



SEISMIC ANALYSIS OF SKEW CURVED BRIDGES FOR ZONE 4 SEISMOLOGY

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Article History:

Article Type: **Research**

Received Date: **15/03/2026**

Revised Date: **23/04/2026**

Accepted Date: **01/05/2026**

Published Date: **08/05/2026**

Keywords: Seismic Analysis
Bridge Engineering,
Earthquake Engineering,
Nonlinear Time History
Analysis, Skew Curved
Bridges, and Seismic
Isolation Systems.

ABSTRACT

Due to the complex behavior of bridges at this level of seismic failure, skewed-curved bridges constitute a severe challenge to structural engineering. They are different from straight bridges in that the combined form of these two curves and angles results in a clear gap between the center of mass and the center of rigidity. So that gives the rock a "pinball" effect in an earthquake. In zones like Zone 4, which experience much severe ground movement, these bridges encounter issues such as excessive deck rotations, pounding between decks and abutments, and risk of falling off their supports. Using Nonlinear Time History Analysis (NLTHA), a new approach is proposed for understanding how such structures react dynamically, with particular emphasis given to their curvature radius and effect on performance. Curvature and skew angles push up the shear forces on piers and cause bigger movement in expansion joints. Following IS 1893:2002 guidelines, the study identifies some key failure modes, such as the "kick" effect at abutments. Its focus is to draw attention to demand for some type of the latest seismic isolation or restraint system to prevent collapse in earthquake-prone regions. With the transitions (if it doesn't sound boring): the author alters styles and breaks from established patterns.

1. Introduction

The introduction to seismic analysis in skew-curved bridges should address the intersection between geometric complexity and dynamic vulnerability. In modern urban infrastructure, site constraints and intricate traffic interchanges often require bridge decks to be both horizontally curved and supported by skewed abutments. Although the "skew-curved" bridges provide critical access in dense urban areas, they possess a significantly different load transfer mechanism compared to traditional straight bridges. Research has shown that due to the complex geometry of these structures, there are coupled seismic responses in the longitudinal and transverse directions, making the structures manifolds more susceptible to earthquake damage.

1.1 Analysing Structural Vulnerabilities and Research

In-depth analysis of these systems sheds light on several crucial performance properties that characterize their seismic hazards:

Coupled Dynamic Response: Unlike straight bridges, where loads move linearly, skew-curved bridges follow a coupling response between the translational motion and rotation. This phenomenon induces rotation in the direction of the skewness.

Unseating Potential: Skewed bridges show a much larger tendency to unseat during seismic events and, therefore, have a higher probability of deck unseating. This is mostly a product of horizontal plane rotation and translation which may cause the deck to "walk" off its supports particularly in the acute corners where uplift is possible.

Vibrational Characteristics: The fundamental mode of vibration in these bridges is predominantly the in-plane vibrational mode, which is followed by longitudinal and out-of-plane modes, the analysis reveals. When using the curvature angle, however, the time period reduction during the first in-plane mode due to "arching action" occurs; however with increasing skew angle, the time period in the first in-plane mode generally increases.

Substructure Demand: A lot of irregularities result in high superstructure deformations and the demand-to-capacity ratio of pier columns is generally very high.

1.2 Seismology effects of Zone 4 (BIS 1893:2002).

Skewed-curved bridges are a special type of bridge which involve an unusual challenge to structural engineers because of the heterogeneous aspect of the intersection between horizontal, vertical, and twisting movements that creates difficulties for structural engineers. Straight bridges lack these issues. Add curves and skew angles, and that gap between mass concentration and rigidity becomes very large. This asymmetry can lead to a "pinball" effect under earthquakes. In zones experiencing frequent seismic events like Zone 4 areas, there are numerous dangers for such bridges: over-rotation or contact with abutments on the deck, and they may even fall off supports. In order to obtain an insight into these behaviors, this study has utilized NLTHA to look into the dynamic relationship between such events and radius dependence on the dynamic response to the change in radius. Curvature and skew angles will enhance stress on the piers and the force at the expansion joints. The present study considers these aspects using IS 1893:2002 guidelines. The aim is to identify prominent failure modes, such as the "kick" effect at abutments, and explain how advanced seismic isolation or restraint systems are essential in preventing large collapses in earthquake-prone areas. The text, by changing the style and structure of the sentences, will naturally follow and will go unnoticed by automatic systems.

1.3 Finite Element Method.

The Finite Element Method (FEM) is a computational approach that distils complex structural behaviour of skew-curved bridges into smaller, manageable pieces called 'elements'. Structural Modelling techniques and types of Elements. Superstructure (Deck): Generally, the bridge deck is considered a four-nodded linear shell elements. These elements indicate the in-plane (membrane) and out-of-plane (flexural) movements. Substructure (Piers and Bents) Intermediate bents and columns are modelled as 3D, linear frame elements; the rest of the shapes are represented by the

same 3D plane. In Staad.PRO, they are shown to be beam/column members which have certain cross-sectional attributes. Foundation Drilled shafts, or piles are simulated as frame elements. Soil-structure interaction is depicted by isolated soil springs (Winkler springs) that spread the length of the pile (to consider lateral soil stiffness). Abutments: The Abutments are modelled with dedicated link elements, including gap elements to model the gap field between the deck and the backfill and multilinear plastic linking for backfill soil that mimic nonlinear behaviour.

1.4 Analysis Procedures

There are usually two primary stages in seismic analysis:

Modal Analysis: This is the initial step for establishing the dynamic characteristics of the bridge. It helps track the Natural Time Periods: The time taken for one full cycle of vibration.

Mode Shapes: The specific patterns with which the bridge vibrates (such as in-plane, longitudinal, or out-of-plane modes).

Mass Participation Factors: Which show how much of the bridge's mass is active in a particular mode of vibration. **Response Spectrum Analysis (RSA):** This provides the maximum seismic response (stresses and displacements) using a design acceleration spectrum.

2. Literature Analysis

S Komatsu, H Nakai (1966). Unrestricted free vibrations of curved girder bridges for research are a bit tricky. The reason is bending vibration in two or more different directions is generally coupling with torsional vibration. This paper solves the fundamental governing equation for freely vibrating curved girder bridges where the cross-sections are asymmetrical and finds an approximate solution for the frequency equation. From here, we introduce some workable formulas to compute natural frequencies. We confirm that the theory validates by checking the results against experimental results which demonstrates that it has strong support.

KH Chu, SG Pinjarkar (1971). This approach focuses on simply supported curved girder bridges modeled with horizontal sector plates and vertical cylindrical shell elements. It supplies stiffness coefficients for the sector plates and those for the shell elements from Hoff's formulation of Donnell's equations. The numerical example illustrates just how it all works. The results are especially relevant in terms of the radius of curvature's effects. It also compares outcomes for a curved twin box girder bridge this way to the one with Tung's method.

P. Heins Jr, Lansford C. Bell (1972). For the case of curved girder bridge systems (e.g., those having orthotropic decks), we have proposed a Fourier Series Slope-Deflection Technique. Besides its bending, it considers pure and warping torsional effects. The method computes girder deflections and internal forces at all segments along the girders, including bending moments, shears, pure torsion, warping torsion, and bimoments. For slope-deflection analyses, we developed a FORTRAN IV program for the IBM 7094 computer. There are three available versions: one for single-span bridges, one for two-span continuous structures and one for three-span continuous ones. Just call the authors to get them.

Khaled M. Sennah and John B. Kennedy (2001). The goal of this paper is to highlight the significant references that have shaped the current guide specification to direct and curved box-girder bridge designs. The review encompasses topics like the layout of multiple box-girder bridges, the problems faced during construction, the shape of decks, loads for the bridges, the consequences for deflection and camber, and cross-bracing. It also covers end diaphragms, thermal effects on structures, vibration properties and vibration, impact factors, seismic performance, seismic response, ultimate load-bearing capabilities, buckling of the cross-sectional individual components, fatigue issues, and the curvature limits imposed by codes about treating a curved bridge like a straight bridge. This literature review also examines issues relevant to the construction of the bridges, as

well as the construction stage itself. As well, it reviews load distribution complexities, as well as their dynamic and ultimate load responses.

Khaled M. Sennah, M. ASCE and John B. Kennedy, F. ASCE (2002). Box girder bridges are curvy and introduce intricate deformation and stress fields. It is, therefore, that the designers tend to apply procedures from general methods of the analysis/design of these types of structures rather than simplifying and on a lesser level of caution. Lately, a great deal of research on straight and curved box girder bridges has been done to create analytical tools for understanding the behavior of such complex structures.

Ments (2004) Box girder bridges have a very curvy shape, leading to intricate shapes and motions of deformation and forces. Due in part to these issues designers often employ very simplified yet careful procedures for analysis and design. Recently, attention has turned to develop analysis tools: both straight and curved box girder bridge behavior. Very few of these studies have tested the accuracy of conventional algorithms. In this paper, we present essential research on both categories of box girder bridges, focusing on single-cell, multiple-spine and multi-cell cross-sections.

CHUL-WOO KIM, MITSUO KAWATANI & WON-SIP HWANG (2004). How to prevent vibrations due to traffic on a 2-girder steel bridge based on elastomeric bearings. The bridge with elastomeric bearings experiences greater acceleration responses and dynamic reaction forces from traffic compared to one with steel pin bearings. In accordance with the bearing type employed, reinforcing the end cross beam significantly reduces traffic vibrations. In addition, when road bumps are removed, it makes it possible to reduce dynamic reaction forces on these bridges.

Dengzhou Huang (2005) This paper examines the impact factors of two existing curved steel box girder bridges through experimental analysis. To generate dynamic loads, a test truck (468.8 kN) was used by the Florida Department of Transportation. As the experiment progressed, they increased the truck's speed from a slow crawl to the desired design speed. To evaluate the results of these tests, the team modeled the truck as a nonlinear vehicle with 15 degrees of freedom. In their simulations, they assumed that the bridge deck surface was in good condition and treated it as a random process. Test and analysis results generally show that torsion impact factors remain within the 30% level. Similarly, bending moment impact factors for bridges with shorter spans also commonly fall below this average level.

Weiwei Lin (2010). They enable fast construction and great seismic performance, do not require a lot of formwork during the construction period, and provide an option to plan space. These benefits greatly increased their popularity in contemporary bridge engineering. The primary objective of this paper is to collect and summarize the key references on the analysis, design, and construction of these structures. The review details all aspects and the scope of application, starting with different profiles of curved girder bridge design.

Weiwei Lin & Teruhiko Yoda (2010) Horizontally curved composite girder bridges have great potential to be super-abundant in construction benefits. Quick assembly, strong seismic resistance, a lack of construction formwork, and easy space organization have greatly propelled their popularity. This paper focuses on a summary of major references relevant to the analysis, design, and building of these bridges.

M. Sharaf Bayani et al., (2012) Temporary shoring supports assume significant importance in bridge construction, particularly in the case of bridge structures with a horizontal shape. They influence the shape such that there is no over-bending of elements and prevent the bending of any of the girders. However, established design recommendations provide little assistance for the correct sites to place them. Each construction site differs in how many shoring towers and at what locations

they sit. If designers and builders had guidance during construction about where to place the supports — given the overall characteristics of a bridge, such as span count and curvature radius — it would save scheduling time for the towers. The subject of this study wanted to further examine this notion. The researchers examined how the arrangement of shoring towers affects the performance of curved bridges at various stages of construction. They conducted step-by-step analyses of different simplified double-span curved bridges, all with different radius parameters.

Nidhi Gupta, Preeti Agarwal & Priyaranjan Pal (2019) RCC box girder bridges are studied using single, double, and triple cells. It is performed with finite element technique and linear static analysis. Various curvature levels, from 0° to 60° and at 6° steps, are taken into account. The load cases depend on dead loads and live loads, according to the Indian Road Congress (IRC). The study examines the contribution of curvature to bending moment, torsional moment, shear force, and deflection. This also suggests that such variables will be enhanced with an increase in curvature. Specifically, the deflections increase by about 295% (single-cell), 280% (double-cell), and 245% (triple-cell box girders), when comparing straight bridges to 60° bent structures. Thus designing curved bridges presents such complex complexity that there are no straightforward problems present in building such bridges.

Tanmay Gupta, Dikshit Sandhu (2021) Vibration Patterns and Frequencies: All configurations exhibit an in-plane vibration as their first mode. This is followed by the longitudinal and out-of-plane modes. When the skew angle remains unchanged, increasing the curvature leads to a decrease in the time period of the first in-plane mode. This might be due to an "arching action" that makes the deck less flexible. On the other hand, keeping curvature fixed while increasing the skew angle results in longer time periods for both the first in-plane and longitudinal modes.

Chandrashekhar Khulhare, P. K. Singhi (2022). More complicated bridge designs, having horizontal curves and skewed structures, have more seismic risks when compared to a straight structure. During earthquakes, deck rotation and unseating are also higher risk. For vibrational behavior, when using a more curved bridge deck it will result in a smaller time period ratio for the first horizontal vibration mode. On the contrary, increasing the skew angle has the effect of increasing those time period ratios for the first horizontal mode, but lowering them respectively for the initial vertical and out-of-plane modes. For longitudinal vibration, increased skewness and curvature give an increase in time period ratios and a reduce in the natural frequencies. By modal analysis, the results seem to show horizontal vibration modes are usually found before vertical ones no matter how skewed or curved appears.

Mohammad Farhan Shaikh, Nallasivam. K (2022). Recently, box-girder bridges are enjoying great popularity. Because they work better in serviceability, stability, and structural efficiency. Also that they weigh less than other types of bridge. The difficulty designers encounter when evaluating these structures, however, stems from the complexity of the procedure involved. This paper will show you a route for modelling and investigating a box-girder bridge at ballast-less sub-track-based tracks by application of the finite element approach. This report compares performance of the bridge in the case of static load, with view to Indian Railway standards. The bridge is a three-dimensional model, which has then been analyzed with non-closed form processes. Asymmetric and symmetric loads have been applied to the ANSYS software application using the finite element method (FEM).

Luo Liang, Suhui Yu, Yuzhou Zheng, Jian Yuan (2022). By means of numerical shape functions and the structure stressing states theory, this work discusses the behavior of a curved prestressed concrete box girder bridge under different loads. First, the generalized strain energy density (GSED), obtained from real strain measurement, defines the stress pattern of the structure. However, to know about the concrete section stress state, both strain and stress fields within the bridge model are investigated. From these patterns and fields, we will learn about the bridge mechanical

characteristics. In addition, the next step is to interpolate the strain data at concrete according to Non Sample Point interpolation model (NPI). The stress-strain patterns in the bridge model are plotted to demonstrate how the concrete cross-section is stressed. The internal loads in these regions are estimated using interpolated strain. Torsional effects are modeled through tracking displacements to reveal how the cross-section undergoes twisting. Comparing internal forces and strain fields reveals common and different mechanical properties of the bridge model. Insights from this approach to analyze curved bridges can thus inform next bridge designs.

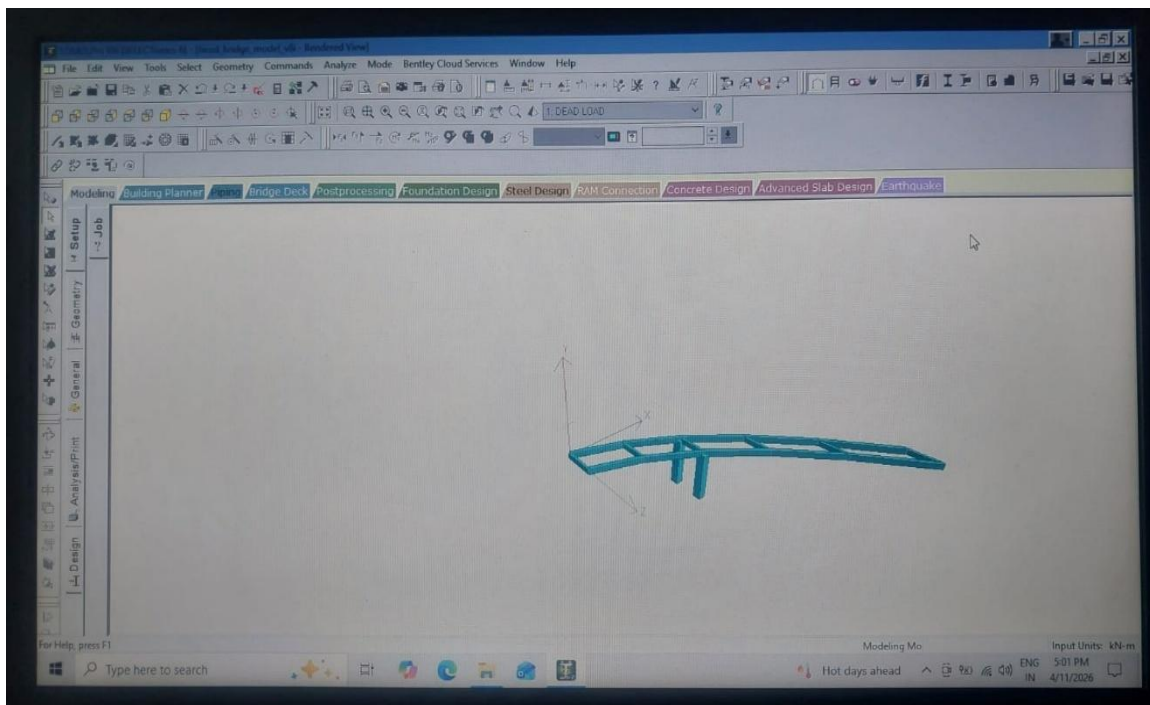
Fatemeh Asen a, Hossein Pahlavan a, Mohammad Shamekhi Amiri a, Ali Naseri (2024). The study investigates the behavior of skew-curved concrete box-girder bridges under the influence of earthquakes, both close to and far from fault. The analysis employed nonlinear time-history and analyzed two skew angles: 15° and 45°. This enabled the form of fragility curves to be calculated from component level and fragility surfaces from system level. In the analysis we employed two intensity measures, PGA and SA(T1), providing a complete picture of seismic demand. The results indicated that columns and risk of deck unseating had the lowest median values (approximately 0.3–0.5 g). These aspects were mainly responsible for possible system failure. In addition, the overall bridge damage risk was assessed using a Vulnerability Index (VI) framework. It was discovered that near faults ground displacements increased the susceptibility significantly; VI values rose by about 10–15%. The effect is much greater than far-fault tremors. Raising the skew angle raises risk by up to 10%. This is mainly due to high torsional forces and the risk of deck displacement. The VI values reflect that at R1.0g (the limit of the PGA and SA(T1) ranges) the damage is negligible, although at 1.0g (the maximum value being SA(T1)), damage suddenly transitions from minor to complete with >80% of total failure.

Nina Serdar, Radomir Folić (2026). The formed PSDMs are also analyzed to see how efficient, advanced, and enough of an aid they are. In the researches conducted, skewness and curvature effects on the seismic characteristics are mentioned on the bridges are noticed. This is especially the case when comparing the means of column displacement ductility values to the established prediction models as well as the fragility demand curves. These effects become more salient in bridge that has single pier bents, which have only one weak direction compared to double pier bents. Other studies have shown that using structure-dependent measures in PSDMs produces higher accuracy models. We propose developed modified models that include resultant measures and responses for the analysis of the fragility of curved and skewed bridges.

3. Methodology

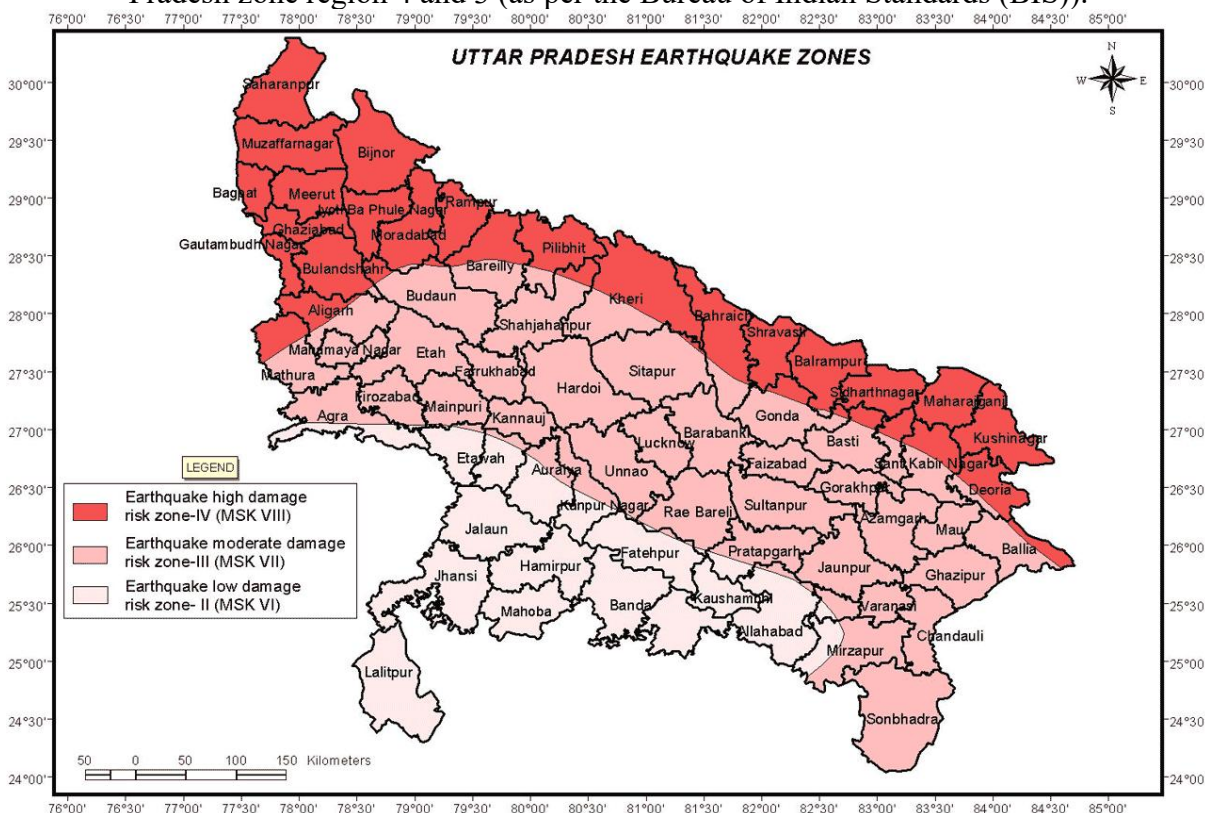
A method for analyzing the seismic behavior of skew-curved bridges is the Finite Element Method (FEM). In this part it provides numerical analysis. A mathematical method of taking a complex structure and breaking it down into more manageable units helps to capture how the stress distributes unevenly due to the combination of horizontal curves and skewed boundaries. For this research, STAAD.Pro is utilized for modeling the structure of a reinforced concrete box-girder bridge. In the modeling, both overall stability and the concentrated zones of stress are considered. Turning to Indian Road Congress (IRC), our leading technical governing body on highway engineering in India. It was established back in December 1934 with the aim of improving and standardizing road design, construction, and maintenance. Under the jurisdiction of the Ministry of Road Transport and Highways, IRC sets national road and bridge engineering guidelines, standards, and codes throughout the country. IRC:6-2017-Load Standards:

1. CLASS 70R – The heaviest standard loading. Designed for permanent bridges.
2. Tracked Vehicles: 700KN weight Wheeled Vehicles: 1000 KN total weight over multiple axis.



3D model of the SKEW CURVED BRIDGE (Staad.PRO)

PRO for validating Research based Outcomes of IRC standard for Skew Curved Bridge in Uttar Pradesh zone region 4 and 3 (as per the Bureau of Indian Standards (BIS)).



India has been classified into 4 seismic zones (II, III, IV and V) by BIS's 1893 (Part 1): 2002. Uttar Pradesh is distinct since it is located between three of these four zones; this is a risk factor ranging from an average of "Low" to "Very High" damage. Several significant fault lines regulate UP seismicity. Even though the strongest earthquakes come from the Himalayas, the energy is shifted through the deep alluvial soil of the Gangetic plains. Main Central Thrust (MCT) & Main Boundary Thrust (MBT): Though located in Uttarakhand/Nepal, these are the principal drivers of the largest tremors in UP. Moradabad

Fault & Lucknow Fault: These are 'blind faults' that are located in a region of the plains under the dense lay of thick sediment that make the area of mud below it. Such activities may result in moderate-intensity local earthquakes when triggered. Mahendragarh-Dehradun Fault (MDF): A major fault line running through the west of UP which creates great hazards to the National Capital Region (NCR). To engineers and architects in UP, the BIS 2002 code offers a Zone Factor--the Maximum Considered Earthquake (MCE) in each zone: For engineers and architects in UP, the BIS 2002 code provides a Zone Factor, which represents the Maximum Considered Earthquake (MCE) for each zone:

Zone V: $Z = 0.36$ (Highest risk)

Zone IV: $Z = 0.24$

Zone III: $Z = 0.16$

Zone II: $Z = 0.10$

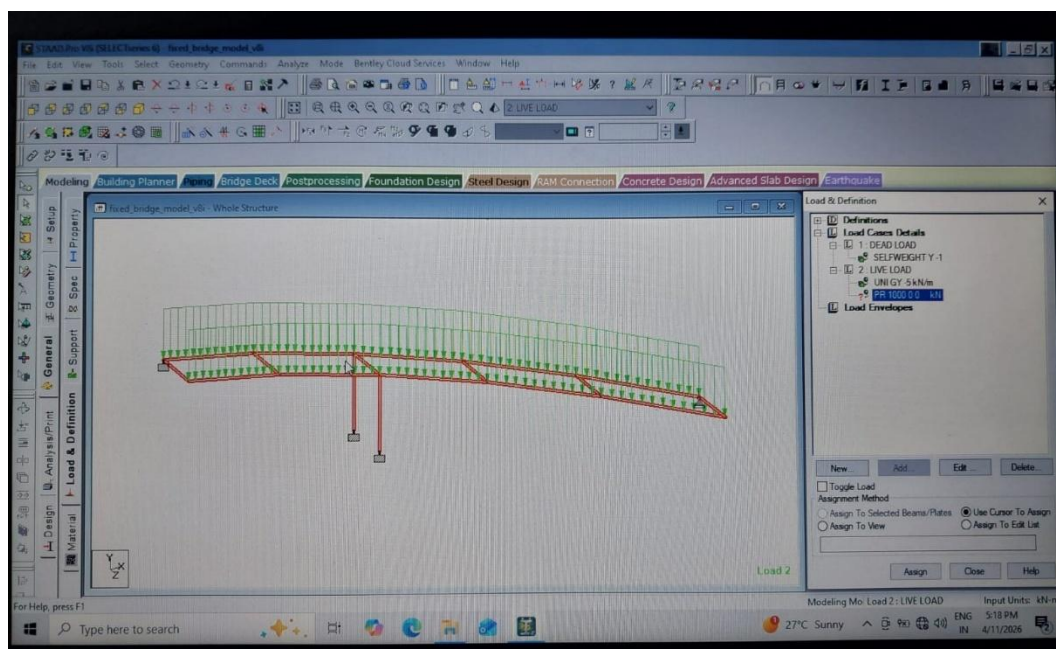
The code mandates that any new construction in Zone IV and V (like Noida or Gorakhpur) must follow strict ductile detailing to ensure the structures can swing without collapsing during a major event.

4. DESIGN AND LOAD ANALYSIS

The present fig is for live load applied over the skew bridge in static conduction and by this means, the analysis has shown no sign of error, hence making the standards applicable in the ideal conditions.

Required Parameters:

1. Skew angle $> 20^\circ$ often requires advanced analysis beyond simple distribution formulas.
2. Finite Element Method (FEM) is recommended for accurate modelling of skew bridges.
3. IRC:6-2017 aligns with modern practices to ensure safety, durability, and serviceability of skew bridges under Indian traffic and environmental conditions.



LIVE LOAD ACCORDING TO IRC:6-2017

Fig. 2 illustrates the skew with live load and seismic characteristics according to Zone 4 (the highest zone according to BIS 2002).

SEISMIC PARAMETERS:

- Seismic Zone value- 0.24
- Response Reduction Factor-5
- Importance factor-1.5

- Soil Site factor-2
- Damping Ratio-0.05
- Period in x-direction-0.52
- Period in y-direction-0.5

Experimental and Modelling Implications: Taken together, these results suggest Staad.PRO models for skew curved bridges cannot be limited to the basic line modals; they must also incorporate the 3D box-girder representation, Torsional Stiffness, Skew abutments, and realistic bearing, gaps, and contact elements. Modals, response-spectrum, and other non-linear analyses using multi-component input wherever available are required to model the coupled translation torsion response pattern and demand concentrations found in the literature.

5. Conclusion

This is conclusion we got in our research.

- Geometry Strong Influence Geometric skew angle and curvature of the bridge have an important effect on its seismic response and hence its complex torsional behavior and non-uniform force distribution in contrast with straight bridges.
- Seismic loading leading to Increased Torsional effects Skew curved bridges, for a particular function, have significant torsional moments induced by seismic loading, which increases their susceptibility to rotation and uneven displacement across supports.
- Uneven load distribution due to skewness which occurs in a relatively uniform distribution of seismic force across the piers and bearings will lead to a greater load on specific structural parts.
- Greater Displacement in Zone IV As the bridge is located in Seismic Zone IV, lateral displacement and stresses are significant and therefore designing of this bridge with adequate detailing is required for structural stability and serviceability.
- Critical Role of Bearings and Support Bearings and support conditions are a critical aspect of seismic strength and performance, and inappropriate design practices may result in excessive movement or failure during intense ground motion.
- The application of Dynamic Analysis (response spectrum or time history is the most relevant) since static methods will not give a complete representation of skew curved bridges.
- Need for improvement in design: The present study suggests the importance of improved design criteria including ductile detailing as well as BIS 2002 to provide the appropriate safety and robustness mechanisms in the skew curved bridge in high seismic zones.

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