysis methodologies has intensified, driven by the ever-evolving complexities of bridge construction projects. In response to this demand, advanced computational software tools have emerged as indispensable assets, facilitating intricate analyses and precise design optimizations. Within this framework, the utilization of CSI Bridge software stands out as a pivotal methodology for evaluating the behavior and performance of segmental constructed bridges. This methodology leverages sophisticated algorithms and modeling techniques to simulate real-world conditions, providing engineers with invaluable insights for ensuring structural integrity, durability, and safety of bridge infrastructures. In this study, we delve into the application of CSI Bridge software, elucidating its role in the comprehensive analysis of segmental constructed bridges, thereby contributing to the advancement of structural engineering practices.

Finite element analysis

In the finite element analysis of the bridge, the software CSI Bridge was utilized, and a linear bridge element model based on the classical theory of bending was employed. However, considering the importance of the structure, which consists of 159 segments and 188 stages with 1259 different profiles of tendon shown in figure 4, the use of a beam element model was deemed suitable.

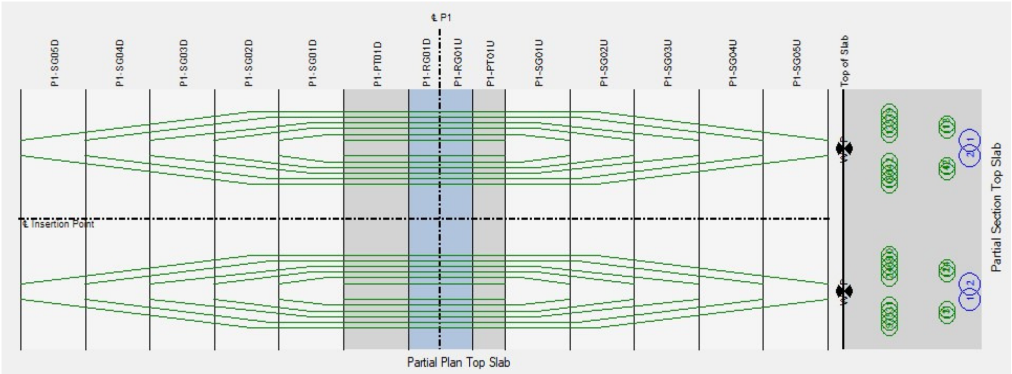


Figure2: Tendon profile in bridge model.

Post-tensioning

Reinforced concrete is widely used in various applications due to its cost-effectiveness and durability. Concrete itself has low tensile strength, but it can be effectively reinforced by embedding steel bars to compensate for this weakness. The combination of concrete and steel in reinforced concrete works well because concrete, when properly designed, is resistant to degradation, while steel provides the necessary tensile strength.

The interaction between concrete and steel can be observed in the behaviour of a concrete prism subjected to axial tensile force, as shown in Figure 8. Before cracking occurs, both the concrete and steel bars work together to resist the applied load. The area of both materials contributes to the overall stiffness of the section, resulting in the initial slope of the stress-strain curve.

Once the concrete reaches its tensile strength and cracks start to develop, the stiffness of the cross-section is significantly reduced. However, by employing prestressing techniques, as depicted in Figure 7, an initial compression is induced in the concrete. This precompression helps to delay the formation of cracks and increases the load-carrying capacity of the structure. As a result, deformations are reduced, and the embedded steel is also protected from corrosion.

Prestressing is a technique commonly used in reinforced concrete structures to enhance their structural performance and durability. It involves applying an initial compressive force to the concrete before the service loads are applied. This technique effectively reduces tensile stresses in the concrete, minimizing cracking and improving its overall performance under load.

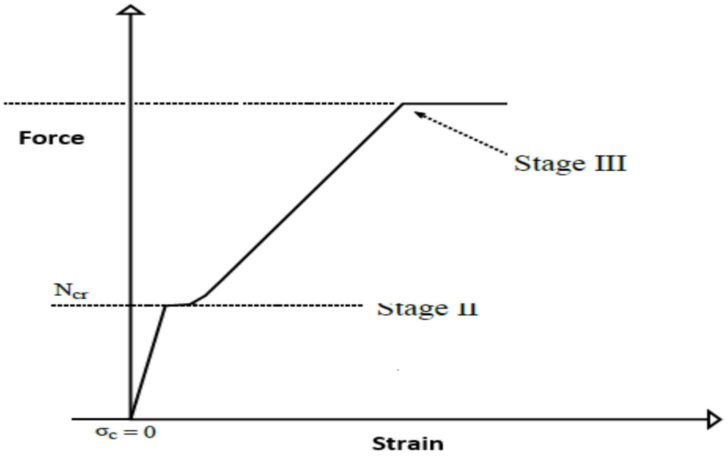


Figure 4: Force-strain curve of a concrete member subjected to tension.

Time -dependent analysis

In the analysis of segmental bridges, three inter-related time-dependent effects should be taken into consideration. These effects are as follows:

Creep of Concrete: Creep refers to the gradual deformation or strain that occurs in concrete under a sustained load over time. It is a time-dependent phenomenon where the concrete experiences additional deformation beyond immediate elastic deformation. Creep can cause long-term deflections and stress redistribution in segmental bridges.

$$\sigma c \leq 0.4fcm \qquad (1)$$

$$\varepsilon_o(t) = \frac{\sigma c}{E_{c_i}}\psi(t)(2)$$

Where ψ= creep coefficient; Ec= Elastic modulus of concrete; J = Creep compliance

Shrinkage of Concrete: Shrinkage is the reduction in volume or dimensions of concrete as it undergoes drying and curing. This time-dependent effect results from the loss of moisture in the concrete, leading to shrinkage strains. Shrinkage can cause cracking, changes in geometry, and additional stresses in segmental bridge elements.

$$\varepsilon_{ca}(t) = \beta_{as}(t)\,\varepsilon_{ca}(\infty) \quad \text{(As per IS 456:2000)} \qquad (3)$$

where εca (∞) =linear function of concrete strength; βas(t) = is an exponential function of time; εca(t) = reduced variation over time.

Relaxation of Prestressing: Prestressed concrete segmental bridges utilize pre-tensioning or post-tensioning techniques to introduce compressive forces into the concrete. Over time, these prestressing forces may experience relaxation, which is the gradual loss of tension in the prestressing tendons. Relaxation can lead to a decrease in the prestress force and affect the overall structural behaviour, including deflections and internal forces.Considering these time-dependent effects is crucial for accurately analysing the behaviour and performance of segmental bridges over their service life. By accounting for creep, shrinkage, and prestressing relaxation, engineers can make informed design decisions and ensure the long-term durability and functionality of the bridge structure.

$$E = E(28)\left(\frac{t}{4+85t}\right)^{1/2} \qquad (4)$$

(5) $$\frac{\Delta\sigma_{pr}}{\sigma_{pi}} = c\rho_{1000}\left(\frac{t}{1000}\right)^{0.75(1-\mu)}$$

Where σpr=Relaxation losses; σpi = Initial prestress; t = time after tensioning

The estimating long-term creep deformation in prestressed concrete using the ACI 209 creep model is as follows:

$\varepsilon_{c(t)} = \beta_{(t)} \times \sigma_p$ (As per IS 1343:2012) (6)

where: εc(t) =creep strain at time t; β(t) =creep coefficient at time t; σp =applied stress (prestress) in the concrete.

The creep coefficient, β(t), is given by the following expression:

$\beta_{(t)} = \beta_0 \times \varphi_{(t)}$ (As per IS 1343:2012) (7)

where:

β_0 is the long-term creep coefficient,

$\varphi_{(t)}$ is the age adjustment factor.

The age adjustment factor, $\varphi_{(t)}$, takes into account the age of the concrete at the time of loading and is given by:

$\varphi_{(t)} = (1 + \alpha 1 \times t + \alpha 2 \times \sqrt{t}) \times (1 - \exp(-\alpha 3 \times t))$ (As per IS 1343:2012) (9)

where:

t is the age of the concrete at the time of loading, α1, α2, and α3 are coefficients that depend on the type of concrete and environmental conditions.

It's important to note that the specific values for β0, α1, α2, and α3 are determined based on experimental data and may vary depending on the specific characteristics of the prestressed concrete and the conditions of the structure.

Creep and shrinkage lead to time-dependent deformations in the concrete, which can result in a non-uniform distribution of stresses within the structure. This redistribution of stress affects the overall behaviour of the structure under service loads. By studying the effects of creep and shrinkage on stress redistribution, engineers can gain insights into the long-term performance and behaviour of statically indeterminate structures, ensuring their safety and durability throughout their service life.

II. MODELING AND ANALYSIS

The objective of this study is to conduct a comprehensive analysis of a balanced cantilever bridge spanning with a main span of 120 meters. In its proposed design, each direction of the carriageway will feature two traffic lanes, accompanied by a hard shoulder and a hard strip to accommodate safe vehicular movement. Additionally, the bridge design incorporates parapets on both sides, serving the dual purpose of ensuring safety for motorists and pedestrians while also providing a protective barrier between the roadway and the edges of the bridge, enhancing overall structural integrity.

To facilitate an accurate analysis of the bridge's behavior and performance, the balanced cantilever method will be employed utilizing CSI Bridge software. This method involves a systematic sequence of segment erection, commencing from the piers and gradually extending the cantilevers on each side until meeting at the mid-span. Precast segments, manufactured with precision, will be utilized and interconnected using post-tensioning tendons and concrete to ensure optimal structural strength and stability throughout the bridge's lifespan.

The utilization of travelling formwork is integral to the construction process, enabling efficient and systematic extension of the bridge sections. This innovative approach not only streamlines the construction process but also ensures uniformity and consistency in segmental placement and alignment, contributing to the overall robustness and longevity of the structure. By employing the balanced cantilever method and leveraging advanced analysis capabilities offered by CSI Bridge software, this study aims to provide valuable insights into the behavior and performance of segmentally constructed bridges, contributing to advancements in bridge engineering practices and infrastructure development.

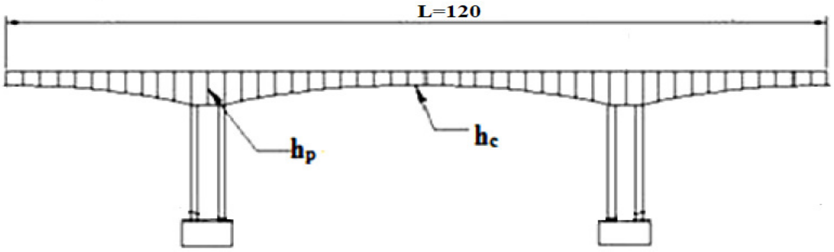


Figure 5: Side view of bridge model with span dimension.

Project setup

Table 1. Comparison of displacement of all 4 cases

Specification	Data
Type of Bridge	Box Girder
Span length	120 m
Concrete Grade	M-40
Support Condition	Fixed
Analysis Type	Time- Dependent
Design analysis consideration	Considering construction stages
Design Software	CSI Bridge 24.2.0
Modelling Type	Finite Element modelling
Live load	Considering by IRC:6-2017
IRC loading	Class -AA Loading

In this study, the balanced cantilever construction method serves as a pivotal approach for erecting the bridge structure. This specific construction technique involves systematic segmental placement, ensuring structural stability and integrity throughout the construction process. The concept of balanced cantilever construction is elucidated in the following section, offering a detailed understanding of its methodology and principles.

Figure 18 serves as a visual aid, presenting a conceptual representation of the balanced cantilever bridge erection process. Through sequential segmental placement, starting from the piers and gradually extending outward in a balanced manner, the bridge structure takes shape. This visual depiction offers insight into the intricate construction process, showcasing the orchestrated sequence of segment installation that characterizes balanced cantilever construction.

By employing this method and providing a visual representation through Figure 18, this study aims to elucidate the intricacies of balanced cantilever construction, highlighting its significance in the successful realization of the bridge structure. Through comprehensive explanation and visual aids, readers can gain a deeper understanding of this construction technique's application and its role in ensuring the structural integrity and longevity of the bridge.

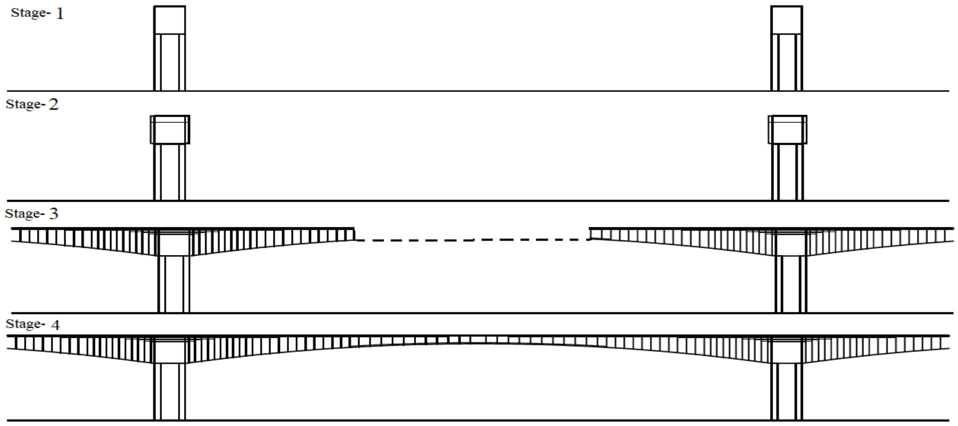
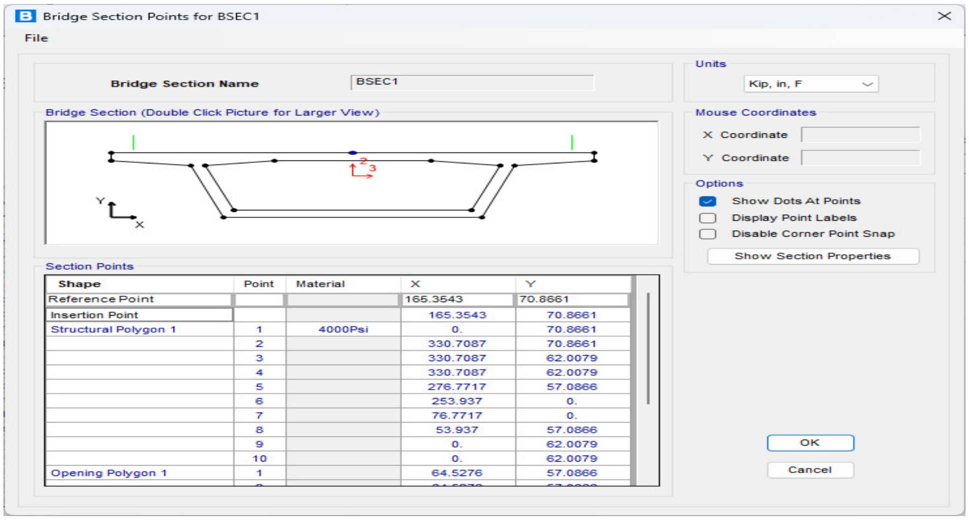


Figure6: Construction stages of segmental constructed bridge.



Bridge Section Name: BSEC1

Units: Kip, in, F

☑ Show Dots At Points
☐ Display Point Labels
☐ Disable Corner Point Snap

Section Points

Shape	Point	Material	X	Y
Reference Point			165.3543	70.8661
Insertion Point			165.3543	70.8661
Structural Polygon 1	1	4000Psi	0.	70.8661
	2		330.7087	70.8661
	3		330.7087	62.0079
	4		330.7087	62.0079
	5		276.7717	57.0866
	6		253.937	0.
	7		76.7717	0.
	8		53.937	57.0866
	9		0.	62.0079
	10		0.	62.0079
Opening Polygon 1	1		64.5276	57.0866

Figure7:Section details of bridge model in CSI.

III. RESULTS AND DISCUSSION

The skewed and straight box girder bridge models have been subjected to analyses considering both non-post tensioning and post tensioning techniques. Two different load scenarios have been considered: 2000 kN (450 kips) load and 3113kN (700 kips) load, representing the dead load and moving load as per IRC, respectively. Various response parameters have been monitored in each analysis to assess the structural behaviour of the bridges. These include torsion, bending moment along the horizontal axis, bending moment about the vertical axis, shear force, deflections, and longitudinal stress shown in figure 21. Torsion analysis provides insights into the twisting effects experienced by the bridge structure due to the applied loads. It helps in understanding the resistance of the bridge to twisting forces.

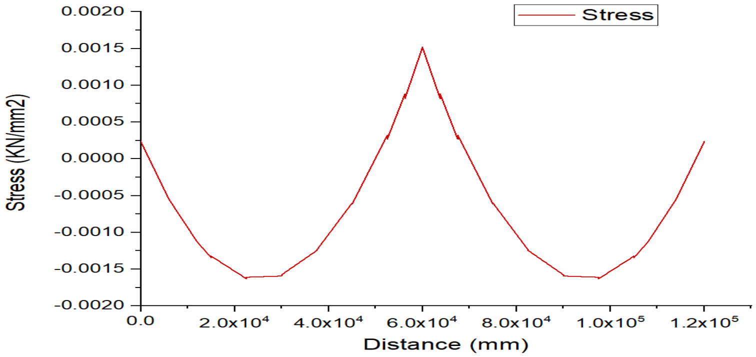


Figure 8: Longitudinal stress variation in bridge girder.

Bending moment along the horizontal axis refers to the moments developed in the bridge girder along the longitudinal direction. This parameter helps in evaluating the bending behaviour of the bridge under the applied loads. Bending moment about the vertical axis indicates the moments acting perpendicular to the bridge deck. It provides information about the bridge's resistance to vertical bending forces.

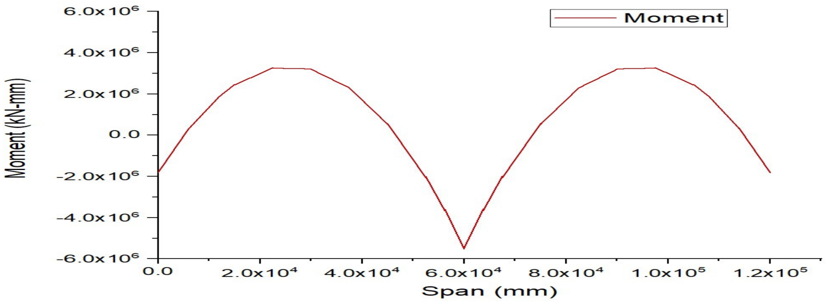


Figure 9: Moment about horizontal axis in segmental bridge

Longitudinal stress analysis focuses on the stress distribution along the length of the bridge. This parameter is essential for assessing the structural integrity and load-bearing capacity of the bridge components. Deflections of the bridge, both vertical and horizontal, are monitored to evaluate the overall deformation and flexibility of the structure. Excessive deflections can affect the serviceability and user comfort of the bridge. Shear force analysis helps in understanding the distribution of shear stresses within the bridge components. It is crucial for assessing the shear capacity and stability of the bridge.

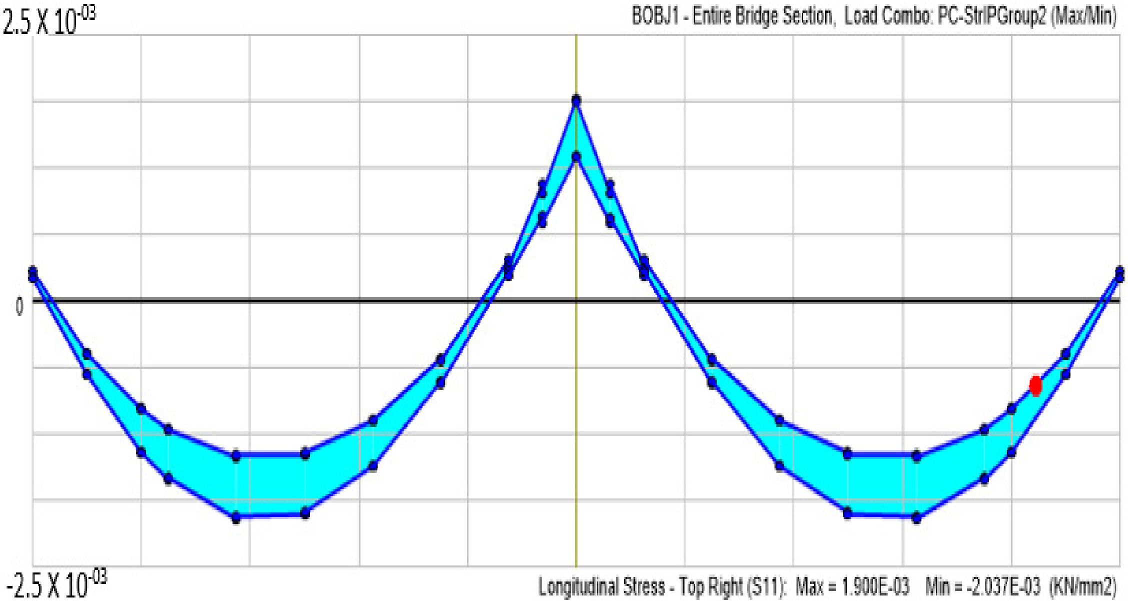


Figure 10: Stress response plot of bridge girder.

By conducting these comprehensive analyses and monitoring the response parameters, a thorough understanding of the structural behaviour and performance of the segmental box girder bridges can be achieved. This information is vital for ensuring the safety, durability, and reliability of the bridge structures under various loading conditions.

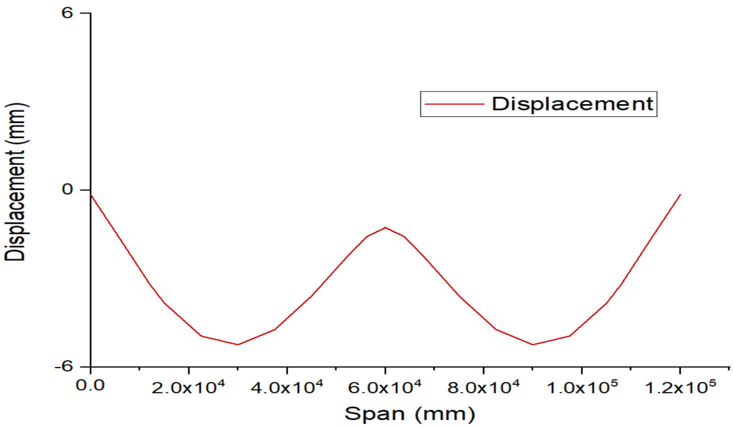


Figure11: Vertical displacement on segmental constructed box girder bridge.

Deflection in model

In the study, the displacement of the bridge is investigated along the entire span, specifically focusing on two locations: the interior edge and the exterior edge. The interior edge refers to the left side of the span, while the exterior edge corresponds to the right side from the origin.

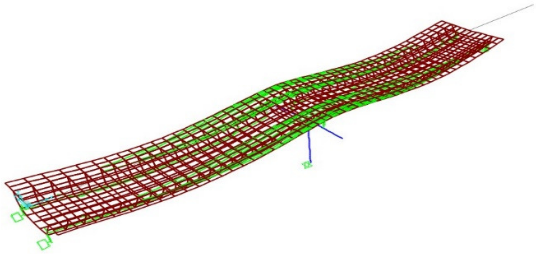


Figure12: Deflection in bridge model in isometric view.

The displacement in the longitudinal direction, denoted as U1, is of particular interest in this analysis. It represents the movement or deflection of the bridge along its length. By studying the displacement at different skew angles, the researchers can evaluate the influence of the bridge's alignment on its response to various loading conditions.The deflection patterns due to both dead load and moving load are observed and analysed using CSI bridge and shows in figure 26. Dead load refers to the static weight of the bridge and its components, while moving load refers to dynamic loads imposed by vehicles or other live loads. By studying the deflection patterns under these different loading conditions, the researchers can assess the structural behaviour and performance of the bridge.

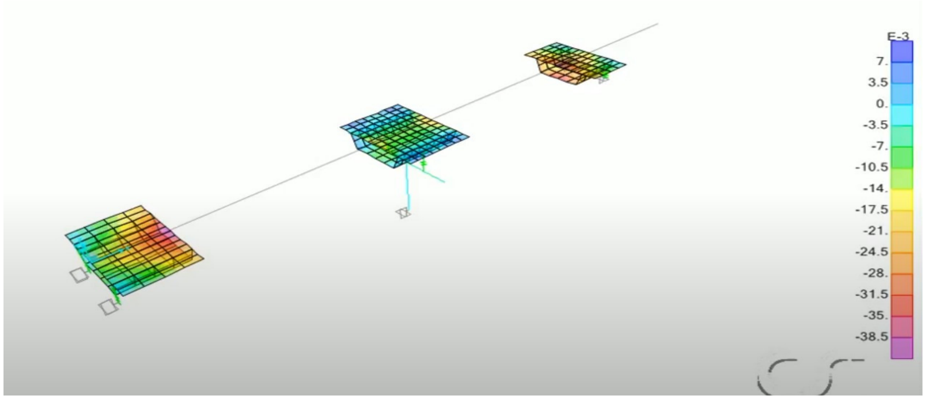


Figure 13: Strain contour during construction stage of box girder bridge.

By analysing the deflection patterns at different skew angles, engineers can optimize the bridge design and evaluate the effectiveness of measures taken to mitigate deflections, such as post tensioning or structural modifications.

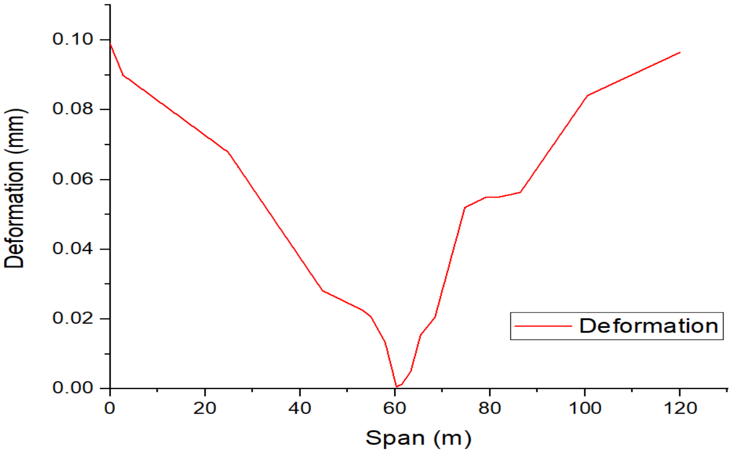


Figure 14: Deflection in post tensioned girder due to moving load.

Plotting and analysing the displacement in the longitudinal direction for different skew angles provide valuable insights into the bridge's behaviour and help inform design decisions and maintenance strategies. In a segmental constructed bridge, the bending moment variation with time shows in figure 32 can depend on various factors such as the construction sequence, time-dependent effects, and long-term creep and shrinkage of the materials. Here, provides a general overview of the bending moment variation during the construction process and highlight some key considerations. During the construction of a segmental bridge, precast concrete segments are typically erected incrementally to form the bridge span. The segments are usually post-tensioned together to provide continuity and ensure load transfer. As each segment is added, the bridge gradually takes shape, and the bending moment distribution evolves.

In the early stages of construction, when only a few segments are in place, the bending moment distribution may be relatively low and uniform across the span. As more segments are added and the bridge progresses towards completion, the bending moments will change due to the increasing weight of the structure and the evolving load paths. Once the entire span is completed, the bending moment distribution will be influenced by both static and dynamic loads. The live loads, such as vehicles and pedestrians, will induce varying bending moments along the length of the bridge. The magnitude and distribution of these bending moments will depend on factors like traffic volume, vehicle types, and bridge geometry.

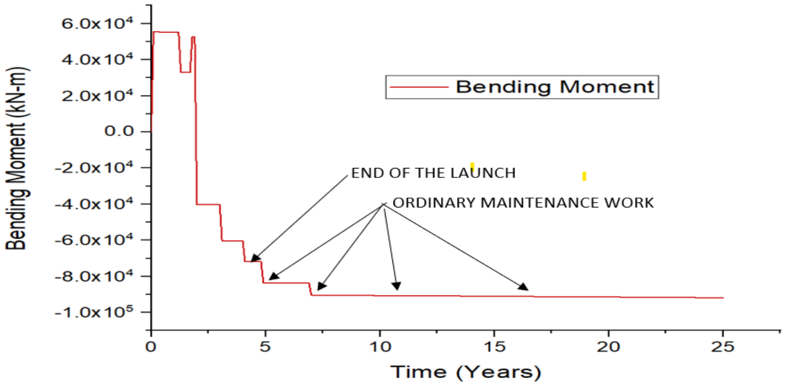


Figure 15: Variation bending moment with time interval of pier.

IV. CONCLUSION

In this thesis, segmental bridges were modeled using CSI-Bridge, with girder sections designed to withstand IRC class AA and IRC class A loading conditions. The analysis conducted using CSI-Bridge compared bending moments and shear forces. Various trial sections were examined to calculate bending moments and deflections. Subsequently, several conclusions were drawn based on the analysis.

1. Effectiveness of Nonlinear Time-Dependent Analysis: Through the utilization of CSI Bridge software, this research demonstrates the effectiveness of nonlinear time-dependent analysis in accurately simulating the behaviour of segmentally constructed structures. The results validate the importance of considering time-dependent effects for such structures to ensure their structural integrity and performance.
2. Improved Understanding of Segmental Construction: The research contributes to a deeper understanding of segmental construction techniques and their behaviour under various loading conditions. The nonlinear time-dependent analysis approach provides insights into the complex interactions between segments and their time-dependent properties, facilitating better design and optimization of segmentally constructed structures.
3. Assessment of Structural Safety and Durability: By incorporating time-dependent effects into the analysis, this study enables a comprehensive assessment of the structural safety and long-term durability of segmentally constructed bridges. The research highlights the significance of considering time-dependent effects, such as creep and shrinkage, to accurately predict the structural response and ensure the longevity of these structures.
4. Design Recommendations and Guidelines: The findings of this research can serve as a basis for developing design recommendations and guidelines for segmentally constructed structures. By accounting for nonlinear time-dependent behaviour, engineers and designers can make informed decisions regarding material selection, construction sequences, and maintenance strategies, leading to safer and more cost-effective designs.

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[25] Manual for CSI Bridge ‘bridge superstructure design’ by CSI Berkley.
[26] IRC 18:2000 ‘Design Criteria for Prestressed Concrete Road Bridges (Post tensioned)’.
[27] IS 456:2000 “Indian Standard Code of Practice for Plain and Reinforced Concrete”.