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SEISMIC ANALYSIS OF CURVED I GIRDER BRIDGE

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Abstract - *This research was conducted with a view to understanding the seismic performance of curved I- girder bridges concerning curvature radius, span length, and intensity of earthquake. Such bridges have been very common in modern infrastructure and grow increasingly and are vulnerable to seismic events. This M-tech project's aim was to analyse the seismic performance of curve I girder bridges. This project focusing on curvature influence, force distribution, deformation pattern during seismic events. The Project involved the linear and nonlinear seismic analysis to understand the static and dynamic response of the bridge. The seismic analysis was done on the curve bridge model of having 5 span and length 100m. The earthquake effect was analysed on the bridge model and tried to analyse the forces on bridge, displacement in bridge and stress distribution by the use of nonlinear time history analysis method. The Advanced CSI bridge v26.1.0 software employed to model bridge structures and simulates seismic loads, considering nonlinear material behaviour and dynamic response. This research work was aimed at evaluating, under different seismic scenarios like along the longitudinal direction or transverse direction. The stress distribution, deformation, and mechanisms of possible failure analysed by the software. The results show a strong curvature effect on the seismic response of these bridges. The earthquake zone 5 of Indian region was taken as reference in this project. The earthquake zone 5 includes the region of Kashmir, POK border with Nepal, Sikkim and northeast region of India. These areas are vulnerable to the severe earthquake*

Key words: **I girder, seismic, earthquake zone, time history, CSI Bridge**

1. INTRODUCTION

Curved I-girder bridges are unique and more complicated than straight bridges. These types of bridges are desirable in hilly and mountainous region where the space and difficult terrain gives less space for highway bridge construction. In hilly and mountainous region curved bridges could be horizontally curved or vertically curve depending upon the terrain. Other than hilly and mountainous region, in city areas where space is constraint these types of curved bridges fulfill the criteria of highways. For city purpose it could be curved steel girder or curved steel box girder and curved concrete box girder. The curved bridges unique geometry brings special challenges to the designers to design structures under earthquake loadings. As opposed to straight members, these structures are exposed more complicated load distributions as a result of interaction between bending moment, torsion and axialforces under the influence of seismic loads. Dynamic forces and torsional forces are prominent due to of curved geometry, and as a result increased stresses, deformations can be caused which vulnerability towards damage. Bridge curves arise from various factors such as site limitations, vertical and horizontal alignment, traffic density as well as speed limit variation. Usually, for the construction of curve bridges, box girder bridges become more advantageous owing to their cellular cross section that is capable of withstanding high twisting moments. However, for this case, I girder curve bridge is being studied. Mainly the arch-shaped bridges are accepted and utilized more because of their effectiveness, stability, functionality, cost efficiency, and beauty. Most often they are designed to be circular in shape with transitional curves. In the case of curved bridges, torsion being induced influences the bridges response in axial, shear andtorsional bending moments. This causes a distortion on the cross-section of the bridge and leads to differential stresses on the flanges. Edged over by the availability of computer technology with sophisticated analysis tools, the design and analysis of highly curved bridges are now easier. Analytical evaluation of the bridges that are curved in plan involves more challenges compared to straight bridges because they are affected by both bending and twisting due to the curvature of the girders. Hence the section selected for curved bridge design should possess a high torsional rigidity for effective use of the section. In the case of small curvature bridge, effect of curve angle on BM, SF, TMand VD can be ignored if it is within the limits.

1.1. SESISMIC EFFECT ON BRIDGE

1.1.1. SEISMIC DISPLACEMENT: Seismic displacements in bridges refer to the movements or shifts in a bridge structure caused by seismic forces during an earthquake. When an earthquake occurs, ground motions induce forces that travel through the earth, causing the bridge's foundation and superstructure to experience displacement, both horizontally and vertically. These displacements can have significant effects on the bridge's performance, safety, and overall stability.

1.1.2. PIER FAILURE: Pier failure in bridges due to seismic forces is a critical concern in earthquake engineering. During an earthquake, seismic forces can

induce lateral and vertical ground motions that place significant stress on these piers. If the forces exceed the piers' capacity, failure can occur, leading to severe damage or even collapse of the bridge. Factors like horizontal acceleration and vertical forces played a great role in pier failure. During an earthquake, the ground moves horizontally, which can generate large lateral forces acting on the piers. If the piers are not designed to resist these forces, they may fail due to shear or bending stresses. In addition to horizontal forces, vertical accelerations from seismic waves can create additional loads on the piers, which can cause buckling or failure, particularly in shorter piers that are more susceptible to these vertical motions.

1.1.3. EXPANSION JOINT FAILURE: Expansion joints are essential components in bridge design, allowing for the controlled movement of the bridge deck as it expands or contracts due to temperature fluctuations, settlement, or seismic activity. During an earthquake, the ground motion generates powerful lateral forces that cause the bridge deck to move horizontally. These forces can exceed the design limits of the expansion joints, leading to their deformation, rupture, or complete failure. If the joints cannot accommodate the horizontal movement during an earthquake, they may become overstressed, leading to structural damage. In addition to horizontal displacements, seismic forces can also cause vertical movements in the bridge deck due to vertical accelerations from the earthquake. If the expansion joint is not designed to accommodate both horizontal and vertical movements simultaneously, it can fail under these conditions. Vertical displacements can cause misalignment or even damage to the joint's sealing and connection components.

1.1.4. BEARING FAILURE: Bearings are critical components that transfer loads between the bridge superstructure (deck) and substructure (piers, abutments). They also allow for the relative movement between these components caused by temperature changes, settlement, and seismic activity. During an earthquake, seismic forces can subject bearings to extreme stresses. During an earthquake, horizontal ground motion generates lateral forces that cause the bridge superstructure to move relative to its foundation. Bearings are designed to accommodate such movements, but if the seismic forces are too great, they may exceed the bearing's capacity, leading to failure. This could result in the bridge deck moving off alignment or collapsing. Bearings that are intended to allow movement (sliding bearings) may experience excessive displacement during an earthquake, leading to slippage or loss of control over the movement. This can cause instability and misalignment of the bridge deck.

1.1.5. ABUTMENT SLUMPING: Abutment slumping in bridges refers to the failure or displacement of the bridge's abutment, which is the structure that supports the ends of the bridge and transfers loads from the bridge deck to the foundation or underlying soil. Abutments are typically designed to resist vertical and horizontal loads, including the forces exerted by the bridge deck and traffic. However, during seismic events, seismic forces (horizontal ground motion, vertical shaking, or both) can cause the abutment to move or slump, potentially compromising the stability of the entire bridge structure. During an earthquake, horizontal ground motion exerts lateral forces on the abutment. The lateral forces may push the abutment back or sideways, causing it to shift or even fail. Seismic forces also cause vertical ground accelerations that may affect the stability of the abutment. If the ground beneath the abutment becomes unstable due to the shaking, it may result in settlement or tilting, causing the abutment to slump. This vertical displacement can further misalign the bridge deck or lead to foundation failure. When soil liquefaction occurs beneath or around the abutment, it can cause significant settlement or tilting of the abutment. This loss of support can result in the abutment slumping and, in severe cases, cause the collapse of the bridge.

X1.1.6. FOUNDATION FAILURE: The foundation of a bridge plays a critical role in transferring the loads from the superstructure (bridge deck and other elements) to the ground or underlying bedrock. During an earthquake, lateral ground motion generates significant horizontal forces that can cause sliding or shifting of the foundation. Seismic shaking can cause uneven settlement of the foundation, especially in areas with soft or loose soils. The differential settlement (where one part of the foundation settles more than another) can lead to tilting or distortion of the bridge deck, potentially causing it to crack or displace. Settlement failure occurs when the foundation sinks unevenly, often due to the soil beneath the foundation being unable to support the weight of the bridge during an earthquake. Differential settlement can cause the foundation to tilt or distort, affecting the entire bridge structure. Shear failure occurs when the foundation experiences excessive shear forces that cause it to crack, break, or fail. This can happen when the foundation is not properly reinforced or when the seismic forces exceed the shear capacity of the materials used in the foundation.

1.1.7. COLLAPSE DUE TO SOIL LIQUIFACTION: complete collapse of bridges because of soil liquefaction is a significant concern during seismic events, particularly in areas with loose, saturated soils. Soil liquefaction is a condition that occurs during an earthquake when saturated, loose soils (usually sandy soils) experience an increase in pore water pressure due to seismic shaking. As the soil particles lose contact with each other, the soil temporarily loses its shear strength and behaves like a liquid. This can cause the ground to become unstable, resulting in differential settlement,

lateral spreading, or tilting of structures that are supported by this soil. Differential settlement occurs when the soil beneath the bridge foundation undergoes uneven liquefaction. Different areas of the foundation may experience varying degrees of settlement, which can cause the bridge deck to tilt, crack, or become misaligned. Liquefaction causes the soil to lose its ability to bear loads.

1.2. EARTHQUAKE

Earthquake is the shaking of the earth surface that causes tremendous disaster in the world. It causes because of sudden release of energy from the lithosphere that creates seismic waves. Earthquake causes naturally or be induced by man-made activities such as mining, nuclear test and fracking. Naturally Earthquake generally caused by geological faults, volcanic activity, land slide, tsunami and other seismic events. The location below which earthquake starts is called hypocenter and on the surface it is called epicenter. The earthquake generally occurs along fault lines and narrow zones where two tectonic plates or part of rock slides over one another. Seismology is the science which studies seismic events. Through this we know about the causes of earthquake and intensity of earthquake. Major earthquakes tend to occur in regions where tectonic plates meet, with one of the most significant earthquake zones being the Pacific Belt. The belt, which surrounds the Pacific Ocean, experiences frequent seismic activity that affects areas such as New Zealand, Papua New Guinea, and Japan. Seismic activity within the Pacific Belt is not uniform, and it includes several branches in different regions. Many of these areas are also associated with volcanic activity, earning the belt the name "Ring of Fire." In addition to pacific belt The Alpide belt also vulnerable to earthquake. Alpide belt stretches from east of Mediterranean to the west of East Indies. This belt accounts for about 15% of the energy released by earthquakes, but it has less volcanic activity compared to the Pacific Belt.

1.2.1 CAUSES OF EARTHQUAKE

1.2.1.1 TETONIC

This is the most common cause. The Earth's outer shell, or lithosphere, is divided into large, rigid plates that float on the semi-fluid asthenosphere beneath them. These plates constantly move, and when they interact (collide, slide past, or pull apart), stress builds up and is released as seismic energy. The fracture in rock propagated in the same direction or in the area of weak direction and extended too many kilometers. This theory was given by harry fielding Reid after observing and research on san Andrea fault which causes san Francisco earthquake in 1906. As fault rupture progresses towards the fault the rock masses tried to move in opposite direction and thus due to strain it bounces back to a position where there is less strain. This movement when happens again and again there is rise in vibration and that propagates as seismic waves.

Example of earthquake due to tectonic movement

1976 Tangshan Earthquake
1999 Taiwan Earthquake

1.2.1.2 VOLCANISM

Earthquake in volcanic regions often occurs due to both tectonic faults and magma movement in volcanos. Earthquake swarms serves as markers for the location of the flowing magma throughout the volcanos. These swarms recorded through seismometers and tilt meters.

Example: - 1980 mount Helens earthquake.

1.2.1.3 FAULTING

Faults are fractures in the Earth's crust where blocks of rock have moved relative to one another. When stress builds up along a fault and overcomes the friction holding the rocks together, it causes a rupture, resulting in an earthquake.

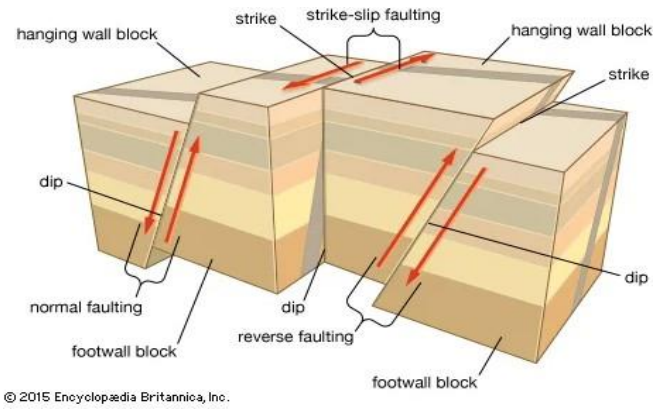

Fig -1: Faults in tectonic plates

1.3. EARTHQUAKE ZONES IN INDIA

The earthquake zones in India are identified by using the modified Mercalli intensity. It measures how earthquake affects areas. After the Latur earthquake in Maharashtra in 1993, the seismic map was updated. According to map low danger zone called seismic zone 1 was combined with seismic zone 2. So zone 1 not shown after update.

1.3.1. ZONE- 2

It is low intensity area and it covers around 40% of India's land. This includes the Karnataka plateau and peninsular region of India.

1.3.2 ZONE- 3

It includes the area of Kerala, goa, Lakshadweep Island along with the parts of Punjab, Rajasthan, MP, Bihar, Jharkhand, Odisha, and Tamilnadu and so on. It covers the area around 30% of country.

1.3.3 ZONE- 4

It covers around 18% of land. It is a high intensity zone. It includes the area of J&K Himachal Pradesh, border with Nepal, Sikkim, UP, West Bengal, Bihar, and coast of Maharashtra.

1.3.4 ZONE- 5

It is extremely severe zone. It covers around 10% of land of country. It includes Himachal Pradesh, Rann of Kutch, north Bihar and Andaman & Nicobar Island.

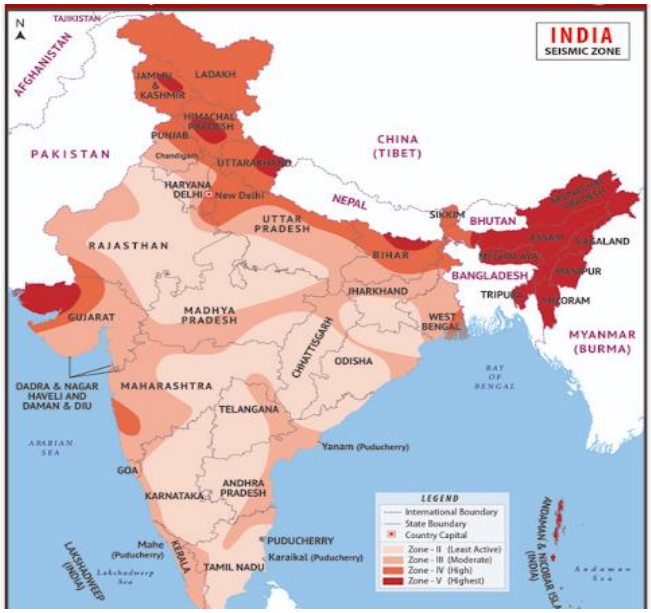

Fig -2: Earthquake zones of India

1.4 AASTHO LRFD CODE

The AASHTO LRFD Code is a set of design guidelines for highway bridges in the United States. It provides a modern, comprehensive method for designing and evaluating the structural integrity of bridges and transportation-related infrastructure. The LRFD approach is based on probability and reliability theory, which ensure the safety, performance, and durability of bridge structures over time, even under unpredictable conditions. The code incorporates load and resistance factor design, where different factors are applied to account for various uncertainties in both the loads (such as traffic, wind, and seismic forces) and the structural resistance (such as material properties and construction variations). This design methodology ensures that bridges can withstand extreme events without overestimating or underestimating their safety margins. One of the key principles of the AASHTO LRFD Code is to ensure that bridge designs are cost-effective while still meeting safety and performance standards. The code is regularly updated to reflect advancements in materials, technology, and engineering knowledge. It considers a wide range of bridge types, including both simple and complex structures, and it provides detailed guidance on materials, geometry, and load distribution for various scenarios. The AASHTO LRFD Code is essential for ensuring that bridges are designed and built with the highest level of safety, efficiency, and sustainability. It plays a crucial role in maintaining the integrity of the U.S. transportation system, providing engineers and designers with the tools they need to create infrastructure that can safely handle the demands of modern traffic, weather conditions, and other environmental factors. It also ensures that new bridges are capable of performing over the long term, minimizing the need for costly repairs or replacements.

1.5 METHOD OF SEISMIC ANALYSIS (IRC CODE)

As per IRC code IRC SP-114-2018, the seismic analysis on bridge structure could be done by three methods.

1.5.1 Seismic coefficient Method

1.5.2 Elastic response spectrum method

1.5.3 Time history method

1.5.1 Seismic coefficient method

This method of analysis is used for low and medium height structure. Other than this the structure with small span and length be analyzed by this method. The structure is analyzed by this method in single mode vibration. The seismic force resisted by bridge computed by,

F= A× (Dead load or Live load)

Where,

F= Horizontal seismic force

A= Horizontal seismic coefficient

Horizontal seismic coefficient determined by formula,

$$A = (Z/2) \times (S/g)/ (R/I)$$

Where,

Z= Zone Factor

I= Importance Factor

R= Response Reduction Factor

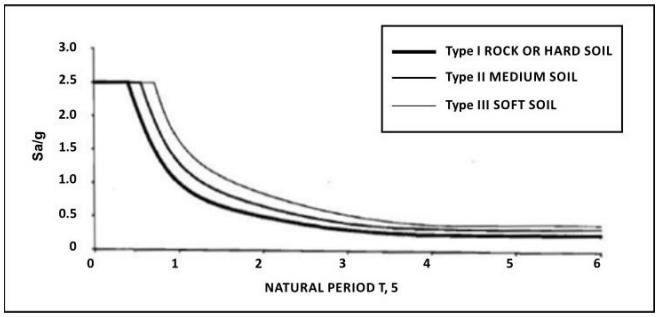

Chart- 1: s_a/g curve for seismic coefficient method

Where,

$$\frac{S_a}{g} = \begin{cases} \text{For rocky or hard soil site}: \begin{cases} 2.5 & 0 < T < 0.40\ s \\ 1/T & 0.40\ s < T < 4.00\ s \\ 0.25 & T > 4.00\ s \end{cases} \\ \text{For medium stiff soil sites}: \begin{cases} 2.5 & 0 < T < 0.55\ s \\ 1.36/T & 0.55\ s < T \le 4.00\ s \\ 0.34 & T > 4.00\ s \end{cases} \\ \text{For soft soil sites}: \begin{cases} 2.5 & 0 \le T \le 0.67\ s \\ 1.67/T & 0.67\ s \le T \le 4.00\ s \\ 0.42 & T > 4.00\ s \end{cases} \end{cases}$$

Table- 1: Zone Factor

Zone No.	Zone Factor (Z)
V	0.36
IV	0.24
III	0.16
II	0.10

Table-2: Importance Factor

Seismic Class	Illustrative Examples	Importance Factor 'I'
Normal Bridges	All Bridges except those mentioned in other classes	1
Important Bridges	a) River bridges and flyovers inside cities b) Bridges on National and State Highways c) Bridges serving traffic near ports and other centres of economic activities d) Bridges crossing two existing/proposed railway lines (Future lines shall not be considered as proposed railway line)	1.2
Large critical bridges in all seismic zones	a) Long bridges more than 1km length across perennial rivers and creeks b) Bridges for which alternative routes are not available c) Bridges crossing more than two existing/ proposed railway lines	1.5

Table-3: Response Reduction Factor

BRIDGE COMPONENT	'R' WITH DUCTILE DETAILING	'R' WITHOUT DUCTILE DETAILING (for Bridges in Zone II only)
Substructure		
(i) Masonry / PCC Piers, Abutments	1.0	1.0
(ii) RCC Wall piers and abutments transverse direction (where plastic hinge cannot develop)	1.0	1.0
(iii) RCC Wall piers and abutments in longitudinal direction (where hinges can develop)	3.0	2.5
(iv) RCC Single Column	3.0	2.5
(v) RCC/PSC Frame (Refer Note VI)	3.0	2.5
(vi) Steel Framed	3.0	2.5
(vii) Steel Cantilever Pier	1.5	1.0
Bearings and Connections (see note(V) also)	1.0	1.0
Stoppers (Reaction Blocks) Those restraining dislodgement or drifting away of bridge elements.	1.0	1.0

1.5.2 Elastic Response Spectrum method

This method is used for the analysis of complex structure. Complex structure includes continuous bridges, Bridges with different pier height and bridges which are curved. The bridges with pier height more than 30m are analyzed by this method.

1.5.3 Time History Method

This method is typically used for bridges with high pier heights or those that experience sudden changes in mass, stiffness, or geometry along their spans. It is also applied when there are significant differences in the parameters between adjacent supports. The dynamic analysis of such bridges is conducted using the time history method, which integrates the equations of motion step by step, ensuring that the highest mode of vibration is properly accounted for. The key difference between linear and nonlinear time history analysis lies in how the lateral resisting forces are represented. In elastic systems, these forces are a simple function of displacement, whereas, in inelastic systems, they depend on the prior motion history.

Table-4: Analysis of various bridge methods

Type Of Bridge/Pier Height/Span		Condition	Pier Height	Method of analysis in Seismic		Remarks
				II & III	IV & V	
Right Bridge or Skew Up to 30º or curved span having radius more than 100 m	Simply Supported individual span	0 to 60m	Up to 30m	ESAM	ESAM	
			Above 30 m	ERSM	ERSM	
	Simply Supported individual span	60 to 150m	Up to 30m	ESAM	ERSM	
			Above 30 m	ERSM	ERSM	
	Individual Span	> 150m	Up to 30m	ESAM	ERSM	
			Above 30 m	ERSM	ERSM	
	Continuous/Integral Bridges	<150m between exp. joints.	All heights	ERSM	ERSM	
		>150m between exp. joints	All heights	ERSM	ERSM*	Spatial Variation of ground motion to be considered
	Bridges Located on Geological discontinuity	All Spans	All heights	ERSM*	ERSM*	Refer Note 3
	Major Bridges in "Near field or Bridges on soils consisting of marine clay or loose sand (eg where soil up to 30m depth has an avg SPT value≤10)	All Spans	All heights	ERSM*	ERSM#	#site Specific Spectrum preferable
	Arch Bridges	Filled up Arch	-	ESAM	ESAM	
		All other Arch	-	ERSM	ERSM	
Bridge With	Difference in Pier Heights/ Stiffness	Large	All heights	ERSM	ERSM	Refer Note 4
	Curved in Plan	< 100 m radius	All heights	ERSM	ERSM*	
	Skew Angle	>30 ◦	All heights	ERSM	ERSM*	
	Cable Stay, Suspension & Extradosed span	Main Span <600m	All heights	ERSM*	ERSM#	#site Specific Spectrum for zone IV & V preferable
Bridges founded on site with sand or poorly graded sand with little or no fines or in liquefiable soil in all seismic zones			All heights	ERSM	ERSM	Evaluation of liquefaction potential shall be carried out as given in Appendix A2
Bridges with Shock Transmission Units (STU), Seismic isolation devices or Seismic dampers etc			All heights	ERSM#	ERSM#	#site Specific Spectrum preferable

2. LITERATURE REVIEW

Mohammad Farhan et al (2020)

A review study on seismic analysis of RCC Bridge with Nonlinear pushover analysis method was conducted by the [md Farhan et al]. Nonlinear pushover analysis method currently used for analytical evaluation of the behaviour of the structure in inelastic range. Previously nonlinear analysis method was limited by its assumptions such as taking fundamental node which control structure response, distribution of lateral forces was fixed for monitoring nodes and target displacement. Currently this method being upgraded to include higher modes as compared to limited modes previously. Due to the induction of higher modes the standard pushover analysis method is equivalent to the level of the time history method. Previously this method was used to investigate only building frames. The aim of study was to investigate the applicability of the standard pushover analysis method in case of complex bridge structure. The study reviewed numbers of literatures of various researchers.

Anurag Deshpande ET all (2017)

The main aim of the research was to conduct the comparison between box Girder Bridge and I Girder Bridge along with some column skewness. The horizontal curvature and column skewness simultaneously implement lot of instability to the bridge. The study was conducted on a bridge model of 2 spans, each span had length of 50m, both ends of the bridge had an abutment and the mid span of the bridge was supported by a circular column of 1.5m diameter. One bridge model had box girder and other had I girder and rest of the item was same for both the bridge model. The radius of curvature was taken as 150m and 250m. The study was conducted for three cases of column skewness i.e. 0, 15, 25 degree. The bridge model was made by the use of software CSI bridge v 21.1.1. Research was conducted for both seismic loading and vehicular loading. The vehicular loading was conducted by IRC class AA and IRC 6 of vehicle loading. The research conducted by the researchers i.e. [Anurag Deshpande et al] concluded that I girder bridge model vibrates in both transverse and longitudinal direction but box girder bridge model did not behave like that. Box Girder Bridge only vibrates in the longitudinal direction so, from this result it was concluded that box Girder Bridge has more stability as compared to I Girder Bridge. As column skewness increases there is increase in transverse vibration and decrease in longitudinal vibration. The result showed as the radius of curvature increases the base reaction decreases. So, high radius of Curvature Bridge would be more stable as compared to the low radius of curvature.

Andreija raseta et al (2016)

The study was aimed to evaluate the seismic performance of reinforced concrete (RCC) structures, focusing on their resilience against earthquakes. The design involved a continuous girder bridge with four spans (35m, 50m, 50m, 35m), with piers of varying heights (7m, 14m, and 21m), fixed to the ground. The analysis considered both geometric nonlinearity (P-Delta effect) and material nonlinearity (fibre model for plastic hinges) to assess the bridge's response to seismic forces. Artificially generated and recorded earthquake Accelerograms were applied during the dynamic analysis. The main findings highlighted that bridges in earthquake-prone areas should be designed to remain functional post-earthquake. Structural damage should be minimized, especially in critical components like piers, to prevent failure and ensure safety.

Thomas Wilson ET all (2014)

The study was focused on the seismic response of skewed and curved RCC bridges in mountainous regions. Researchers analysed eight different bridge configurations with varying degrees of skewness and curvature, under low to moderate seismic conditions, which are typical in mountainous areas. To assess how these bridges respond to earthquakes, they performed nonlinear time history analysis using finite element models. The results showed that skew and curvature significantly affect seismic performance, and when combined, they create stacking effects, making the bridge

more vulnerable. Understanding how skewed and curved bridges behave during earthquakes is crucial for designing safe and resilient transportation systems. Since these bridges have complex geometries, their seismic response is also more complex compared to regular straight bridges. While skewed bridges offer design flexibility, they have historically been linked to earthquake-induced failures due to excessive superstructure deflection. The study examined the seismic Response of RCC bridges with continuous deck designs, integral abutments, and stiff backing soils. It also explores how different combinations of skew and curvature impact bridge stability, providing valuable insights for safer bridge design in earthquake-prone regions.

N. K Manjula et al. (2013)

The study compared various pushover analysis methods outlined in international standards; using an RCC building frame designed according to the provisions of IS 1893-2002. The building, designed with a strength-based approach and sufficient ductile detailing, was also evaluated for its performance. Pushover analyses were conducted using two different levels of ground motion, applying the ATC-40 method, FEMA340 method, and their modified method from FEMA440. The results showed that for low seismic activity, the differences between the four methods were negligible. However, in the case of high seismic activity, there was a notable variation in the results.

John L Bignel et al (2005)

The study was focused on assessing the seismic vulnerability of highway bridges supported by wall piers. The analysis was done by nonlinear pushover analysis. The research models the nonlinear structural and material behaviour of various bridge components, including the superstructure, expansion joints, approach embankments, abutments, bearings, wall piers, footings, pile caps, and piles. It also defines failure measures for each component to evaluate their ability to withstand earthquakes. The study was conducted in the Midwestern USA, a region highly vulnerable to earthquakes. Researchers analysed 90 different wall pier bridge models, performing both transverse and longitudinal pushover analyses due to the three-dimensional nature of bridges. In a transverse pushover analysis, a gradually increasing horizontal force is applied perpendicular to the bridge span, testing its resistance to lateral seismic forces. In a longitudinal pushover analysis, the force is applied parallel to the span to examine how the bridge withstands front-to-back movement during an earthquake. By analysing these structural responses, the study provides valuable insights into how wall pier-supported highway bridges behave under seismic loads. The findings help engineers design earthquake-resistant bridges, ensuring greater safety and durability in seismic-prone regions.

3. METHODOLOGY

Geometrical modelling had been done by the use of AUTO CAD software and CSI Bridge v 26.1.0 software. A detailed three dimensional model of I girder bridge including all curved sections for the, I girder, piers and abutments had been made by AutoCAD 2D & 3D software. For carrying out the seismic analysis of curved I Girder Bridge of 100m length of 5 spans, CSI Bridge v 26.1.0 software had been used in this study. Detailed 3d modelling of deck slab and deformation of wearing coat as well as deformation of piers was analyzed through this software. Other than these the base shears, base reaction, shear force, stresses, relative acceleration, relative displacement, relative velocity computed by the use of this software using time history method. The seismic behavior of the bridge had been checked and detailed it through graphs. CSI bridge software is very versatile and productive for the analysis of different kind of bridges.

4. BRIDGE MODEL ANALYSIS

A Typical 3-Dimensional RCC I GIRDER Bridge with up to five spans consist of a continuous 100m long continuous 20m each span with abutment both side had been taken in this study. CSI bridge v26.1.0 software had been used for analyzing the seismic performance of the bridge by the use of time history analysis method.

Table-5: Geometric properties of bridge

Parameters	Unit	value
length of bridge	m	100
No. of spans	NOs	5
No. of girder	NOs	4
Length of each span	m	20
Bridge width	m	9.5
Bridge depth	m	1.5
Deck slab thickness	mm	230
Abutment depth	m	4
Abutment width	m	1.5
Pier cap depth	m	1.5
Pier cap width	m	1.2
Height of pier	m	7
Diameter of pier	m	1.5
Concrete grade used	Mpa	M40
Live load	IRC class A	
Regulations	IRC-5, IRC-6, IRC-SP-114	
Seismic loading	IS:1893-2016	

4.1. MODEL ANALYSIS

The I GIRDER has a seismic response defined by the earthquake forces EQ+X which had been considered in load cases and also other load cases that include a parapet wall, footpath, and wearing coat under vertical loading.

The following figures depict the deformation modes of the I Girder Bridge under seismic loading.

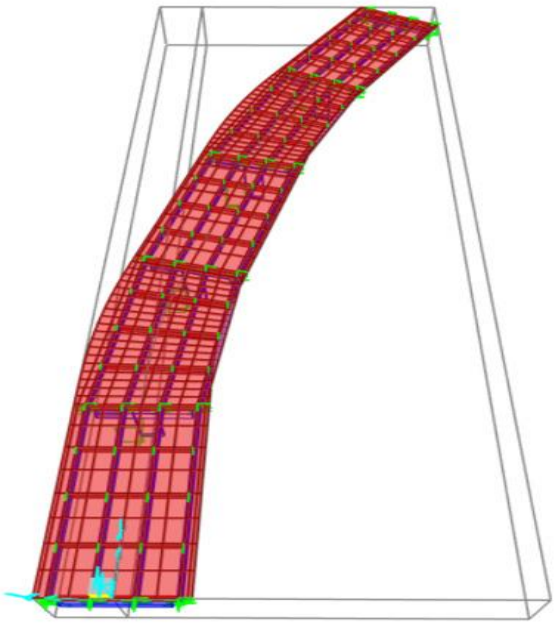

Fig-3: 3D model (plan view)

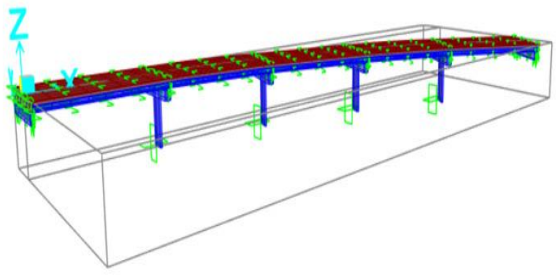

Fig-4: 3D model (sectional view)

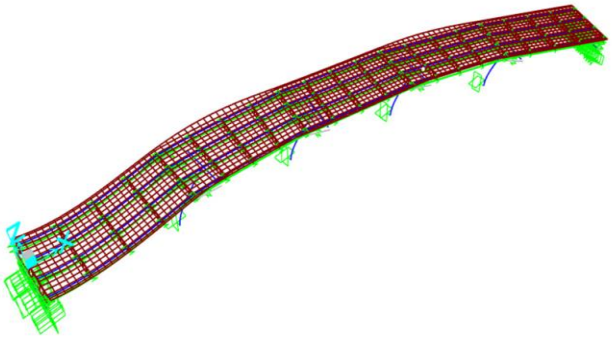

Fig-5: 3D model (Deformed shape of bridge)

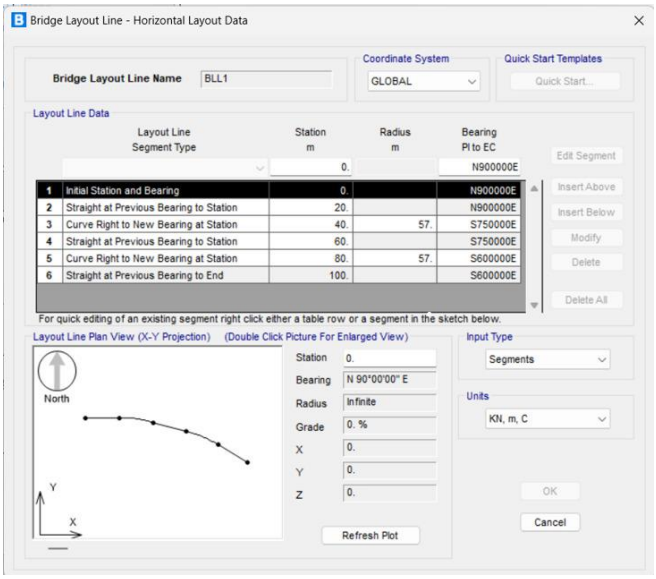

Chart-2: Horizontal layout of bridge model

This graph represents the horizontal layout of the bridge model which had been made by CSI bridge v26.1.0 software. The bridge is horizontally curved of radius 57m at 40m and 80m. The total bridge length is 100m. The bridge alignment is north east. The seismic response of bridge had been checked in EQ+X direction.

5. RESULT

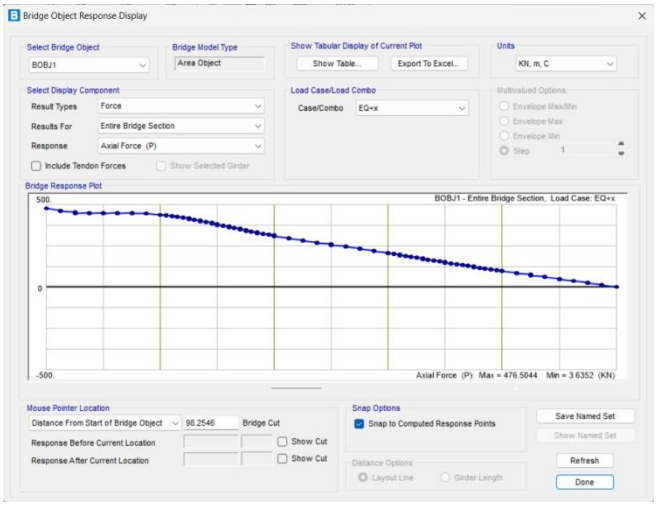

Chart-3: Graph of axial force in entire bridge section

The graph represents the effect of axial force in the entire bridge section. The y- axis represents the axial force that has range between 500 to -500 KN and the x-axis represents the length of bridge. The axial force had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. the

overall axial force on the bridge comes postive. The maximum axial force of 476.504KN comes at starting i.e at 0m of the bridge and minimum 3.635KN comes at the end i.e at 100m of the bridge. The all axial force effect on entire bridge section had been tabulated in table no. 6

Table-6: Axial force (entire bridge section) load case:EQ+x

SR NO.	Layout line distance (m)	Axial force (KN)	SR NO.	Layout line distance (m)	Axial force (KN)
1	0	476.504	13	45	285.73
2	2.5	462.719	14	50	260.044
3	5	446.825	15	55	234.579
4	10	451.043	16	60	202.227
5	12.5	446.605	17	65	175.02
6	15	444.377	18	70	153.841
7	17.5	445.902	19	75	126.364
8	20	436.201	20	80	101.086
9	25	418.081	21	85	76.556
10	30	375.264	22	90	46.801
11	35	347.433	23	95	22.381
12	40	313.563	24	100	3.635

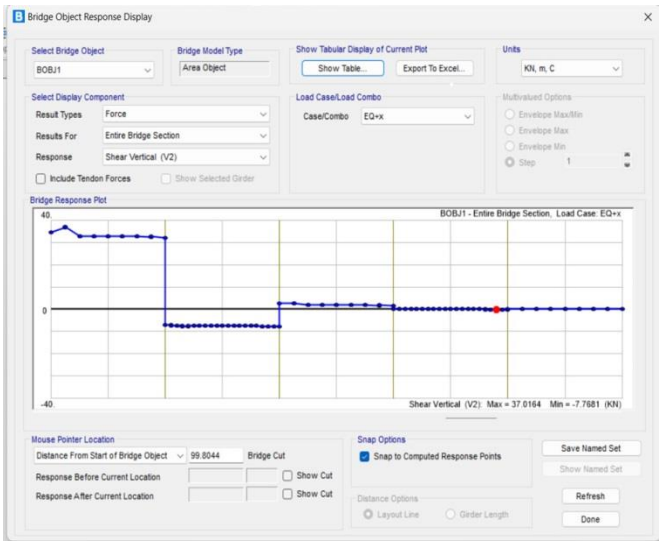

Chart-4: shear vertical (entire bridge section)

The graph represents the effect of vertical shear force in the entire bridge section. The y- axis represents the shear force that has range between 40 to -40 KN and the x- axis represents the length of bridge. The vertical shear force had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall vertical shear force on the bridge comes both postive and negative. The maximum vertical shear force of 37.016KN comes at starting i.e at 0m of the bridge and minimum of -7.768KN comes at the 38m section of the bridge. The negative shear vertical force comes at the range of 20m to 40m section of the bridge model. The all shear vertical force effect on entire bridge section had been tabulated in table no. 7

Table-7: shear vertical(entire bridge section) load case: EQ+x

SR No.	layout line distance(m)	Shear vertical(KN)	SR No.	Layout line distance(m)	Shear vertical(KN)
1	0	34.412	13	45	2.031
2	2.5	36.714	14	50	2.031
3	5	32.825	15	55	2.031
4	10	32.825	16	60	0.291
5	12.5	32.825	17	65	0.07
6	15	32.825	18	70	0.07
7	17.5	32.769	19	75	0.07
8	20	32.022	20	80	-0.042
9	25	-7.267	21	85	0.072
10	30	-7.267	22	90	0.072
11	35	-7.267	23	95	0.072
12	40	-7.748	24	100	0.068

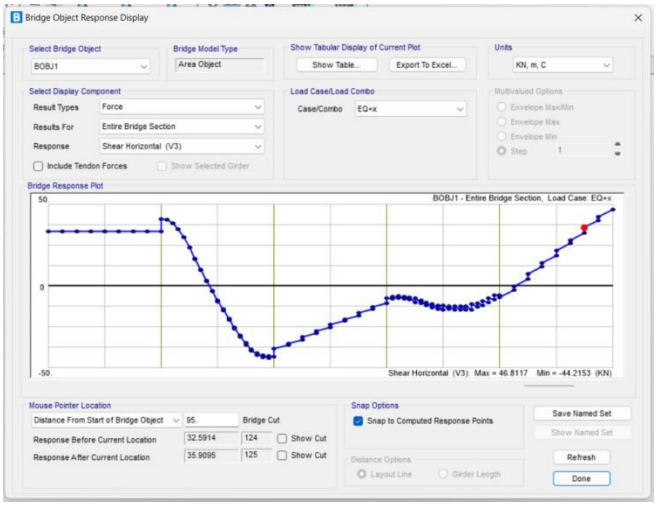

Chart-5: Shear horizontal(entire bridge section)

The graph represents the effect of horizontal shear force in the entire bridge section. The y- axis represents the horizontal shear force that has range between 50 to -50 KN and the x- axis represents the length of bridge. The horizontal shear force had been calculated by the

software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall horizontal shear force on the bridge comes both postive and negative. The maximum horizontal shear force of 46.811KN comes at the end i.e at 100m of the bridge and minimum of -44.215KN comes at the 39m section of the bridge. The negative shear vertical force comes at the range of 29m to 82.5m section of the bridge model.

The all shear horizontal force effect on entire bridge section had been tabulated in table no. 8

Table-8: shear horizontal (entire bridge section)

SR NO.	Layout line distance(m)	Shear horizontal(KN)	SR NO.	Layout line distance(m)	Shear horizontal (KN)
1	0	33.235	13	45	-31.103
2	2.5	21.984	14	50	-23.743
3	5	33.235	15	55	-16.34
4	10	33.235	16	60	-7.54
5	12.5	33.235	17	65	-9.915
6	15	33.235	18	70	-11.731
7	17.5	33.235	19	75	-14.609
8	20	33.235	20	80	-6.83
9	25	23.556	21	85	7.39
10	30	-9.591	22	90	21.608
11	35	-34.619	23	95	35.91
12	40	-38.464	24	100	46.812

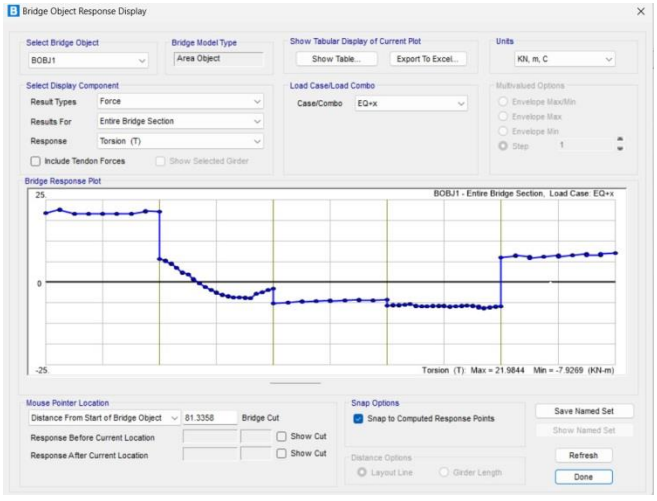

Chart-6: graph of torsion (entire bridge section)

The graph represents the effect of torsional force in the entire bridge section. The y- axis represents the torsional force that has range between 25 to -25 KN-m and the x-axis represents the length of bridge. The torsional force had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall torsional force on the bridge comes both postive and negative. The maximum torsion of 21.984KN-m comes initially i.e at 2.5m of the bridge section and minimum of -7.926KN-m comes at the 77m section of the bridge. The negative torsional force comes at the range of 27m to 80m section of the bridge model.

The torsional force effect on entire bridge section had been tabulated in table no. 9.

Table-9: Torsion (entire bridge section)

SR NO.	Layout line distance(m)	Torsion (KN-m)	SR NO.	Layout line distance(m)	Torsion (KN-m)
1	0	21.016	13	45	-5.907
2	2.5	21.844	14	50	-5.698
3	5	20.791	15	55	-5.493
4	10	20.797	16	60	-7.083
5	12.5	20.797	17	65	-7.269
6	15	20.797	18	70	-7.406
7	17.5	21.631	19	75	-7.357
8	20	7.126	20	80	7.526
9	25	2.371	21	85	7.359
10	30	-3.208	22	90	7.763
11	35	-4.765	23	95	8.157
12	40	-6.422	24	100	8.747

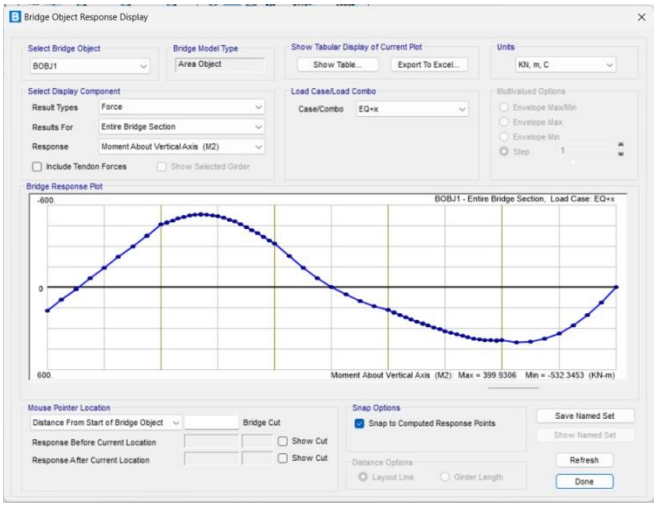

Chart-7: moment in vertical direction (entire bridge)

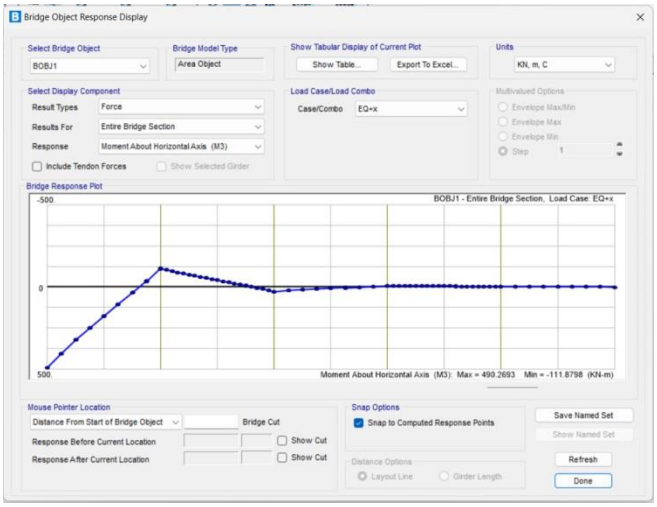

Chart-8: moment in horizontal direction (entire bridge)

The graph represents the effect of moment about vertical axis in the entire bridge section. The y- axis represents the moment about vertical axis that has range between 600 to -600 KN-m and the x-axis represents the length of bridge. The vertical moment had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall moment on the bridge comes both postive and negative. The maximum moment of 399.930KN-m comes at intermediate portion i.e at 82.5m of the bridge section and minimum of -532.345KN-m comes at the 27m section of the bridge. The negative torsional force comes at the range of 7.5m to 50m and at the end i.e at 100m section of the bridge model. The moment about vertical axis effect on entire bridge section had been tabulated in table no. 10

Table-10: vertical moment (entire bridge section)

SR NO.	Layout line distance(m)	Moment about vertical axis(KN-m)	SR NO.	Layout line distance(m)	Moment about vertical axis(KN-m)
1	0	172.476	13	45	-142.751
2	2.5	90.014	14	50	-3.0729
3	5	11.521	15	55	99.658
4	10	-142.543	16	60	164.559
5	12.5	-220.223	17	65	249.144
6	15	-298.896	18	70	320.995
7	17.5	-376.204	19	75	372.403
8	20	-457.212	20	80	387.792
9	25	-524.199	21	85	396.581
10	30	-517.781	22	90	335.579
11	35	-439.540	23	95	202.668
12	40	-319.523	24	100	-1.885

The graph represents the effect of moment about horizontal axis in the entire bridge section. The y- axis represents the moment about horizontal axis that has range between 500 to -500 KN-m and the x-axis represents the length of bridge. The horizontal moment had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall moment on the bridge comes both postive and negative. The maximum moment of 490.269KN-m comes at starting portion i.e at 0m of the bridge section and minimum of -111.879KN-m comes at the 20m section of the bridge. The negative horizontal moment force comes at the range of 17.5m to 36m and from 57.5m to 97.5m section of the bridge model.

The moment about horizontal axis effect on entire bridge section had been tabulated in table no. 11.

Table-11: moment abourt horizontal axis (entire bridge)

SR NO.	Layout line distance (m)	Moment about horizontal axis(KN-m)	SR NO.	Layout line distance (m)	Moment about horizontal axis(KN-m)
1	0	490.269	13	45	16.583
2	2.5	405.218	14	50	8.727
3	5	320.757	15	55	0.830
4	10	178.282	16	60	-6.441
5	12.5	107.423	17	65	-6.081
6	15	35.290	18	70	-4.645
7	17.5	-34.884	19	75	-3.228
8	20	-111.679	20	80	-1.920
9	25	-75.097	21	85	-1.640

10	30	-42.24	22	90	-1.039
11	35	-8.966	23	95	-0.454
12	40	27.407	24	100	0.626

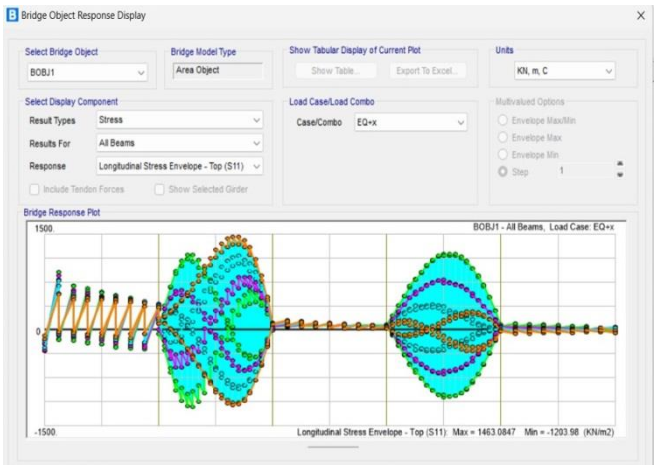

Chart-9: longitudinal stress envelope for all beams (top)

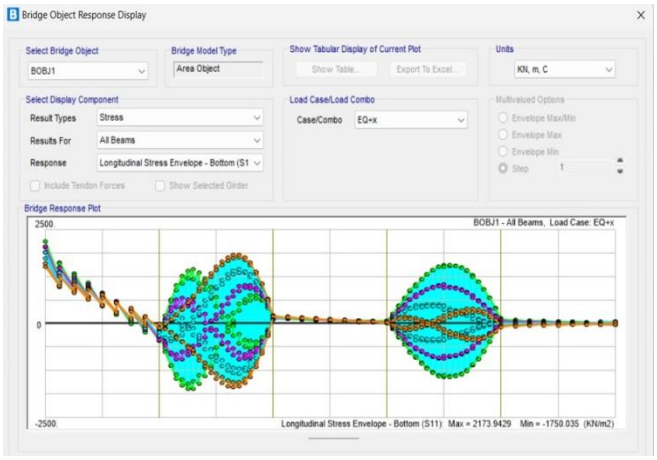

Chart-10: longitudinal stress envelope for all beams (bottom)

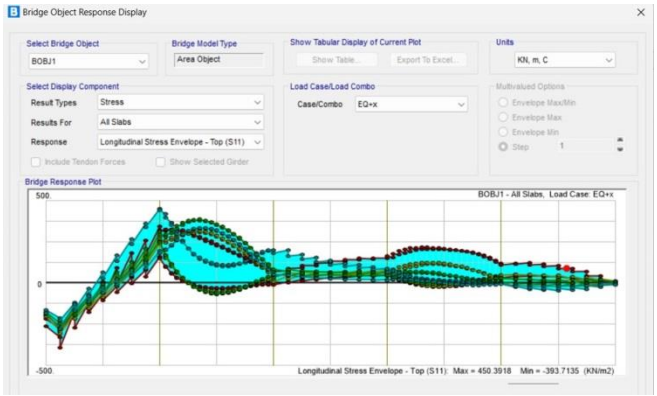

Chart-11: longitudinal stress envelope for all slabs (top)

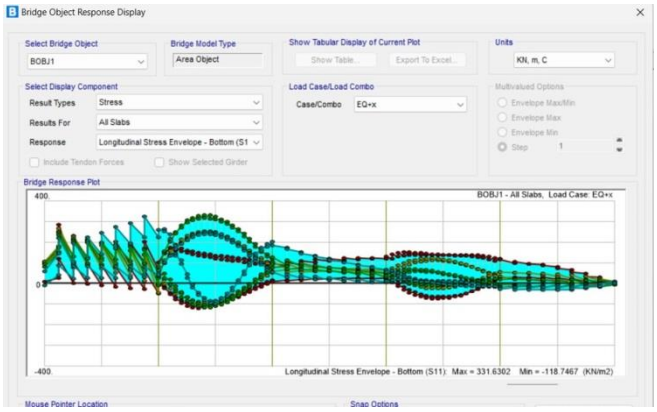

Chart-12: longitudinal stress envelope for all slabs (bottom)

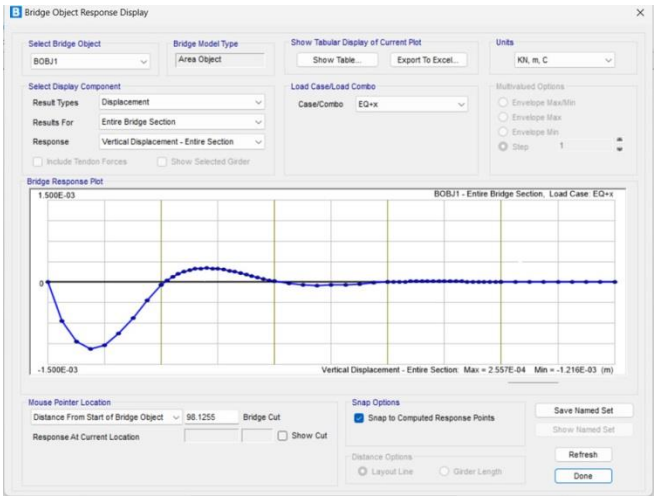

Chart-13: vertical displacement (entire bridge section)

The graph represents the displacement of entire bridge section in vertical direction.The y- axis represents the vertical displacement of entire bridge section that has range between 1.5×10^{3} to -1.5×10^{-3}m and the x-axis represents the length of bridge. The vertical displacement had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall vertical displacement in the entire bridge section comes both postive and negative. The maximum vertical displacement of 2.557×10^{-4}m comes at intermediate portion i.e at 28m of the bridge section and minimum of -1.216×10^{-3}m comes at the 22m section of the bridge. The negative vertical displacement comes at the range of 2.5m to 20m and from 42.5m to 60m section of the bridge model. The vertical displacement effect on entire bridge section had been tabulated in table no. 12 .

Table-12: vertical displacement (entire bridge)

SR NO.	Layout line distance (m)	Vertical displacement(m)	SR NO.	Layout line distance(m)	Vertical displacement(m)
1	0	7.35E-07	13	45	-0.000048
2	2.5	-0.000704	14	50	-0.000053
3	5	-0.001086	15	55	-0.000028
4	10	-0.001148	16	60	-3.63E-07
5	12.5	-0.00094	17	65	0.000014
6	15	-0.000647	18	70	0.000016
7	17.5	-0.00033	19	75	9.83E-06
8	20	-0.000044	20	80	1.23E-06
9	25	0.000222	21	85	5.83E-06
10	30	0.000244	22	90	5.78E-06
11	35	0.00014	23	95	3.22E-06
12	40	0.000013	24	100	-5.14E-09

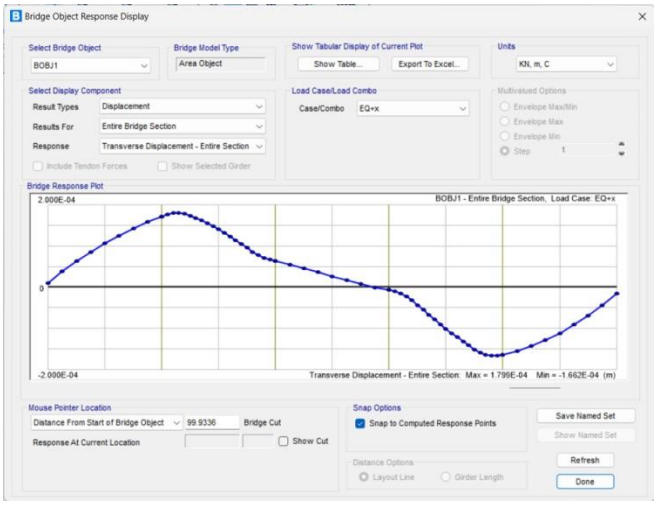

Chart-14: transverse displacement (entire bridge)

The graph represents the displacement of entire bridge section in transverse direction.The y- axis represents the transverse displacement of entire bridge section that has range between 2×10^{-3} to -2×10^{-3}m and the x-axis represents the length of bridge. The transverse displacement had been calculated by the software intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall transverse displacement in the entire bridge section comes both postive and negative. The maximum transverse displacement of 1.799×10^{-4}m comes at intermediate portion i.e at 22m of the bridge section and minimum of -1.662×10^{-4}m comes at the 79m section of the bridge. The negative transverse displacement comes in the range of 57.5m to 100m section of the bridge model. The vertical displacement effect on entire bridge section had been tabulated in table no. 13.

Table-13: transverse displacement(entire bridge)

SR NO.	Layout line distance(m)	Transverse displacement(m)	SR NO.	Layout line distance(m)	Transverse displacement(m)
1	0	8.86E-06	13	45	0.000046
2	2.5	0.000038	14	50	0.000026
3	5	0.000063	15	55	7.51E-06
4	10	0.000106	16	60	-6.79E-06
5	12.5	0.000125	17	65	-0.000043
6	15	0.000142	18	70	-0.000101
7	17.5	0.000158	19	75	-0.000151
8	20	0.000171	20	80	-0.000164
9	25	0.000174	21	85	-0.000143
10	30	0.00014	22	90	-0.000111
11	35	0.000095	23	95	-0.000069
12	40	0.000063	24	100	-0.000015

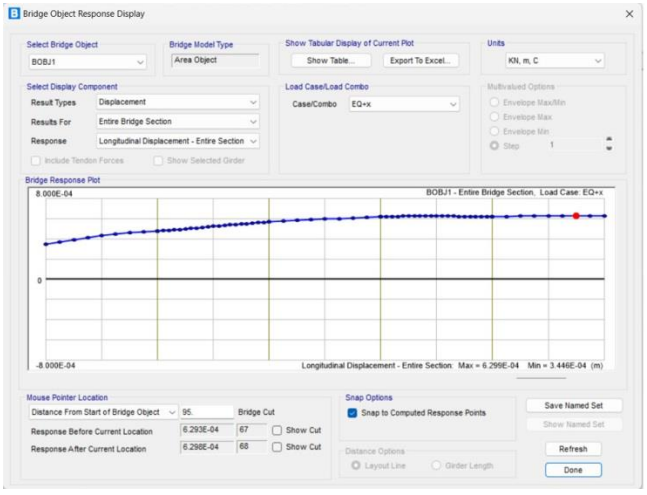

Chart-15: longitudinal displacement (entire bridge)

The graph represents the displacement of entire bridge section in longitudinal direction.The y- axis represents the longitudinal displacement of entire bridge section that has range between 8×10^{-4} to -8×10^{-4}m and the x-axis represents the length of bridge. The longitudinal displacement had been calculated by the software

intially at 2.5m interval upto the 20m length of bridge, at 1m interval upto 40m length of bridge, again 2.5m interval fot the next 20m, 1m interval upto 80m length of bridge and last upto 100m it had been calculted at an interval of 2.5m. The overall longitudinal displacement in the entire bridge section comes postive. The maximum longitudinal displacement of 6.299×10^{-4}m comes at almost end portion i.e at 95m of the bridge section and minimum of 3.446×10^{-4}m comes at the starting portion i.e 79m section of the bridge. The longitudinal displacement effect on entire bridge section had been tabulated in table no. 14.

Table-14: longitudinal displacement(entire bridge)

SR NO.	Layout line distance(m)	Longitudinal displacement(m)	SR NO.	Layout line distance(m)	Longitudinal displacement(m)
1	0	0.000345	13	45	0.000582
2	2.5	0.000367	14	50	0.000595
3	5	0.000391	15	55	0.000607
4	10	0.000431	16	60	0.000617
5	12.5	0.000447	17	65	0.000625
6	15	0.00046	18	70	0.000626
7	17.5	0.00047	19	75	0.000621
8	20	0.000479	20	80	0.000621
9	25	0.000498	21	85	0.000625
10	30	0.000523	22	90	0.000628
11	35	0.000547	23	95	0.000629
12	40	0.000566	24	100	0.00063

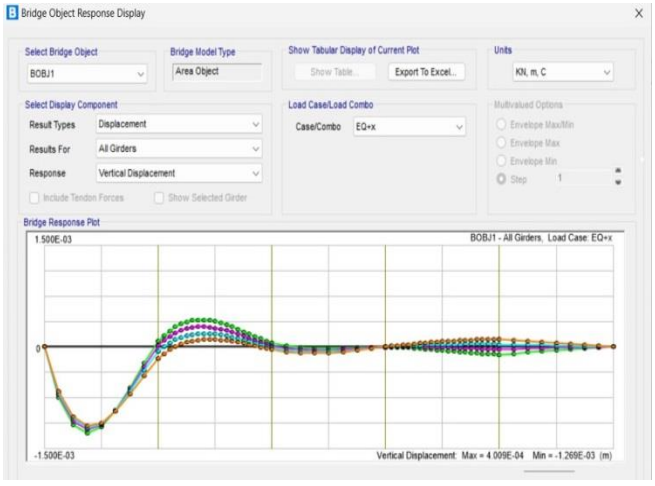

Chart-16: vertical displacement for all girders

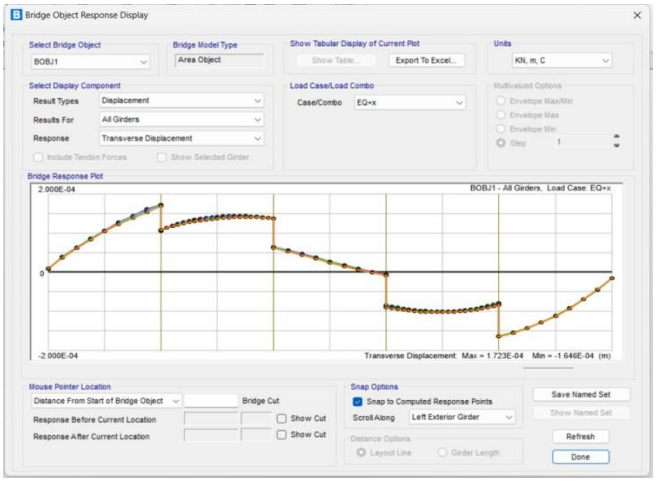

Chart-17: transverse displacement for all girders

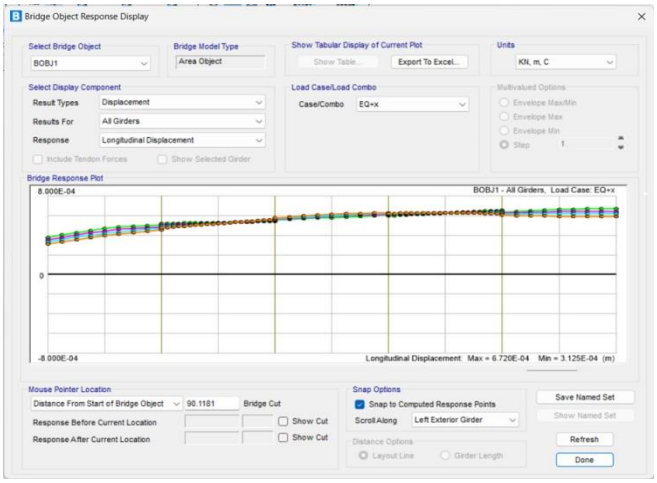

Chart-18: longitudinal displacement for all girder

6. CONCLUSION

The values of axial force, vertical shear, horizontal shear, vertical moment, horizontal moment for (entire bridge section), stresses in all beams and all slabs for (longitudinal direction in top and bottom) and displacement in longitudinal, transverse and vertical direction for (entire bridge section), displacement in longitudinal, transverse and vertical direction for (all girders) have been evaluated for EQ+X components at the Entire bridge structure in this study. The outcomes are represented in the form of Graphs and tables as illustrated above. Therefore, the findings allow reaching the following conclusion.

- From the above findings, it is evident that the value of axial forces in entire bridge section was positive throughout the length of the bridge. The positive axial force whose maximum value 476.504KN was the positive sign for the bridge sustainability. The curve bridge is safe up to this value of axial force in the entire bridge section.

- The shear force in vertical direction in the entire bridge section was up to the limit whether it was positive or negative. The maximum value of 37.016KN was at the initial portion of the bridge at the junction of abutment and girder.

- The longitudinal stress envelope for all beams in top section had maximum value of 1463.084 KN/m^2 and minimum value of 1203.98 KN/m^2.

- The longitudinal stress envelope for all beams in bottom section had maximum value of 2173.94KN/m^2 and minimum value of 1750.035KN/m^2.

- The longitudinal stress envelope for all slabs in top section had maximum value of 450.391KN/m^2 and minimum value of 393.713KN/m^2. For the bottom section the maximum value of 331.630KN/m^2 and minimum value of 118.746KN/m^2.

- The vertical displacement of entire bridge section had maximum value of 2.5×10^{-4}m and minimum value of 1.2×10^{-3}m. Transverse displacement of entire bridge section had maximum value of 1.7×10^{-4}m and minimum value of 1.6×10^{-4}m. longitudinal displacement of entire bridge section had maximum value of 6.2×10^{-4}m and minimum value of 3.4×10^{-4}m.

As per the all these results the analysis of structure was at safe direction.

7. FUTURE SCOPE

The main focus of the research and development is on future scope regarding seismic response analysis for RCC (Reinforced Cement Concrete) I-girder bridges, which assumes a great dimension in seismic regions. Advanced Modelling Techniques: In addition to these methods, other computational techniques can improve the seismic response prediction accurately (for example, finite element analysis). Except these, the other most advanced models are under development by taking into consideration nonlinear behaviour, material degradation, as well as interaction effects. Retrofitting and Strengthening: as time lapses most of the bridges falls in danger due creep loading and other environmental factors. So, retrofitting techniques needed very much for the continuous operations of the bridge. Advance materials, like FRP and smart materials, can make aging infrastructure more resilient to seismic resistive. Performance-based design: In the near future, performance-based design will take place other design criteria. It will focus on seismic loading to produce expected behavior of structures instead of compliance with prescriptive codes. Such design integrates detailed risk assessment and cost effective considerations. Seismic Isolation and Damping Systems: A new system the seismic isolation bearings and damping systems can be used to cushion the impact of the earthquake. These systems are fast becoming part of new designs and retrofitting strategies. Monitoring and Data Acquisition: with the advancement in technology Integration of real-time monitoring systems with sensors can provide real information regarding structural performance during seismic events. Such data can add to knowledge bases and prepare bases for further designs. As per the sustainability considerations in new RCC I-girder bridge construction and the retrofitting of existing RCC I-girder bridges require sustainable materials and practices. Future work could consider further balancing seismic resilience with environmental effects and sustainable to the nature and people. Regulatory Frameworks: The codes and guidelines on seismic design will inevitably become obsolete as new seismic standards continue to emerge, and it would require collaboration between these different parties-including researchers, engineers, and those regulatory agencies-to render new research Climate Resilience: Since climate change amplifies seismic risks-for example through increased flooding-future studies could integrate the various hazards into response analysis against seismic activity. International Cooperation: Global cooperation can help expand the knowledge pool and collaboration in seismic design and retrofitting at the international level, especially by combining third world and developed countries' resources and experience. In summary, seismic response analysis of RCC I-girder bridges can be expected to be more of an interdisciplinary approach with new technologies, materials, and methodologies to provide resiliency against earthquakes.

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