# Seismic Performance and Construction Stability of Long-Span Continuous Rigid-Frame Bridges with Tall Piers

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## Abstract

*This study investigates the construction stability and seismic performance of long-span continuous rigid-frame bridges (CRFBs) with extremely tall piers, a first for Nepal, exemplified by Bridge 37 on the Kathmandu - Terai/Madhesh Fast Track (Expressway) Road Project (KTFT). CRFBs, constructed using the Free Cantilever Method, offer advantages such as smooth driving, low cost, adaptability, and aesthetics. However, their design and construction in mountainous regions require meticulous detailing, particularly to handle the flexural requirements and seismic loads. Using finite element modeling with Midas Civil, this study evaluates construction loads, wind loads, and incidental loads. Key analyses include interaction curves, modal analysis, response spectrum analysis, and construction stage analysis. Results indicate that the fundamental time period of the bridge is 2.847 seconds with a fundamental frequency of 0.35 Hz. Maximum displacements due to seismic loading were found to be 220mm and 357mm in x and y directions, respectively. The findings align with contemporary research, demonstrating adequate stability and performance under seismic conditions. This research provides valuable insights and guidelines for the design and construction of CRFBs in seismic regions, contributing to enhanced safety, stability, and durability of bridge infrastructure in Nepal.*

**Keywords:** KTFT, balanced cantilever bridge, free cantilever method, continuous rigid-frame bridge, construction stage analysis, tall pier

## Introduction

Nepal's progress has led to a growing need for new road development and traffic infrastructure. Since Nepal is a mountainous country, bridges must cross valleys, rivers, and other difficult terrain. In these regions, long-span continuous rigid-frame bridges (CRFBs) with extremely tall piers are typical. CRFB is commonly known as balanced cantilever bridge and constructed by using Free Cantilever Method (FCM). Long-span CRFBs provide for easy and smooth driving and have a flexural structure, low cost, good adaptability, and aesthetics. The high piers must be suitably flexible in order to restrain undesired mechanical influence on the superstructure from temperature changes, shrinkage, concrete creep, and natural disasters like earthquakes. In order to handle their enormous height, the piers are usually built-in short portions. When a bridge spans over a mountain or a deep body of water, the pier height needs to be even higher. Longer spans, larger box sections, and cantilever construction technologies are needed for CRFBs with piers higher than 50 meters. Because of their span and height, the overall and local stability of these structures have a significant impact on the safety of their construction and maintenance (Yadav, 2017). The overall stiffness and local stiffness of this type of bridges tend to be vulnerable and it must be mitigated accordingly.

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Numerous earlier studies examined the effects of various loads on CRFBs (Li et al., 2011; Pan et al., 2011; Yao et al., 2014; Zong et al., 2016)and examined their structural stabilities at various phases of construction. Some have also talked about the different ways to analyze the mechanical principles. The impact of the primary pier design characteristics on stability has been studied by others. Numerous people have worked to continuously improve the materials and configurations of CRFBs while also conducting in-depth investigations on stability.

Still, there lack of research that are especially concerned with seismic performance, construction stage analysis (Harper et al., 2017; Hastings et al., 2010; Zhao et al., 2009)of CRFBs.

The benefits of curved girder bridges and CRFBs are combined in curved CRFBs with high piers. A CRFB has a continuous main span; its lower piers and upper girder are combined(Wang & He, 2008). Girders and piers can support loads concurrently thanks to the consolidation system(Stith et al., 2013); however, the kind of pier greatly affects the internal forces and deformation of the bridge.

We evaluated the impact of construction loads, wind loads, and other unintentional loads on structural stability in order to examine the construction stability of curved CRFBs.

For this study bridge number 37 of Kathmandu Terai/Madhesh Fast Track (Expressway) Road Project [KTFT] is considered. The KTFT expressway is a national pride project to connect the Terai region of Nepal with the capital city, Kathmandu which reduces the length and travel time from terai to the capital city. The general arrangement of bridge is shown in Figure 1. This type of bridge is built first time in Nepal also having the tallest pier bridge in the history of Nepal till the date.

## Bridge Description

Total length of this bridge is 245m having 6 spans of 3 number of 25m RCC I-girder and 3 number of balanced cantilever girder of central span of 80 m and side span of 45 m. The total width of the bridge is 12.80m. For this study only central part of balanced cantilever having span arrangement 45+80+45 m portion is considered. The deck shows varying depth through the spans, provided by a curved soffit, which characterize the typical parabolic shape of the deck girder. The longitudinal section is shown in Figure 2. The depth of the deck cross section varies from a maximum value of 5.0m, at the pier axis, to

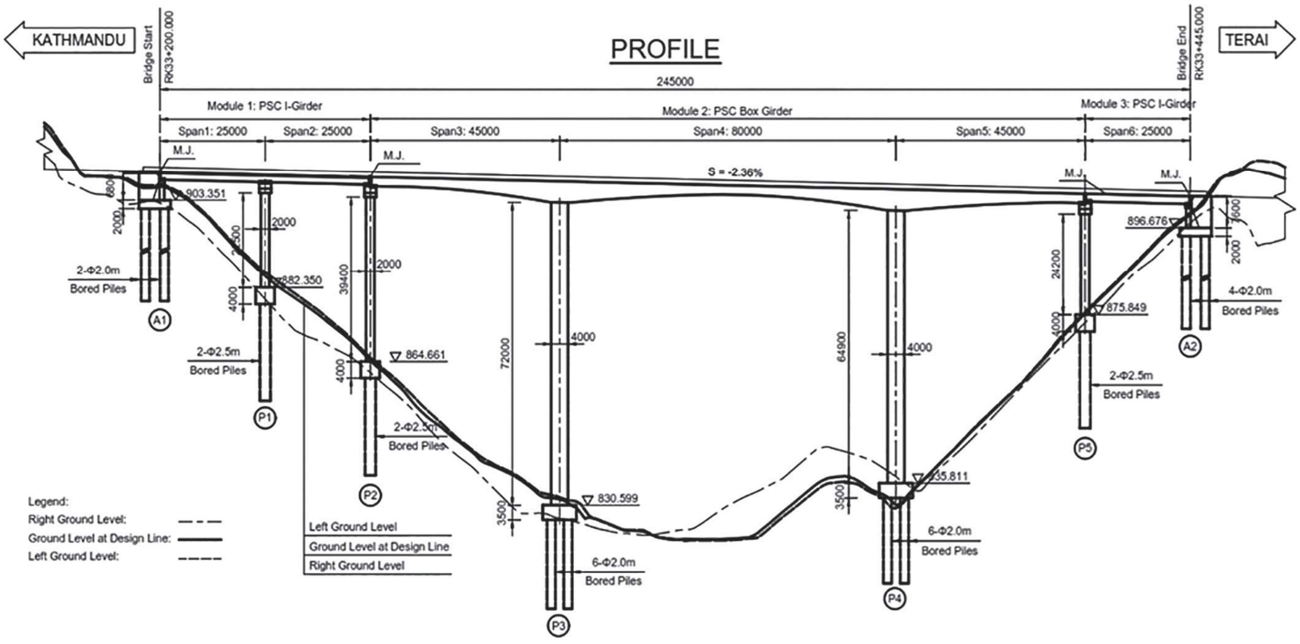


Figure 1: Longitudinal Section of the Bridge

a minimum value of 2.20m, at the mid span and the abutments supports which is shown in Figure 3. The upper slab is 12.8m wide, longitudinal slope is 2.36% as gradient and transversally inclined at 2.5%, same as the road transverse slope. The upper slab shows a variable thickness from a minimum of 200mm, at the cantilever of the box girder section, 300mm, at the center of the box girder section, to a maximum of 650mm, at two intermediate web supports.

The highway classification is Asian standard Class I, an expressway with four traffic lanes, design speed of 60 km/h, traffic load of Highway grade I, and designed flood frequency of grand bridge 1/200. Indian standard codes are used for the design of bridges.

**Materials:**

1. Concrete: M50 used for superstructure, M40 used was for abutments, piers and foundations as per IRC:112(Congress, 2016).
2. Prestressed tendon: Prestressed tendons were considered only in the longitudinal direction with a nominal diameter of 15.2 mm, comprised of a steel strand of seven wires with high strength and low relaxation. The tendons had elasticity module Ep = 1.95 × 105 Mpa, standard strength fpk = 1860 Mpa, and less than 2.5% of stress relaxation rate in 1000 hours; a large tonnage grouped anchor system and vacuum mortar suction technique were used to fabricate them.
3. Rebars: The main reinforcements were Fe500D as per IRC:112.
4. Bearings: High Damping Rubber (HDR) bearing is used.

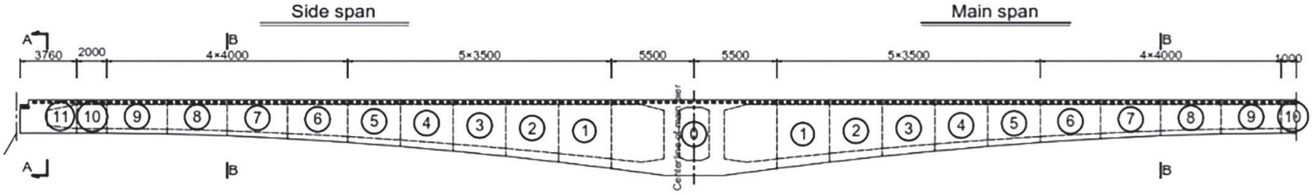


Figure 2: Longitudinal section of box girder

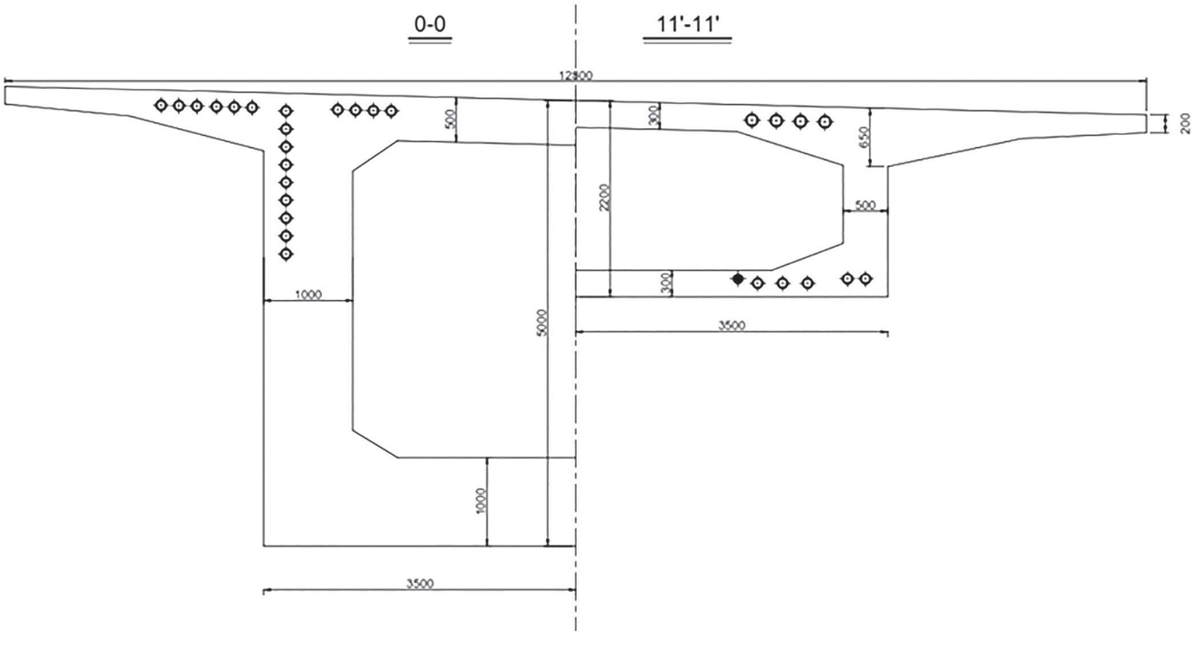


Figure 3: Half cross section of box girder at pier top and mid span (unit: mm).

## Numerical Modelling

Midas Civil program is used for finite element modelling, analysis, and design of bridge structures, which is also used for underground structures, industrial buildings, airports, dams, harbors, and other engineered structures. The FE models of bridges including their superstructure, which was modeled with beam elements. The girder and piers were rigidly connected, the bottoms of piers were comprised of conventional bearings, and the supports on both ends were elastically connected according to support parameters. Analysis was conducted via the lumped mass method. The FE model of the bridge at the finished bridge stage is shown in Figure 4.

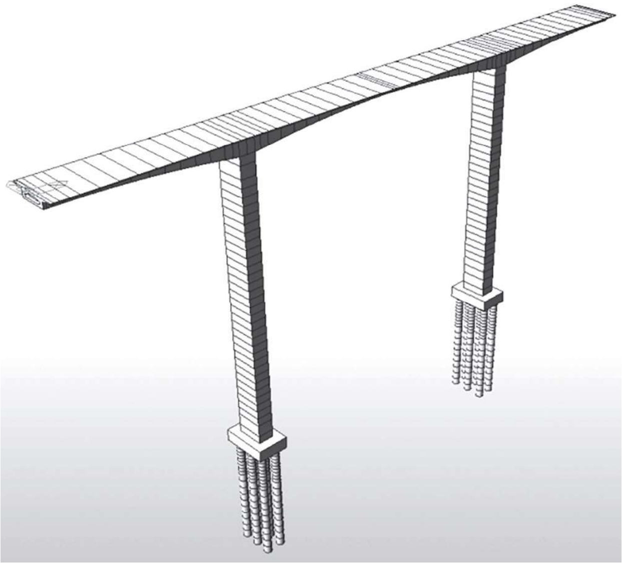


**Figure 4: 3D Finite Element Model of Bridge**

## Analysis and Results

For this bridge model analysis, response spectrum analysis and construction stage analysis are performed. The details of these analyses are briefed below.

### a. Interaction Curve

The interaction diagram is a graphical representation of the ultimate capacity of a column subjected to axial load (Pn) and uniaxial bending (Mn). The interaction diagram depends on the concrete cross sectional area, the material properties (stress and strain) and also the amount and distribution of reinforcement. Therefore, each concrete section with a specific reinforcement distribution is characterized by a unique interaction diagram representing failure as the crushing of concrete at the maximum compressive strain. After the determination of design loads (P, M) three possible load conditions plotted as points can be defined once the interaction diagram for a section is obtained:

i. The load condition coincides with the interaction diagram curve: represents the limit state.

ii. The load condition falls inside the interaction diagram curve: causes no failure in the section.

iii. The load condition falls outside the interaction diagram curve: causes failure in the section.

The interaction diagrams can also be extended to three dimensional surfaces to account for biaxial bending. The principle regarding the load conditions remains the same.

The cross section of the pier is shown in Figure 5 and the interaction curve of the pier in both orthogonal direction is shown in Figure 6. The demand in transverse and longitudinal directions are 35015.26 KN & 45967.01 KN axial force & 267959.02 KN.m & 117001.16 KN.m bending moment respectively in the design governing load combinations. The interaction diagram shows that the design demand is in within limit.

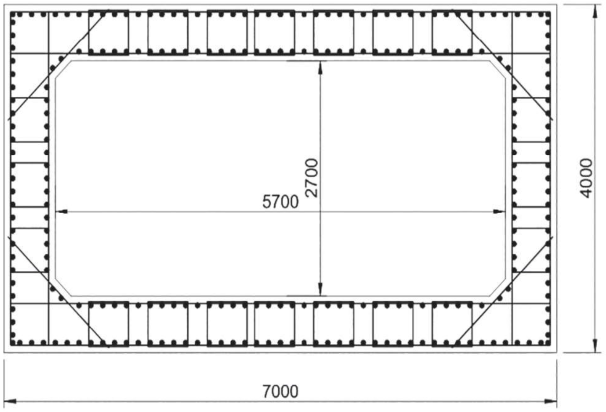
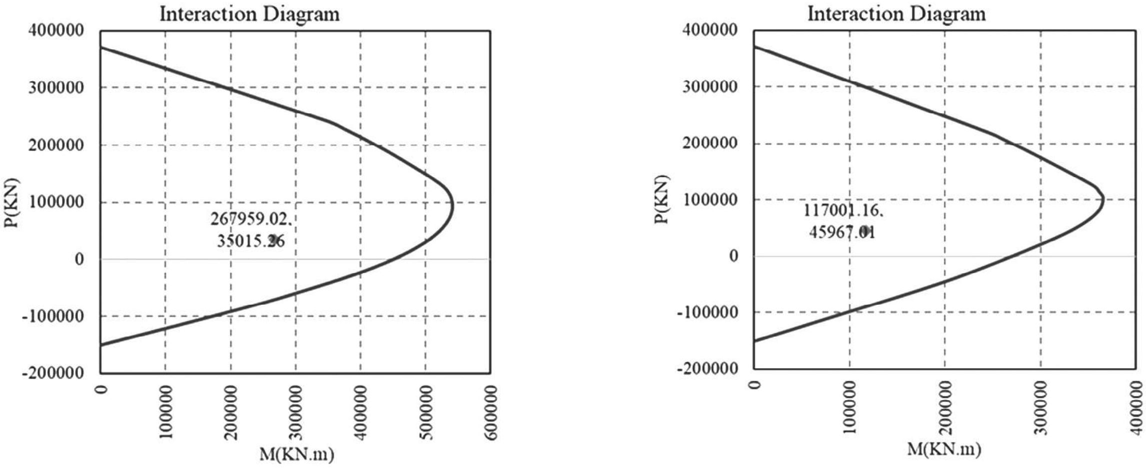


**Figure 5: Cross section of the bridge Pier**

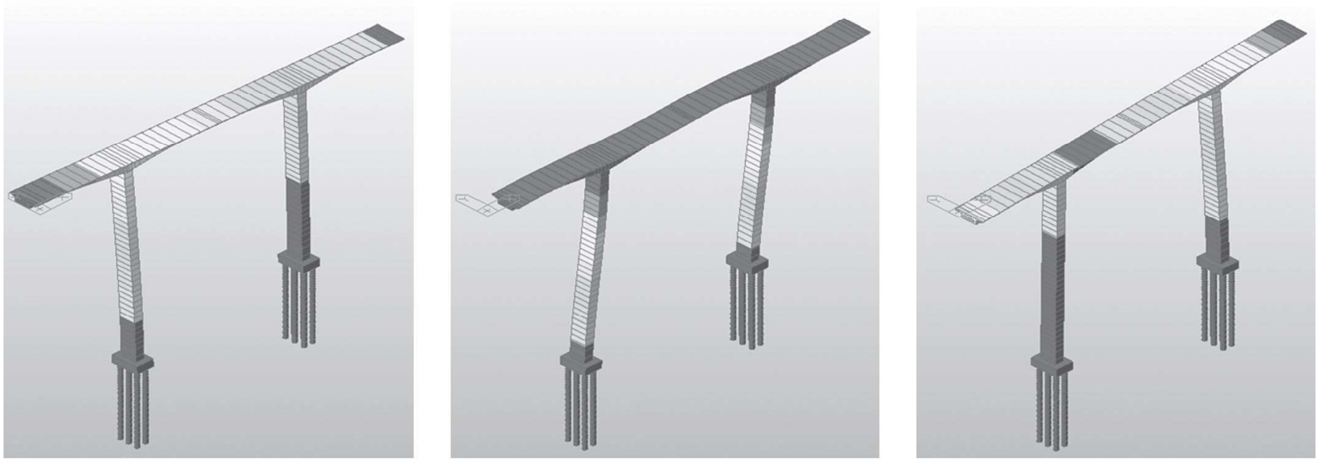


**Transverse Direction** **Longitudinal Direction**

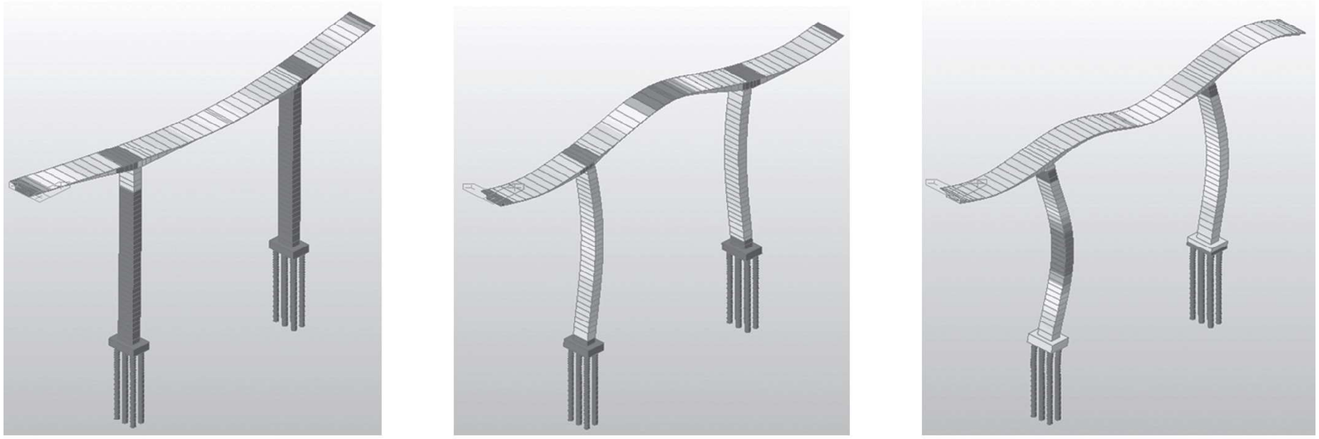
**Figure 6: Interaction Curve of the Bridge Pier**

### b. Model Analysis

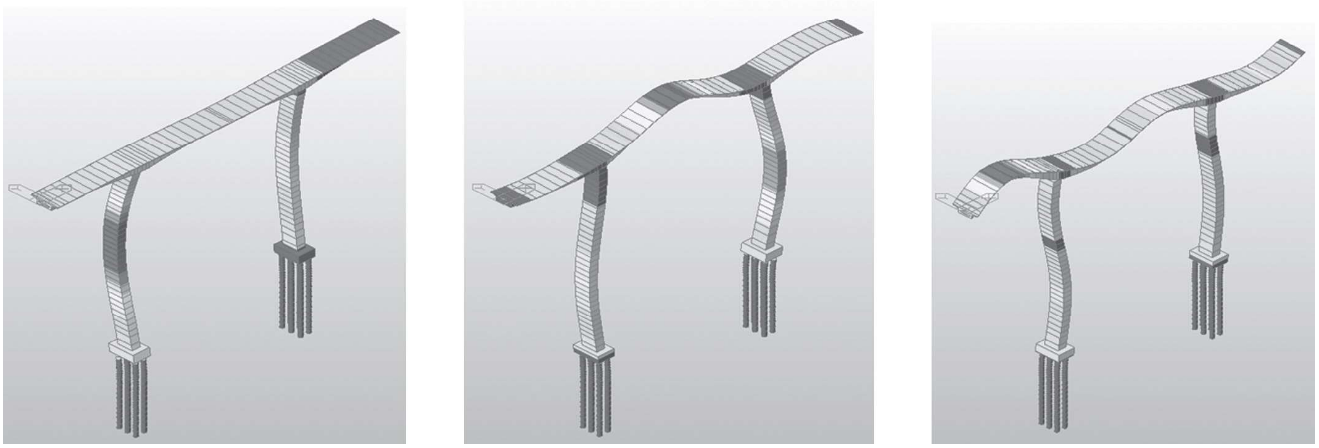
Modal analysis is the study of an object's modes of vibration and the frequencies at which they take place. Every structure has its inherent vibrational characteristics which depend mainly on its stiffness, mass and damping. If a structure is set to vibrate freely (without the influence of external loads) it will vibrate with its natural frequency. Such natural vibrational properties are required to design the structure so that its natural frequency can be adjusted with respect to external forcing frequencies to avoid resonance. Resonance occurs when forcing frequency is matched with natural frequency of the structure and amplitude starts increasing at each cycle of vibration until reaches to its maximum. Consequently, the structure moves from stable state to unstable state. Thus, if frequency of external force (e.g. of ground motion) is known, the natural frequency of structure can be adjusted by modifying stiffness, mass, geometry and load distribution etc. The mode shapes and model time period in shown in Figure 7. The fundamental time period of the structure was 2.847 second and the frequency is 0.35 Hz. It is seen that the first three modes are translational mode and others are rotational.



a. Mode 1 (T=2.847) b. Mode 2 (T=2.663) c. Mode 3 (T=2.412)



d. Mode 4 (0.6481) e. Mode 5 (T=0.5671) f. Mode 6 (0.3968)



g. Mode 7 (T=0.3299) h. Mode 8 (T=0.3225) i. Mode 8 (T=0.2321)

**Figure 7: Mode Shapes and Modal Time Period of the Bridge**

Source: KTFT Road Project, 2023.

### c. Response Spectrum Analysis

Response spectrum analysis is a technique used to estimate the structural response to brief, unpredictable, transient dynamic events, such as earthquakes and shocks. Because the precise time history of these loads is unknown, conducting a time-dependent analysis is challenging. Additionally, the short duration of these events prevents them from being treated as an ergodic (or stationary) process, making a random response approach unsuitable. Instead, the response spectrum method utilizes a specialized form of mode superposition. This approach provides an input that defines the maximum potential excitation of an eigenmode with a specific natural frequency and damping caused by such events. The Elastic Response Spectrum curve used from IRC SP 114 which is shown in Figure 8. Type I soil condition is considered as per geotechnical report of the site.

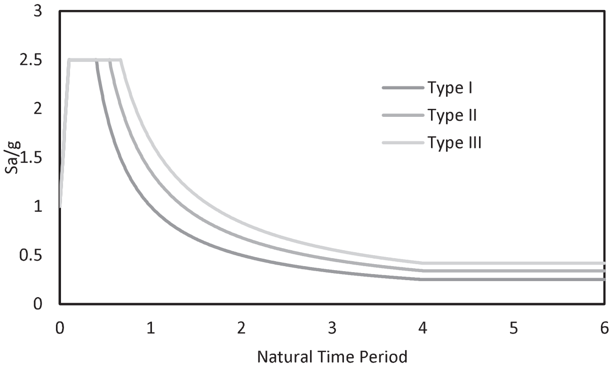
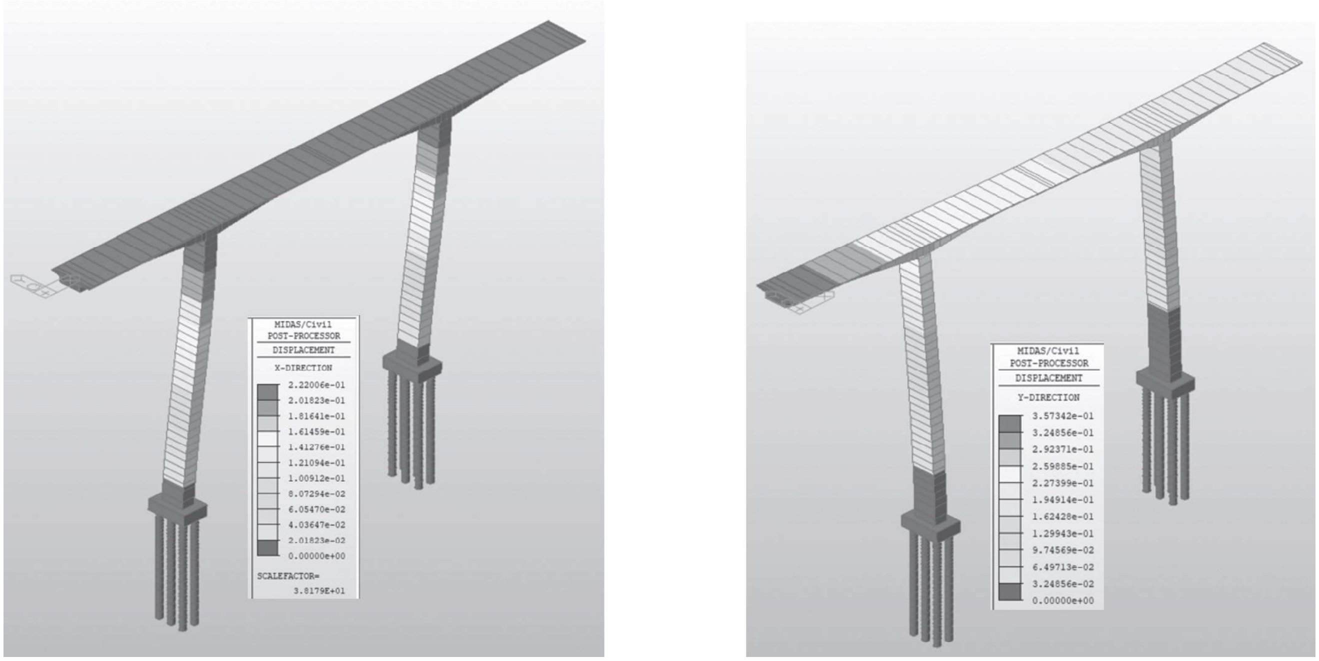


**Figure 8: Spectra for Elastic Response Spectrum**

Source: KTFT Road Project, 2023

Response spectrum analysis was done for the earthquake analysis in two orthogonal axes. Due to earthquake loading, the displacement in x-direction is found 220mm and it is 357mm in y-direction.

The displacement of bridges in different direction is shown in Figure 9.



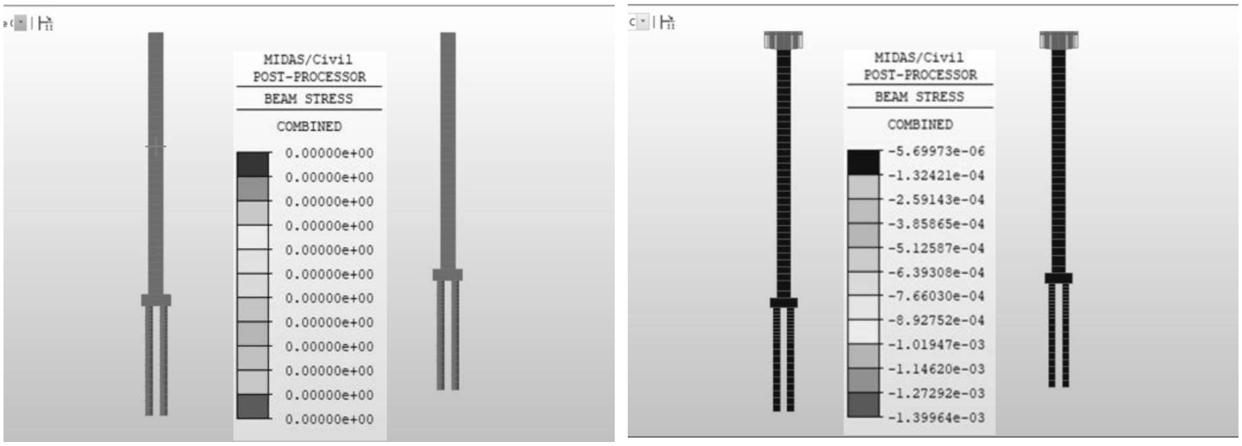
a. X-Direction **b. Y-Direction**

**Figure 9: Displacement Due to Earthquake Load**

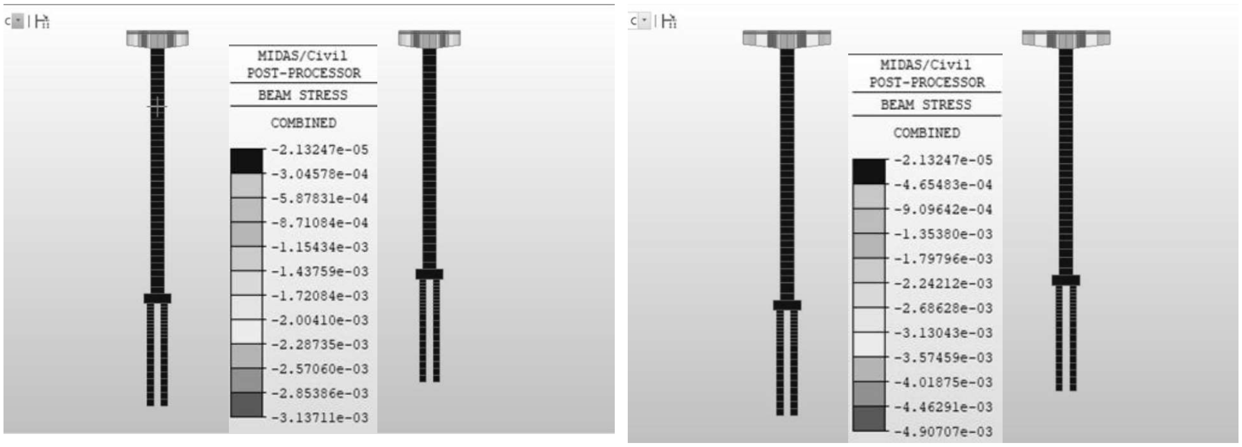
Source: KTFT Road Project, 2023.

### d. Construction Stage Analysis

Construction Stage Analysis is used to observe how a structure behaves during specific phases of construction. Construction stage analysis can also be used to check the final structure for potential future failures or long-term effects like shrinkage (the reduction of volume in concrete material due to moisture loss), creep (additional deformation the concrete will experience over time without additional loads), and prestressing tendon relaxation. The maximum compressive stress was 18.73 N/mm2 and maximum tensile stress was 3.46e-6 N/mm2 found during the construction stage analysis. The tensile stress is negligible.

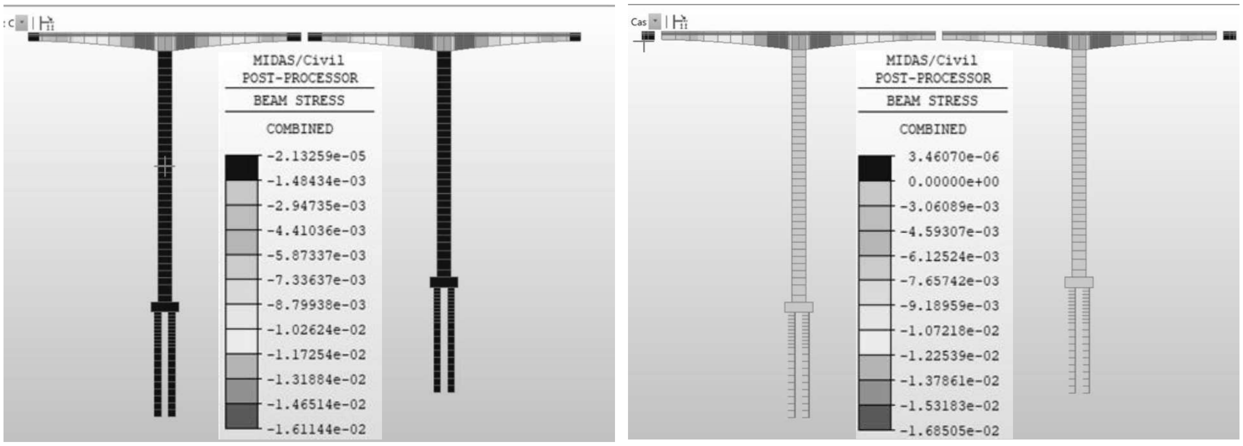


a. Construction of Foundation & Substructure b. Construction of Segment 0#



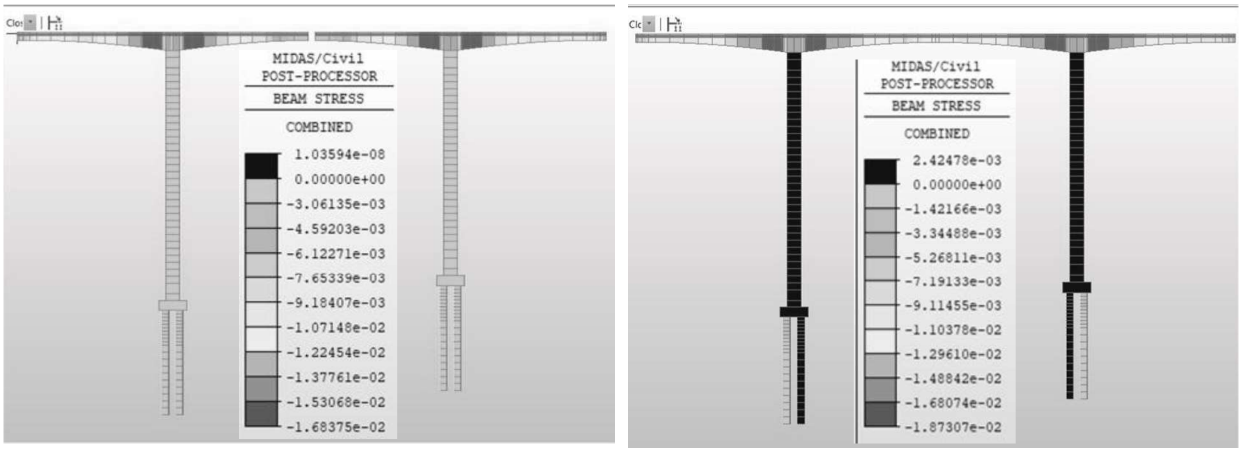
c. Construction of Segment 1#

d. Construction of Segment 2#



e. Construction of Segment 3 to 9#

f. Construction of Side-Span Section



g. Construction of Side-Span Closure Section

h. Construction of Mid-Span Closure Section

**Figure 10: Construction Stage Analysis of Bridge**

Source: KTFT Road Project, 2023

## Discussion

Due to earthquake loading, the displacement in x and y direction is found 220mm and 357mm, respectively. The fundamental time period of the bridge was 2.847 second and the fundamental frequency is 0.35 Hz. It is seen that the first three modes are translational mode and others are rotational. The maximum compressive stress was 18.73 N/mm2 and maximum tensile stress was 3.46e-6 N/mm2 found during the construction stage analysis. The tensile stress is negligible. In their study on 100m tall pier for railway bridge, (Kulkarni et al., 2016) calculated the average top displacement of piers to be 726mm and still the piers to be elastic or immediate occupancy performance level. Additionally, the findings also emphasized the adequacy of non-linear dynamic analysis rather than non-linear static analysis for reliable prediction of seismic performance of such piers. The study also concluded a period of vibration of 2.3s along with varying values for different response reduction factors. (Patel & Parekh, 2016) analyzed 60m tall piers and found average max displacement at pier top to be 370mm. In present study, response spectrum analysis in accordance with the curve given in SP 114 has been considered. Mass participation has been ensured to take into account the effects of higher modes and the corresponding displacements and stress are found to be in line with similar contemporary research works.

## Conclusion

The planning and design of crossing structures are particularly demanding when spanning deep gorges necessitating the construction of extremely tall piers. Continuous rigid frame bridges (CFRB) with tall piers have demonstrated exceptional performance under critical loading conditions, such as seismic events, due to their integral connections between the deck and piers, which enhance stability and seismic load management. The conceptualization of these bridges requires meticulous detailing of structural components in terms of design and construction sequences.

This research aims to illuminate several critical aspects that require attention during the construction of such structures, particularly in regions with limited prior experience in this domain. Various structural parameters are evaluated and cross-referenced with existing standards and research findings to ensure comprehensive understanding and effective implementation. The study also considers the challenges associated with construction in seismic zones, the need for advanced materials and construction techniques, and the importance of adopting innovative design strategies to enhance the resilience and longevity of these complex structures. By addressing these factors, the research contributes to the development of robust guidelines and best practices for the construction of continuous rigid frame bridges with tall piers, ensuring safety, stability, and durability.

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