Analysis of T–beam bridge for seismic characterisation

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ABSTRACT: An existing reinforced cement concrete T-beam bridge was evaluated using inelastic analysis procedures namely capacity spectrum method (CSM) and modal pushover procedure (MPA). MPA was performed in both the transverse and longitudinal directions of the bridge structure independently. The response of the bridge structure to El Centro and Kobe earthquake ground motions was evaluated by the CSM. The capacity curves that represent the response of the bridge in transverse and longitudinal directions for the particular modes of the vibration are generated using MPA. The capacity-demand spectra for mode#1, mode#8 (transverse direction) and mode#2 (longitudinal direction) were obtained using SAP2000 analysis software. When the bridge was subjected to an earthquake similar to the El Centro Earthquake in transverse and longitudinal directions, the bridge capacity spectrum curve extended through the envelope of the demand curves, indicating that the bridge would survive in both the directions. Whereas for an earthquake similar to the Kobe one, the demand was much greater than the capacity and the bridge failed to survive. In the transverse modes, the structure indicates large energy absorption capacities in the inelastic range, without a significant loss of strength and stiffness. The bridge has more displacement ductility in the transverse direction than in the longitudinal direction. Hence, retrofitting applications to the multi-column bents are suggested, to enhance the global stability.

1 INTRODUCTION

Roads are the lifelines of modern transport, and bridges are an integral part thereof. A large number of bridges constructed around the world were designed during the period when bridge codes had seismic design provisions which were insufficient according to the current standards. The failures of bridges during the recent earthquakes have created an awareness, to evaluate the structural vulnerability of the bridges, under seismic ground motions, to develop the required retrofit measures. Also, due to aging and the growth of vehicular loads in magnitude and volume, many existing bridges in India are experiencing deterioration. As the construction of new bridges involves huge time and money, the repair and rehabilitation of old and damaged bridges are necessary, to preserve their load carrying capacity and service performance.

In the present study, an existing reinforced cement concrete T-beam cum slab road bridge (Koyambedu bridge) was assessed for its seismic characterisation. Modal pushover analyses were performed in both the transverse and longitudinal directions independently. The performance of the study bridge was assessed in both the transverse and longitudinal directions using the capacity spectrum method (Yu et al.1999) for two earthquake records, viz., the El Centro Earthquake and the Kobe Earthquake.

2 DESCRIPTION OF THE STUDY BRIDGE

The bridge is built over Coovam River in Koyembedu, Tamilnadu, India. It is multi-span simply supported reinforced cement concrete T-beam cum slab bridge having the total length of 129.7 m with eight equal spans of 16.21 m length. The superstructure consists of four longitudinal girders and five cross girders. It is supported on multi-column bent. Each bent has four columns which are transversely connected by the bent cap. The bridge piers and abutments are supported on well foundations. The cross sectional details of the bridge components are shown in Table 1.

Table 1. Cross sectional details of the bridge components

Bridge Component	Description	Size (mm)
Longitudinal girder	Top flange	2500 x 220
	Bottom flange	500 x 250
	Web	200 x 1355
Cross girder	Cross section	200 x 1400
Bent cap beam	Cross section	1400 x 600
	Length	8800
Bent column	Diameter	800
	Height	4867
Bearing pad	Cross section x depth	500 x 320 x 33.5

The longitudinal view of the bridge, elevation of the bridge bent and cross sectional view of the bridge at the bent location are shown in Figure 1 and Figure 2 respectively.

Figure 1. Longitudinal view of the study bridge

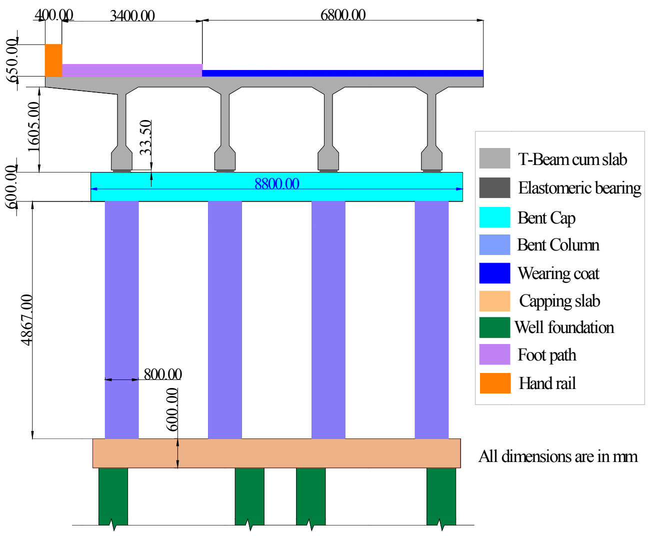
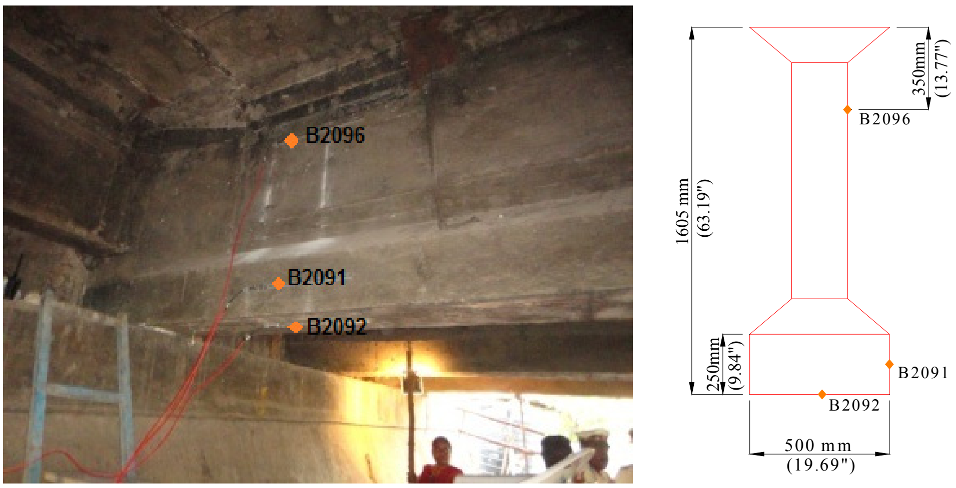


Figure 2. Cross sectional view of the bridge at bent location

3 EXPERIMENTAL INVESTIGATION

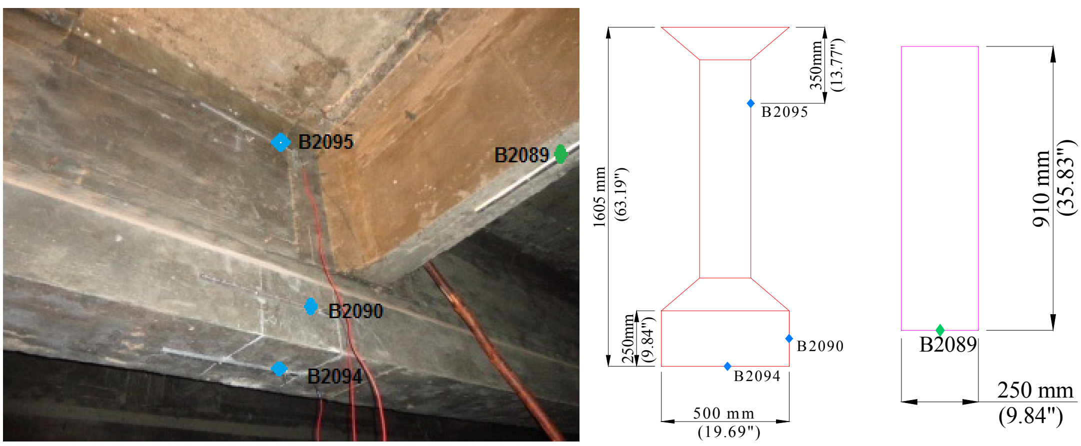
Live load test on the study bridge was conducted to measure the flexural responses of the longitudinal and cross girders. The instrumentation was limited to a single span (first span). The strain transducers were mounted on one of the longitudinal girders and one of the cross girders of a single span in a completely non-destructive manner.

The positions of the gauges in the longitudinal girder near the abutment are shown in Figures 3a and 3b respectively. The gauges mounted in the longitudinal girder near the midspan and at the bottom of the cross girder are shown in Figures 4a, 4b and 4c. In the figures, the dimension details of the longitudinal girder (without the deck slab) and cross girder are shown. After the structure was completely instrumented, controlled load tests were performed with a multi-axle truck with known axle weights. The auto clicker and reflector arrangement was fixed on the wheel to facilitate the automatic recording of strains corresponding to each wheel rotation. When the truck was driven along a prescribed longitudinal path, for each wheel rotation, the strains were automatically measured while the vehicle's position was monitored remotely using the equipment, wireless structural testing system.



(a) (b)

Figure 3. a,b Position of gauges in the longitudinal girder near the abutment



(a) (b) (c)

Figures 4. a,b and c. Position of gauges in the longitudinal girder

The second phase of the investigation was the development of a representative finite element model of the superstructure. The bridge was modeled as a two dimensional (2D) grid consisting of the beam, plate, and spring elements using WINGEN, a model generation program that enables to define a planar bridge model. The load testing procedures that were used in the field, were reproduced through software after the model was developed. A two-dimensional footprint of the loading vehicle was applied to the model along the same path that the actual test vehicle took across the bridge. A direct comparison of the strain values was then made between the analytical predictions and the experimentally measured results.

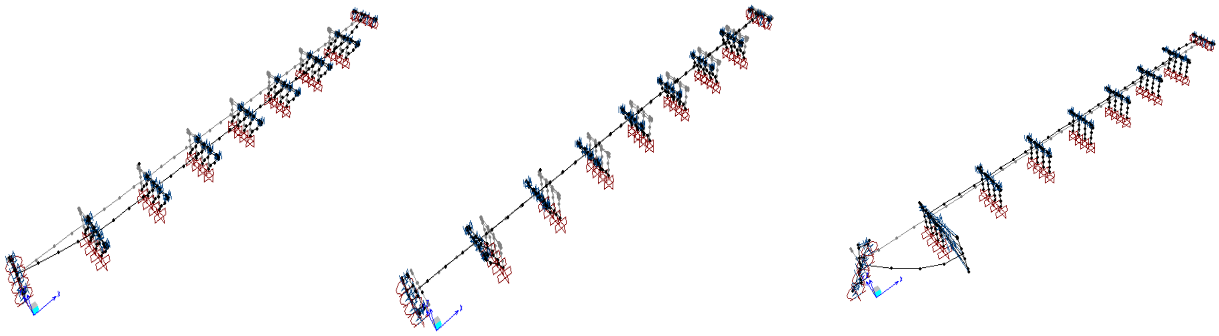
The strain histories obtained from the experimental investigation indicated the nonlinear response of the longitudinal girder and linear response of the cross girder. Examining the measured and computed strain data, the stiffness parameters of the longitudinal girder was changed by the heuristic method to improve the model. By improving the model, a good correlation between the field measured strain values and computed strain values was obtained. The effective stiffness (EIeff) property of the longitudinal girders evaluated from the experimental investigation was found to be 0.8 times the gross stiffness (EIg), i.e., EIeff = 0.8EIg. This result, the stiffness parameter obtained from the experimental investigation was used while modeling the same bridge using SAP2000, for evaluating the survivability, ductility of the bridge structure.

4 MODELLING OF THE BRIDGE

A three dimensional (3D) finite element model (FEM) of the bridge was created using Structural Analysis and Program Software SAP2000. Spine model (a type of superstructure model) was employed for modeling the superstructure (Priestly et al. 1996; Ryan & Richins 2011). The deck edges in each simply supported span were considered rigid. Due to the large in-plane rigidity, the superstructure was assumed as a rigid body for lateral loadings (Priestly et al. 1996; Shatarat & Assaf 2009). The bridge consists of seven multicolumn bents and every bent was modeled as a plane frame. The framing action and coupling between columns in the multi-column bent provides seismic resistance in terms of strength and stiffness. The bent cap and the columns were modeled as beam-column elements. Effective moment of inertia was taken as 0.7Ig (Priestley et al. 1996) for reinforced concrete columns which were modeled using Section Designer (Sub programme in SAP2000). The interface between each column and the corresponding geometric centre of the bent cap was considered rigid. The default hinge properties (PMM – P stands for axial force, M stands for M2 moment, and M stands for M3 moment in SAP2000) were assigned to each end of the columns. The base of the column was assumed as fixed. The girders of the bridge are simply supported over plain elastomeric bearing pads. The horizontal sliding behavior of the interface between the bearing and girder or cap beam was modeled using linear spring element (El-Gawady et al. 2009).

5 MODAL ANALYSIS

The modal analysis of the study bridge was performed to find the dynamic characteristics of the bridge, such as mode shapes, modal mass participation, natural frequencies etc. In the fundamental mode (mode#1), 84.32% of the total mass of the bridge structure participated in the vibration of the structure in the transverse direction. In the second mode, 93.57% of the total mass participated in vibrating the bridge structure in the longitudinal direction. In the 3rd, 4th, 5th, 6th and 7th modes, it was observed that there was no additional mass participation in exciting the bridge structure in the longitudinal and transverse directions. In the 8th mode an additional mass participation of 1.4% was observed in the transverse direction. In the 9th mode there was 0.3% of additional mass participation in the transverse direction. In bridge structures, higher modes may have a significant effect and therefore to evaluate the seismic response of the structure in the higher mode, the 8th mode was also considered in this study. The mode shapes of the bridge structure in the fundamental (first), second and eighth modes are shown in Figures 5a, 5b and 5c respectively.



(a) (b) (c)

Figure 5. a, b and c. Mode shapes of the bridge structure in the fundamental, second and eighth modes.

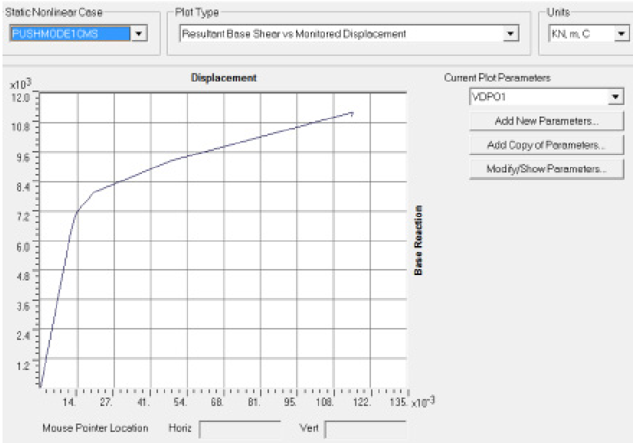
6 MODAL PUSHOVER ANALYSIS

The pushover analysis is an inelastic analysis (Gu, Zhuo 2012; Kappos et al. 2005; Kim, D'Amore 1999; Ryan, Richins 2011; Sharma et al. 2013), which gives a nonlinear response of the structure in the global force - displacement format (capacity curve). Following the initial conditions obtained due to gravitational forces, the pushover analysis was performed in both the longitudinal and transverse directions, considering the P-δ effects. The effects of higher modes were considered, for a better understanding of the structural performance of the bridge. The displacement pattern was configured based on the mode shapes obtained. The bridge was subjected to lateral forces distributed proportionally over the span of the bridge in accordance with the product of the lumped mass at the node, and the modal amplitude at the corresponding node. The lateral loads were distributed vertically in proportion to the nodal masses, height-wise in the bents. The lateral forces were applied in a monotonically increasing fashion, until the target displacement was reached or the structure collapsed. Both material and geometric (P- δ effect) nonlinear parameters were included in the analysis.

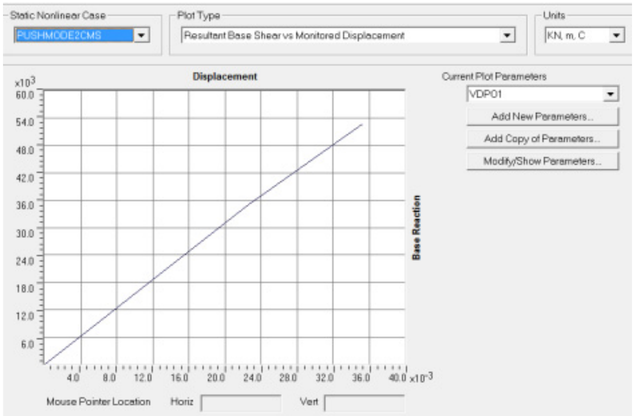
6.1 Results of Pushover Analysis - Capacity curve

The modal pushover analysis was conducted in both the transverse and the longitudinal directions. It is assumed that the shape of the global pushover curve reflects the global or local mechanism involved when the structure approaches dynamic instability. The capacity curve (pushover curve) is the graphical plot of the total lateral force or base shear (V_b) on a structure against the lateral deflection (δ) of the control node of the bridge structure.

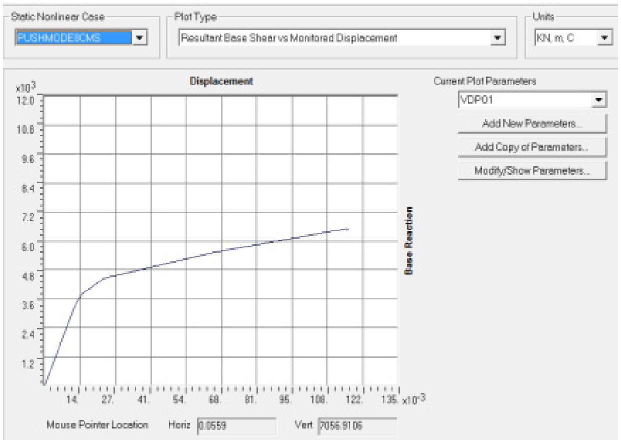
The pushover curve for mode#1 is shown in Figure 6a. The figure indicates that the first yielding occurred at a base shear of 7961.26 kN with the control node displacement of 19.7 mm. Beyond the first yield, the control node displacement increases with the increase in base shear. The softening of the pushover curves associated with the progressive formation of plastic hinges was noticed in the multi-column bents of the bridge structure, with increasing lateral forces. The first mode caused a global plastic mechanism and increasing force intensity, leading to the rotation of the bridge structure about its base (bottom local plastic mechanism). The control node continued to move in the direction of the application of lateral force. The pushover curve displayed normal behaviour without any reversal. The formation of mechanism reduced the stiffness and caused an incremental displacement. The structure experienced a maximum displacement of 115 mm with the base shear of 11229.20 kN with the indication of the loss of lateral stiffness.



(a) Mode #1



(b) Mode # 2



(c) Mode #8

Figure 6. Capacity curves

The capacity curve for mode#2 is shown in Figure 6b. From the pushover curve it was found that the overall strength of the system appeared to be higher (i.e. yielding occurred at a higher level of base shear). The shear force at the base of the structure in the longitudinal direction was much larger than the base shear in the transverse direction. In the longitudinal pushover analysis, when the push load was applied in the longitudinal direction, the expansion joints which are provided between the adjacent sides of a deck joint, permitted relative translations and rotations at both sides of the bridge decks. The first yield occurred at a base shear of 34644.03kN, and a control node displacement of 22.3mm was observed. The structure experienced a maximum displacement of 35.2mm with the base shear of 52610.17kN.

The capacity curve for mode#8 is shown in Figure 6c. In the pushover analysis performed in the transverse direction for mode#8, the first yield occurred at a base shear of 4468.55 kN with the control node displacement of 22.8 mm. The bridge structure had displaced to a maximum of 115.9 mm, with maximum base shear value of 6517.11 kN. The bridge structure had displaced far into the inelastic range with significant degradation in the lateral capacity.

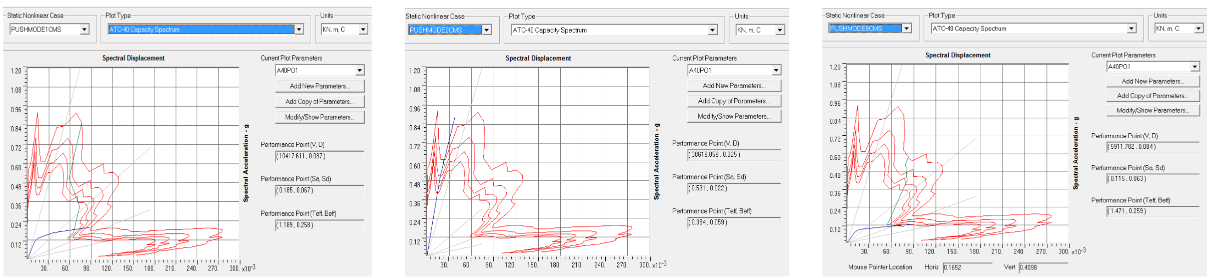
6.2 Response Spectra of Imposed Ground Motions using Capacity Spectrum Method (CSM)

The Capacity spectrum method was originally developed by Freeman et al. (1975). The procedure compares the capacity of the structure (in the form of a pushover curve) with the demands on the structure (in the form of response spectra). The graphical intersection of the two curves approximates the response of the structure. Two different seismic ground motions from historical earthquake records were applied to the bridge models: (a) the NS component record of the El Centro record of the 1940 Imperial Valley earthquake, and (b) the NS component of the Kobe record of the 1995 Hyogo-Ken-Nanbu earthquake. The El Centro earthquake may be considered as a reasonably moderate one, whereas the Kobe earthquake may be regarded a strong one.

6.3 Performance displacement of the bridge model under the El Centro Earthquake demand in mode#1, mode#2 and mode# 8.

The capacity-demand spectra for mode#1(transverse direction) is shown in Figure 7a. Figure 7a, shows the graphical plot of the capacity spectrum of the bridge obtained from the mode#1 pushover analysis, overlaid by the demand spectrum of the El Centro Earthquake, for varying effective damping values. It was found that when the bridge was subjected to an earthquake similar to the El Centro Earthquake, the bridge capacity spectrum curve extended through the envelope of the demand curves, indicating that the bridge would survive. In mode#1 the response of the bridge was governed by the transverse demand, with the performance displacement of 87 mm associated with an effective damping of 25.8 %, i.e., 25.8 % of the energy is dissipated by damping. It is about 5 times that of inherent damping, indicating the ability of the structure to undergo large amplitude cyclic deformations in the inelastic range, without a substantial reduction in the strength.

The capacity-demand spectrum for mode#2 (longitudinal direction) is shown in Figure 7b. It was found that when the bridge was subjected to an earthquake similar to the El Centro Earthquake, the capacity spectrum extended through the envelope of the demand curves, indicating that the bridge would survive. In mode#2 the performance displacement was 25 mm, associated with an effective damping of 5.9%. The energy dissipated in the longitudinal direction was a little above 5% inherent viscous damping.



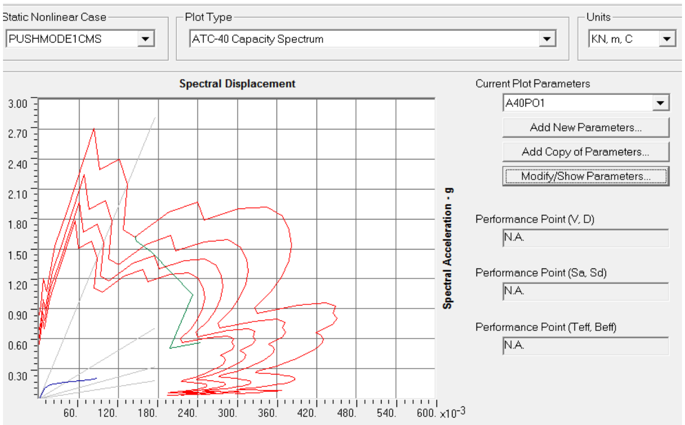
(a) (b) (c)

Figure 7. a, b and c. Capacity - demand spectra of the bridge in mode#1, mode#2 and mode# 8

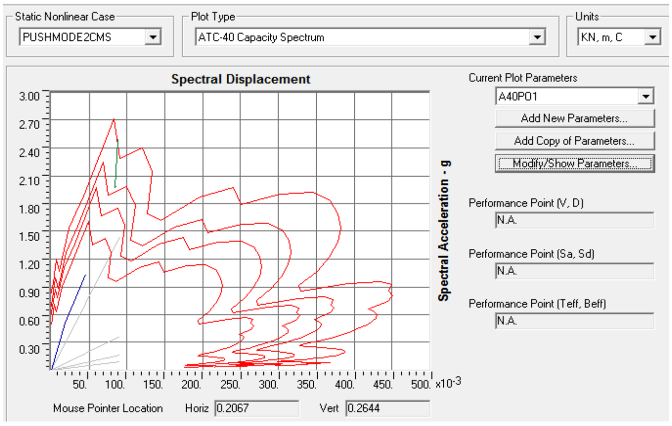
The capacity-demand spectrum for mode#8 (transverse direction) is shown in Figure 7c. It was found that when the bridge is subjected to an earthquake similar to the El Centro Earthquake, the capacity spectrum extended through the envelope of the demand curves, indicating that the bridge would survive. In mode#8 the response of the bridge was governed by the transverse demand with the performance displacement of 84 mm associated with an effective damping of 25.9%.

6.4 Performance displacement of the bridge model under the Kobe Earthquake demand in mode#1, mode#2 and mode#8

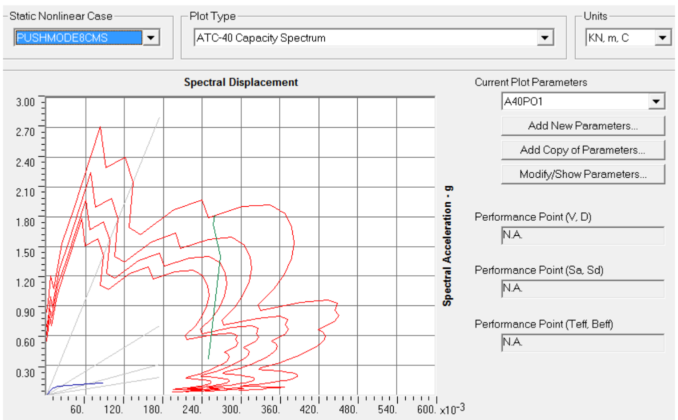
Figures 8a, 8b and 8c show the capacity-demand spectra for mode#1(transverse direction), mode#2 (longitudinal direction) and mode#8 (transverse direction) of the bridge model, overlaid by the demand spectrum of the Kobe Earthquake, for varying effective damping values. For an earthquake similar to the Kobe one, the capacity spectrum curves did not extend through the envelope of the demand curves in both the transverse and longitudinal directions, indicating that the bridge would not survive.



(a) Mode #1



(b) Mode #2



(c) Mode #3

Figure 8. a, b and c. Capacity - demand spectra of the bridge in mode#1, mode#2 and mode#8

7 SURVIVABILITY CHECK OF THE BRIDGE STRUCTURE IN THE TRANSVERSE AND THE LONGITUDINAL DIRECTIONS

From the mode#1 and mode#8 capacity - demand spectra (Figures 7a, 7c), the response of the bridge structure under El Centro earthquake demand in the transverse direction is given in Table 2.

Table 2. Response of the bridge in the transverse direction under El Centro earthquake demand

El Centro Earthquake	Mode#1				Mode#8			
	Demand		Capacity		Demand		Capacity	
	F(kN)	δ(mm)	F(kN)	δ(mm)	F(kN)	δ(mm)	F(kN)	δ(mm)
	10417.60	87.00	11229.20	115.00	5911.72	84.00	6517.11	115.90
Status	**Survive**				**Survive**			

From the mode#2 capacity - demand spectra (Figure 7b), the response of the bridge structure under El Centro earthquake demand in the longitudinal direction is given in Table 3.

Table 3. Response of the bridge in the longitudinal direction

El Centro Earthquake	Mode#2			
	Demand		Capacity	
	F (kN)	δ (mm)	F (kN)	δ (mm)
	38619.86	25.00	52610.17	35.20
Status	**Survive**			

7.1 Structural Ductility

Ductility is the ability of a structural component or a system to undergo both large deformations and several cycles of deformations, beyond its yield point or elastic limit. A measure of the ductility of a structure is the displacement ductility (μ) or ductility factor given in Equation (1).

$$\mu = \frac{\delta_u}{\delta_y} \tag{1}$$

where, δu is the lateral deflection at the end of the post elastic range, and δy is the lateral deflection, when the yield is first reached. The structural ductility of the bridge in the transverse and the longitudinal directions, for the imposed ground motions calculated, is summarized in Tables 4 and 5.

Table 4. Structural ductility of the bridge in the transverse direction

Earth quake	Mode No.	Yield Displacement mm)	Ultimate Displacement (mm)	Performance Displacement (mm)	Displacement Ductility(μ)	Performance Ductility	%
El Centro	1	19.700	115.00	87.00	5.837	1.32	75.65
	8	22.800	115.90	84.00	5.088	1.38	72.41
Kobe	1	19.700	115.00	N.A.	5.837	N.A.	N.A.
	8	22.800	115.90	N.A.	5.088	N.A.	N.A.

Table 5 Structural ductility of the bridge in the longitudinal direction

Earth quake	Mode No.	Yield Displacement (mm)	Ultimate Displacement (mm)	Performance Displacement (mm)	Displacement Ductility(μ)	Performance Ductility	%
El Centro	2	22.30	35.20	25.00	1.60	1.41	71.4
Kobe	2	22.30	35.20	N.A.	1.60	N.A.	N.A.

In the transverse direction, in mode#1, the bridge yields at the transverse displacement of 19.7 mm, and reaches the ultimate displacement of 115 mm. In mode#8 the bridge yields at the transverse displacement of 22.8 mm and reaches the ultimate displacement of 115.9 mm. The higher yield displacement value of 22.8 mm at the higher mode indicates, that the delay between the ultimate state and the yield state was lesser, when compared with that of the fundamental mode (mode#1).

In the transverse direction, the displacement ductility (ratio of ultimate displacement to yield displacement) for mode#1 was 5.837, whereas for mode#8 it was 5.088. In the transverse modes, the structure indicates large energy absorption capacities in the inelastic range, without a significant loss of strength and stiffness. In the longitudinal direction the displacement ductility (mode#2) was 1.6. The bridge has more displacement ductility in the transverse direction than in the longitudinal direction. In the Transverse direction, in mode#1 the performance displacement was 75.65% of its ultimate displacement, while in mode#8 the performance displacement was 72.41% of its ultimate displacement. In the longitudinal direction, for mode#2 the performance displacement was 71.4% of its ultimate displacement. Though the displacement capacity reserved in the longitudinal direction was more than that in the transverse direction, the displacement ductility was lesser in that direction. Hence, retrofitting applications to the multi-column bents is suggested, to enhance the global stability.

8 CONCLUSIONS AND RECOMMENDATIONS

From the analysis of the T-beam bridge, the following are the conclusions and recommendations.

- From the modal analysis, it was found that two modes participated in the vibration of the bridge structure in the transverse direction and a single mode in the longitudinal direction. Thus, for bridges, higher modes have a significant effect in their performance.

- From the results of modal pushover analysis in the transverse direction, it was found that, the hinges at the bottom of all the columns in the mid-bent exceeded collapse prevention (CP) performance level. The performance levels of all other hinges in the other bents were at safe performance levels in the range from immediate occupancy (IO) to the life safety (LS) performance levels. The performance levels of the plastic hinges in all the bent cap beams were in elastic state. As a result, the structure failed due to global instability. When the performance levels of the hinges exceed collapse prevention performance level, it indicates that, significant damages have occurred in the structure. The damages may be concrete cracking, reinforcement yielding and major spalling of concrete, which require either closure of the bridge structure for repair or partial or permanent replacement of the structure.

- The survivability of the bridge structure under El Centro and Kobe earthquake was checked using capacity spectrum method. It was found that the study bridge could survive El Centro Earthquake but fail to survive Kobe Earthquake.

- Hence, retrofitting applications to the multi-column bents is suggested, to enhance the global stability.

9 ACKNOWLEDGEMENTS

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