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Performance-based Seismic Evaluation of Different Concrete Bridges

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Abstract

In this study, analytical fragility curves are developed for the sample concrete bridges of Indian highways to be used in the assessment of their seismic vulnerability. Bridges are first grouped into certain bridge classes based on their structural attributes and sample bridges are generated to account for the structural variability. Nonlinear static analyses and incremental dynamic analyses are conducted for each bridge sample with their detailed 3-D analytical models under different earthquake ground motions having varying seismic intensities. Engineering demand parameters are employed in the determination of seismic response of the bridge components as well as defining damage limit states in terms of member capacities. Fragility curves are obtained from the probability of exceeding each specified damage limit state for each bridge class. Thus, for concrete bridges evaluation of seismic damage is carried out which is most important part to decide seismic vulnerability. Concrete bridges designed as per current Indian seismic codes with shear failure criteria based on capacity design concept are found to be the most vulnerable ones using performance base earthquake engineering. This research highlights urgent need of incorporating capacity design concept based on flexural failure criteria and performance base earthquake engineering in Indian seismic codes. Developed fragility curves can be implemented in the seismic risk assessment packages for mitigation purposes.

Keywords: concrete bridge, seismic, pushover, fragility

1. INTRODUCTION

Bridges are essential elements in modern transportation network and play a significant role in a country's economy. However, it has always been a major challenge to keep bridges safe and serviceable. Modern bridge design codes include seismic detailing in order to ensure ductile behavior. The main parameters affecting the performance of bridge (tie spacing, concrete and steel properties, amount of reinforcement) varies significantly from old to modern bridges. Seismic vulnerability assessment of the highway bridges located within earthquake prone regions and determination of their performance levels under seismic actions play an important role for the safety of transportation systems [1].

The goal of this study is to refine an existing methodology for the development of analytical seismic fragility curves for bridge classes that are typical to the Indian region. India is a moderate seismic zone in which the seismic risk mitigation effort has lagged the effort made by the Western countries.

More focus is now being placed upon the Zone-V of India because of the recognition of potential for large ground shaking. To aid in the assessment of seismic risk for the region, typical bridge classes have been selected for the development of seismic fragility curves. The level of detail that is used and the refinement of the analytical methodology will aid in generating more reliable fragility curves than what are currently available. The purpose of this study is to use analytical methods to generate fragility curves for different bridge classes which are most common to the Indian perspective.

It has been observed that under the recent earthquake excitation, many bridges were either totally collapsed or received major damages and demonstrated the sever vulnerability. Even a moderate damage to such structures will make them non-functional. It may seriously affect the major relief work after earthquake. A different approach for protection of bridges from earthquakes is evaluating seismic performance and suggesting retrofit techniques using latest proven methods of performance analysis [2]. The concept of seismic performance analysis of new bridges and the assessment and retrofit of existing bridges was practically used in America, New Zealand, Canada, China, England, France, Japan, Italy and Mexico etc. The research on evaluation of seismic damage to concrete bridges has great importance, to decide correct approach and methodology for performance base design and it has great concerned in India. Therefore, evaluation of seismic damage to concrete bridges designed as per current Indian Standards is carried out in the present study. The bridge is first analysed using nonlinear static analysis (pushover analysis) by SAP2000 [3]. The seismic performance and overall seismic capacity of the bridge are then investigated through incremental dynamic analyses (IDA) by developing IDA curves [4] using IDARC2D software [5]. Nonlinear dynamic analysis is applied to simulate the earthquake loads over the analytical model. A set of ten Indian ground motions is selected. Fragility curves are generated to define the damage limit states and probability of survival of the structure.

2. GEOMETRIC DESCRIPTION AND DESIGN DETAILS

In this case study T-girder, I-gider and Box-girder three span typical Indian concrete bridges are considered with span length of 24m, 30m and 50m respectively. All the bridges are analysed using nonlinear static analysis (pushover analysis) by SAP2000 and incremental dynamic analysis for substructure type of single-column bents. The substructure types are designed as per provisions of IS 456, IS 1893 and IS 13920 for 1.5(DL+EQ) i.e. load of 5500kN, 8000kN and 12000kN respectively, acting at C.G. of bent cap. Finite element models for all the three types of bridges are shown in figure below. For abutments and connections of super-structure with sub-structure, elastic bearing springs are provided.

Table 1. Details of column cross-sections

Type of bent	Size of column	Longitudinal reinforcement	Shear reinforcement
T girder	2m	Φ32mm 44no.	Φ16mm with 250mm c/c spacing
I girder	2.6m	Φ32mm 74no.	Φ16mm with 250mm c/c spacing
Box girder	3.0m	Φ32mm 88no.	Φ16mm with 250mm c/c spacing

3. METHODOLOGY

3.1. Finite element modeling

A simplified analytical modelling is utilized which allows for more economical analysis time when a large number of simulations are required. The analytical bridge model was established in SAP2000 analysis software. The modelling was performed consistent with Nielson’s [6] findings on typical bridge properties and modelling assumptions. The bridge superstructure consists of three symmetric spans. The superstructure is supported by two seat-type pile abutments at its two ends and single column piers in the middle which are supported by footings and pile caps at the columns bases. The bearing system is provided by an elastomeric rubber pad and two steel dowels under girder’s end over the headstocks. The superstructure is modelled using elastic beam elements by calculating the section properties of each span. The columns and headstock of the piers are however modelled by displacement column elements to reflect the nonlinearities in steel and concrete materials and P-Δ effects. The analytical model of the bridge bearings consists of an elastic material with no hardening ratio as of the elastomeric rubber pad, in parallel with a hysteretic material which represents the behavior of the two steel dowels [7].

Finite element model for the bridge with different superstructure types are shown in Fig.1. For abutments and connections of super-structure with sub-structure, elastic bearing springs having translational and rotational stiffnesses based on their cross sectional and material properties are provided.

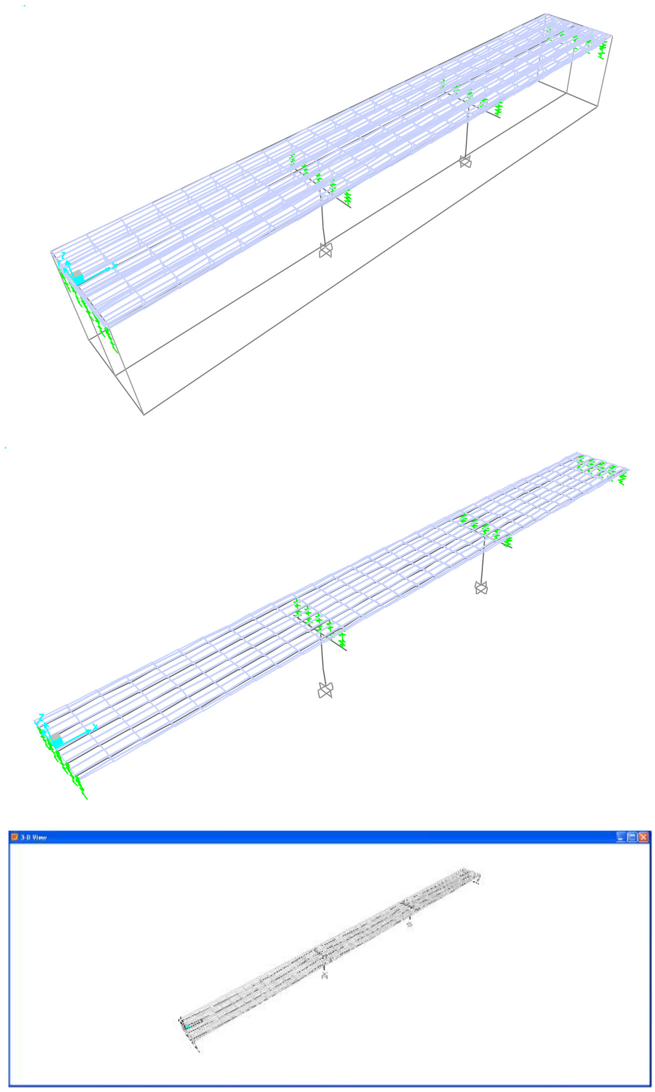

Figure 1. Finite element model for T, I and box girders three span bridges

3.2. Selection of Ground Motion Records

For seismic performance assessment of civil structures and infrastructure in a specific area, it is particularly important to have a representative suit of ground motion time-histories recorded from earthquake sources at the area. A set of ten ground motion records is selected randomly from 20 Indian ground motion records used by Maniyar and Khare [8] to consider maximum ground motion parameters and its effect on seismic performance.

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Table 2. Indian Earthquake records adopted for IDA

Record Id	Event	Year	Station	Φ^{*1}	M^{*2}	R^{*3} (km)	PGA (g)
1	Uttarkashi	1991	GHANSIALI	Longitudinal	6.5	38.0	0.118
2	Uttarkashi	1991	GHANSIALI	Transverse	6.5	38.0	0.117
3	Uttarkashi	1991	UTTARKASHI	Longitudinal	6.5	32.5	0.242
4	Uttarkashi	1991	UTTARKASHI	Transverse	6.5	32.5	0.309
5	Chamoli	1999	JOSHIMATH	Longitudinal	6.4	32.3	0.091
6	Chamoli	1999	UKHIMATH	Longitudinal	6.4	32.3	0.091
7	Chamoli	1999	UKHIMATH	Transverse	6.4	32.3	0.097
11	Uttarkashi	1991	SRINAGAR	Longitudinal	6.5	57.9	0.067
13	Chamoli	1999	GHANSIALI	Transverse	6.4	73.8	0.083
14	Chamoli	1999	GHANSIALI	Longitudinal	6.4	73.8	0.073

[1] Component [2] Moment Magnitudes [3] Closest Distances to Fault Rupture

Source: Department of Earthquake Engineering, IIT, Roorkee

3.3. Pushover analysis

The pushover analysis is an inelastic analysis, which gives a nonlinear response of the structure in the global force - displacement format (capacity curve). The capacity curve (pushover curve) is the graphical plot of the total lateral force or base shear (Vb) on a structure against the lateral deflection (δ) of the control node of the bridge structure [9,10].

Under the Nonlinear Static Procedure, i.e. Pushover Analysis, the mathematical model of the bridge is subjected to monotonically increasing lateral forces or displacements until either a target displacement is exceeded or the bridge collapses. The target displacement is intended to represent the maximum displacement likely to be experienced during the design earthquake. The goal of the static pushover analysis is to evaluate the overall strength, typically measured through base shear Vb, yield, and maximum displacement i.e. δY and δu, as well as the ductility capacity μc of the bridge structure. The pushover analysis can examine the sequence of limit states, formation of plastic hinges, and redistribution of forces throughout the structure, with the increment of the lateral loads or displacement demand. The pushover curve (force vs. deformation) of the bridge also allows identifying any softening behavior of the entire structure due to material strength degradation or P-Δ effects (Fig. 2, 3 and 4).

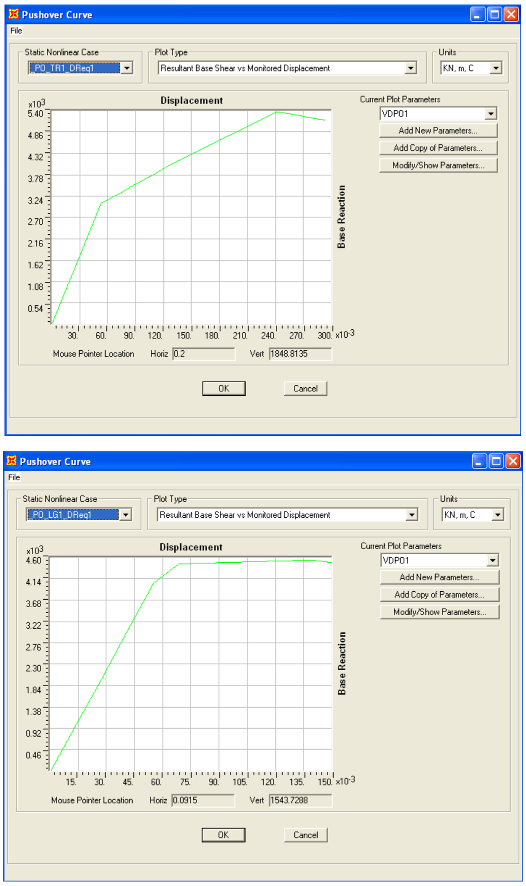


Figure 2. Pushover Curves in transverse and longitudinal direction for T girder

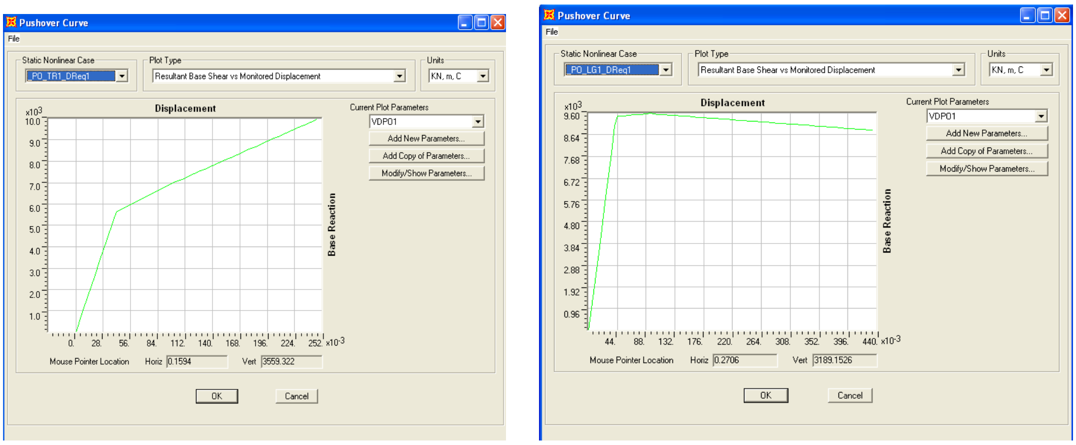


Figure 3. Pushover Curves in transverse and longitudinal direction for I girder

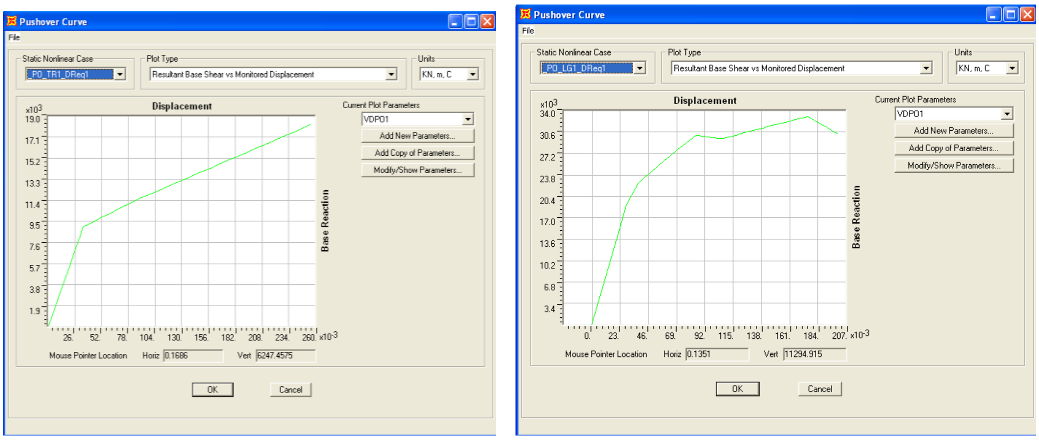


Figure 4. Pushover Curves in transverse and longitudinal direction for Box girder

Table 3. Results of Pushover Analysis

Type of bridge	Design Base shear kN	Base Shear Capacity kN	Displacement Ductility at LS	D/C Ratio
T-girder TR	1485	3966.291	1.609	0.250
LG	1485	4521.863	1.345	1.143
I-girder TR	2160	6656.055	1.487	0.318
LG	2160	9572.479	1.214	0.839
Box-girder TR	3240	10919.159	1.844	0.250
LG	3240	26878.624	1.435	0.345

Table 4. Base shear capacities and vulnerable PGA (g) for transverse direction at different performance level from pushover analysis

Push Step	Base Shear capacity kN			Displacement mm			PGA (g) From Base Shear Capacity			Damage State
	T	I	Box	T	I	Box	T	I	Box	
1	3205.54	5622.369	8988.798	64.367	41.16	33.924	0.39	0.46	0.49	Immediate occupancy
2	3509.746	6065.297	9711.861	87.599	59.994	49.297	0.42	0.50	0.53	Life safety
3	3813.987	6360.664	10434.923	110.83	72.55	64.67	0.46	0.53	0.57	Collapse prevention
4	3966.291	6656.055	10919.159	122.446	85.106	74.919	0.48	0.55	0.60	Damage
5	4233.704	7042.284	11641.491	144.105	102.402	90.98	0.51	0.58	0.64	Complete collapse

Table 5 Base shear capacities and vulnerable PGA (g) for longitudinal direction at different performance level from pushover analysis

Push Step	Base Shear capacity kN			Displacement mm			PGA (g) From Base Shear Capacity			Damage State
	T	I	Box	T	I	Box	T	I	Box	
1	4036.107	9036.601	18503.454	55.06	40.341	27.111	0.49	0.75	1.0	Immediate occupancy
2	4472.749	9507.13	23383.484	81.925	61.76	42.603	0.54	0.79	1.2	Life safety
3	4505.49	9528.911	25131.057	108.789	70.44	53.158	0.55	0.79	1.3	Collapse prevention
4	4521.863	9572.479	26878.624	122.222	87.8	63.173	0.55	0.79	1.4	Damage
5	4543.316	9594.267	28977.402	139.818	96.481	76.733	0.55	0.79	1.6	Complete collapse

3.4. Incremental Dynamic Analysis

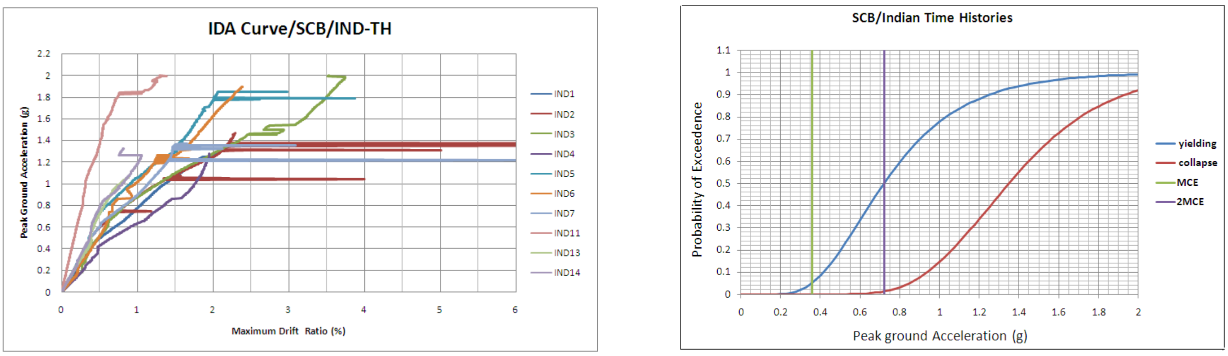
This research adopts nonlinear transient (time-history) analysis to simulate the earthquake loads acting on the analytical bridge model. As said before, the sources of nonlinearity were the nonlinear materials and bridge components behaviors. The ground motions were applied at the nodes representing the pile caps and abutments, in which the main horizontal component was acting along the longitudinal direction and the orthogonal component was applied along the transverse direction. The time-history analyses were performed by a time step of 0.05s which was half of the synthetic accelerograms' time step. Nevertheless, where required the analysis time step was decreased until numerical convergence was achieved. Moreover, the dynamic analyses were conducted using 5% Rayleigh damping. The damping coefficient was calculated deterministically such that the 5% damping occurs in the first two modes of vibration for the bridge analytical model, as calculated by the eigenvalue analysis. Incremental dynamic analysis (IDA), was performed to investigate the seismic performance and loading capacity of the highway bridge. For this purpose, each single ground motion record should be scaled to form different ground shaking levels. Consequently, an IDA curve was constructed using a set of ground motion records which demonstrates the bridge's decaying under increasing ground shaking level. According to Vamvatsikos and Cornell, the seismic capacity performance level is reached on the IDA curve where the local tangent reaches 20% of the elastic slope.

Among the recorded seismic responses, the columns' curvature ductility (μc), longitudinal deformations in the fixed and expansion bearings, and active and passive deformations in the abutments were nominated as the seismic demand parameters for performance assessment of the bridge system, since they have been reported to be determinant in evaluating the seismic capacity of highway bridges [11] IDA results are tabulated in Table 6. Fig. 5 shows the developed IDA curves for bridge components.

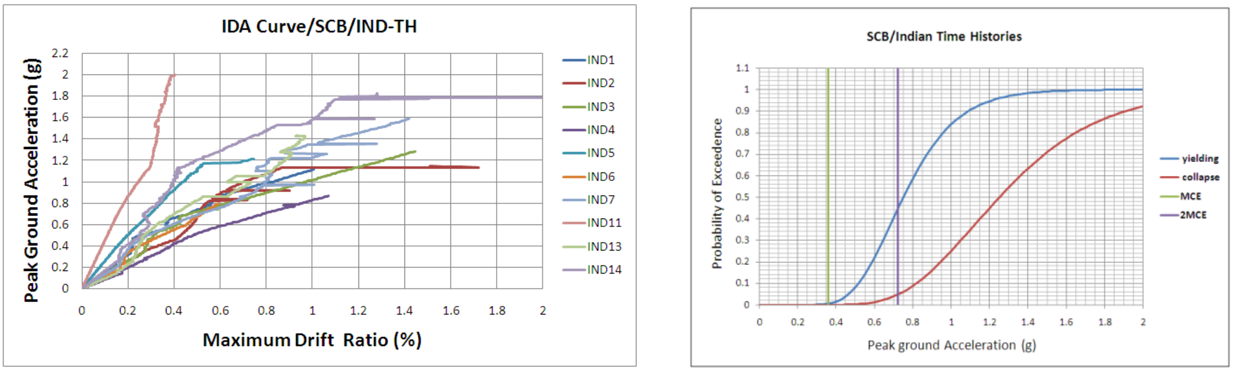
3.5. Fragility analysis results

These fragility curves represent the probability of structural damage due to various ground shakings. They also describe a relationship between ground motion and level of damage.

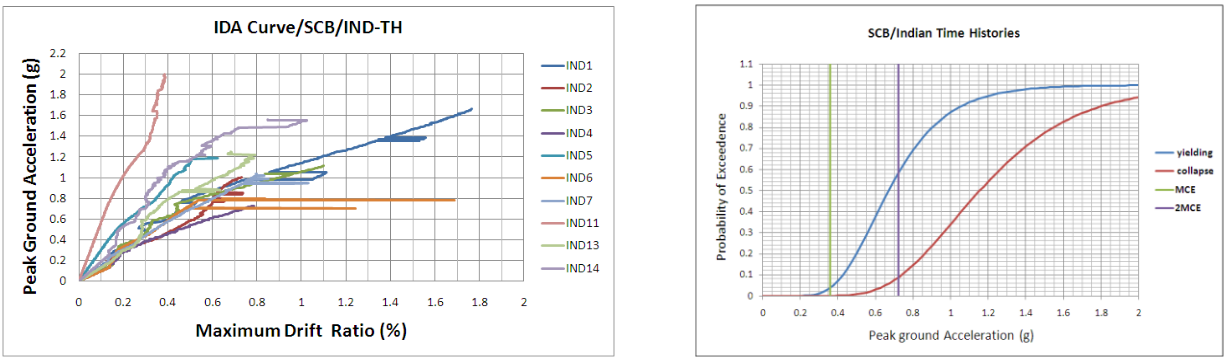
Fragility curves can be used for evaluating the total risk of infrastructures [12,13]. These curves indicate the probable level of damage for a specific class. Fragility curves can be expressed in the form of two parameters (median and log-standard deviation) lognormal distribution functions. Fragility curves (FC) are constructed with respect to PGA (g). The damage indices of the bridge piers are obtained from a non-linear dynamic response analysis. Then using the damage indices and the ground motion indices, the fragility curves are constructed as shown in Fig. 5. The results are tabulated in Table 7.



(a) IDA and Fragility curves For T girder bridges



(b) IDA and Fragility curves For I girder bridges



(c) IDA and Fragility curves For Box girder bridges

Figure 5. IDA and Fragility curves

Table 6. IDA Result Summary

Damage States	T girder		I girder		Box girder	
	PGA(g)	%Drift Ratio	PGA(g)	%Drift Ratio	PGA(g)	%Drift Ratio
At-Yield	0.445 to 1.54	0.414 to 2.836	0.505 to 1.14	0.247 to 2.922	0.455 to 1.34	0.254 to 1.243
At-Collapse	1.04 to 2.0	0.817 to 6.104	0.795 to 2.0	0.403 to 1.713	0.73 to 2.0	0.385 to 1.767

Table 7. Fragility Results Probability of Damage (%)

Type of bridge	MCE PGA(g)0.36		2MCE PGA(g)0.72	
	At Yield	At Collapse	At Yield	At Collapse
T	4	0	50	2
I	0	0	44	4
Box	4	0	58	8

4. DISCUSSION OF RESULTS

From the results of pushover analysis, it is observed that the range of vulnerable PGA(g) for collapse prevention for T girder bridges is 0.39 to 0.46; for I girder bridges is 0.46 to 0.53 and for box girder bridges is 0.49 to 0.57 which is low in transverse direction whereas it is much greater in longitudinal direction (Table 4 and 5).

These results show inadequacy of Indian seismic design code as recent earthquakes experienced worldwide has intensity range of 0.8 to 1.0 PGA(g).

Probabilistic seismic performance assessment of the sample concrete bridges in this study reveals the following key findings:

- From IDA results, it is observed that the drift capacities are acceptable for T-girder bridges and low for I and Box girder bridges.
- A very serious fact has come out from the study of I-girder bridges of 30m span that there exists 34% probability of survival against yield and 78% probability of survival against collapse under MCE levels. Under expected MCE these types of structures will undergo disaster. Therefore, there is an urgent need of appropriate retrofitting measures for such existing bridges to enhance their earthquake resistance over a period of time.
- The results of Box-girder bridges of 50m span show poor performance as compared to T and I girder bridges which is due to span variation. There exists 44% probability of survival against yield and 66%

probability of survival against collapse under MCE levels which is very low.

- From all the case studies it is observed that time period of structures plays an important role in seismic performance levels of concrete bridges. For higher value of the time period single column structures are more vulnerable. Displacement ductility is adequate for all types.

5. CONCLUSION

This paper focuses on the importance of Performance-based earthquake engineering (PBEE) methodology as a key approach for seismic analysis and design. Yet such approach has not been implemented in Indian structural codes

The seismic capacity of different types of concrete highway bridges designed as per Indian Standards is evaluated through a probabilistic method for substructure type of single column bents. Fragility curves are developed and used for evaluation purposes. The results express at a glance the probabilities of yielding and collapse against various levels of ground motion intensities. The results of this study can be further employed for developing performance-based seismic design of typical Indian concrete bridges.

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