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Fragility Analysis of Typical Indian Box-girder Concrete Bridges

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ABSTRACT

Performance-based earthquake engineering (PBEE) methodology has been widely developed during the past two decades, and has become a key approach for seismic analysis and design. Yet such an approach has not been implemented in Indian structural codes. Therefore, further research is required to develop a domestic approach for Indian applications. In this paper, the seismic capacity of a typical Box-girder concrete highway bridge designed as per Indian Standards is evaluated through a probabilistic method as well as nonlinear static analysis (pushover analysis) for substructure type of single-column and multi-column bents separately. Fragility curves are developed and used for evaluation purposes. These fragility curves represent the probability of structural damage due to various ground shakings. And more so they describe a relationship between ground motion and level of damage. This paper presents the method as well as the results in the form of vulnerability and structural reliability relations based on two damage functions.

Keywords: Concrete Bridge, Incremental Dynamic Analysis, Damage Limit State, Evaluation, Fragility Curve

I. INTRODUCTION

Bridges are potentially one of the most seismically vulnerable structures in the highway system during earthquake. It is known that the seismic performance of transportation systems plays key role for the post earthquake emergency management [1]. Hence, it is necessary to be evaluated both physical and functional aspects of bridge structures. The physical aspects of the seismic performance of bridges are evaluated with the seismic fragility functions. A fragility curve, represent the probability of structural damage due to various ground shakings [2,3]. And more so they describe a relationship between ground motion and level of damage.

In this paper, the seismic performance of a typical six span Box-girder concrete highway bridge is studied. For this purpose, a three-dimensional analytical model of the bridge is created, which encompasses all the bridge major components. It is noteworthy to mention that this analytical model was developed for generalised concrete Box girder bridges and not for a specific bridge. The bridge is first analysed using nonlinear static analysis (pushover analysis) by SAP2000[4] for substructure type of single-column and multi-column bents separately.

The seismic performance and overall seismic capacity of the bridge are then investigated through incremental dynamic analyses (IDA) by developing IDA curves [5] using IDARC-2D software [6]. 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.

II. GEOMETRIC DESCRIPTION AND DESIGN DETAILS

In this study, typical Indian Box-girder concrete bridge of six span is considered with span length of 50m. The bridge is analysed using nonlinear static analysis (pushover analysis) by SAP2000 for substructure type of single-column and multi-column bents separately. Both substructure types are designed as per provisions of IS 456, IS 1893 and IS 13920 for 1.5(DL+EQ) i.e. load of 12000kN acting at C.G. of bent cap.

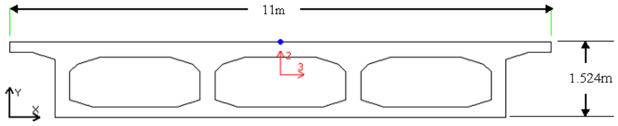


Figure 1. Deck cross-section

Super-structure details

Interior top slab thickness 305mm, Exterior overhang top slab thickness 205mm, Girder interior thickness 305mm, Bottom slab thickness 205mm connecting girder base, centre to centre girder distance 3.0m, overhang top slab portion 1.0m, horizontal length of chamfer 460mm and vertical length of chamfer 150mm.

Sub-structure details

Cross-section of bent-cap used is 2.0m×2.0m which is kept constant for both the bents. Following column cross sections are used for 8m height single column bent and multi column bent respectively. For outer concrete, Mander unconfined concrete model is used and for core concrete, Mander confined concrete model is used. For steel reinforcement Park model is used. M30 grade of concrete and Fe415 grade of steel is used.

Table 1. Details of column cross-sections for single and multi-column bents

Type of bent	**Size of column**	**Longitudinal reinforcement**	**Shear reinforcement**
SCB	3.0m	Φ32mm 88no.	Φ16mm with 250mm c/c spacing
MCB	1.5m	Φ32mm 44no.	Φ16mm with 250mm c/c spacing

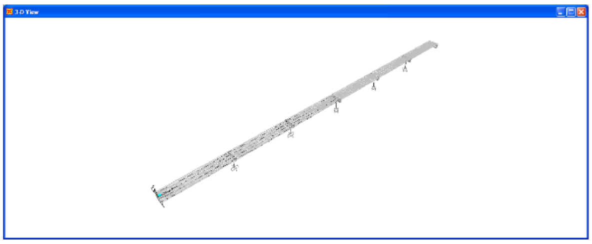
III. METHODOLOGY

A. Finite element modeling

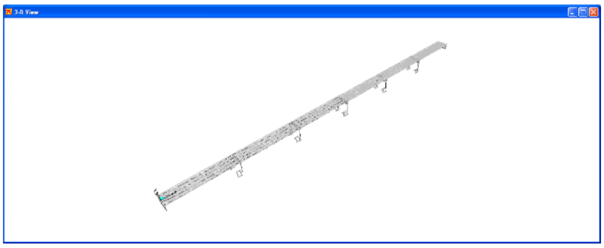
A simplified analytical modelling is utilised which allows for more economical analysis time when a large number of simulations are required. The analytical bridge model was established in SAP2000 analysis software. The modelling was performed consistent with Nielson's [7] findings on typical bridge properties and modelling assumptions.

The bridge superstructure consists of six symmetric spans. The superstructure is supported by two seat-type pile abutments at its two ends and two multi-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. Normally, the superstructure does not dominate the overall seismic response of a concrete highway bridge system because composite deck sections are much stiffer than other bridge components. This means that the concrete girders and slab behave like rigid elements and are expected to remain linearly elastic under seismic loads. Therefore, 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 behaviour of the two steel dowels [8].

Finite element model for the bridge with different substructure types are shown in Figure 2. 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.



(a) Single-column bent



(b) Multi-column bent

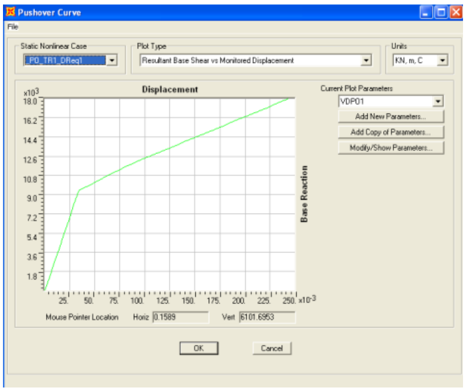
Figure 2. Finite element models

B. 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 [9] to consider maximum ground motion parameters and its effect on seismic performance.

C. Pushover analysis

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 V_b, yield, and maximum displacement i.e. δ_Y and δ_u, as well as the ductility capacity μ_c 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 (Figure 3 and 4).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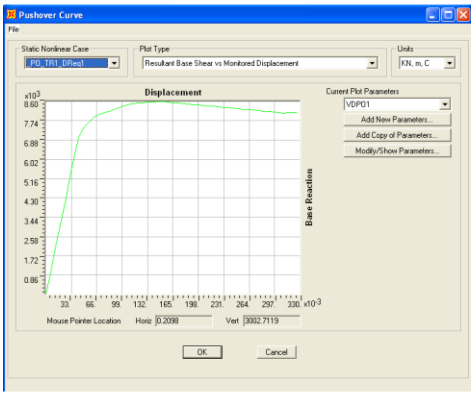
Units: KN, m, C
Current Plot Parameters: VDP01
Mouse Pointer Location Horiz 0.1589 Vert 6101.6953

(a) Single column bent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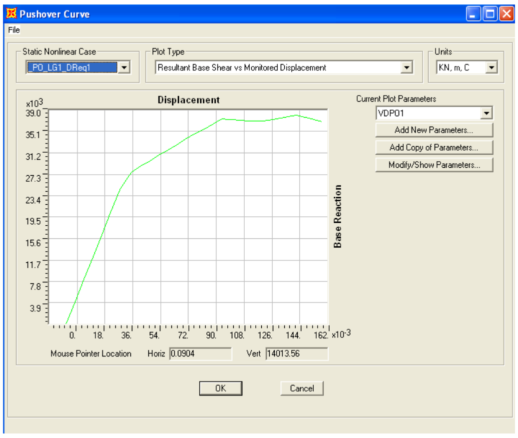
Plot Type: Resultant Base Shear vs Monitored Displacement
Units: KN, m, C
Current Plot Parameters: VDP01
Mouse Pointer Location Horiz 0.2098 Vert 3002.7119

(b) Multi column bent

Figure 3. Pushover Curves in transverse direction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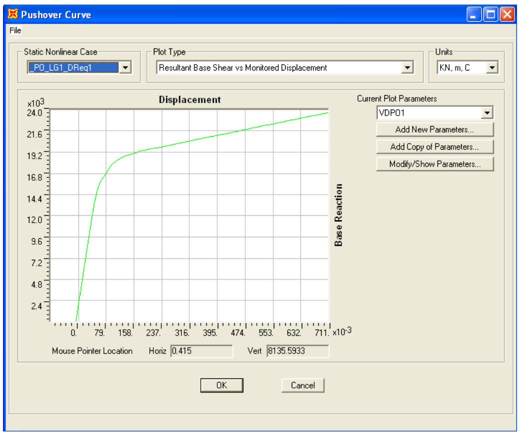
Plot Type: Resultant Base Shear vs Monitored Displacement
Units: KN, m, C
Current Plot Parameters: VDP01
Mouse Pointer Location Horiz 0.0904 Vert 14013.56

(a) Single column bent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Plot Type: Resultant Base Shear vs Monitored Displacement
Units: KN, m, C
Current Plot Parameters: VDP01
Mouse Pointer Location Horiz 0.415 Vert 8135.5933

(b) Multi column bent

Figure 4. Pushover Curves in longitudinal direction

Table 2. Results of Pushover Analysis

Base shear direction	Design Base shear kN	Base Shear Capacity kN		Displacement Ductility at LS		D/C Ratio	
		SCB	MCB	SCB	MCB	SCB	MCB
TR	3240	11252.705	8411.487	3.034	2.421	0.250	0.458
LG	3240	32717.369	18316.816	1.482	1.576	0.493	0.252

Table 3. Base shear capacities and vulnerable PGA (g) for transverse direction t different performance level

Push Step	**Base Shear capacity kN**		**Displacement mm**		**PGA (g) From Base Shear Capacity**		**Damage State**
	SCB	**MCB**	**SCB**	**MCB**	**SCB**	**MCB**	
1	9385.068	7009.585	33.935	42.277	0.52	0.38	Immediate occupancy
2	10085.432	7941.659	48.556	62.933	0.56	0.44	Life safety
3	10785.796	8174.158	63.178	82.525	0.59	0.45	Collapse prevention
4	11252.705	8411.487	72.925	102.116	0.62	0.46	Damage
5	11985.681	8483.124	89.148	110.147	0.66	0.47	Complete collapse

Table 4. Base shear capacities and vulnerable PGA (g) for longitudinal direction at different performance level

Push Step	**Base Shear capacity kN**		**Displacement mm**		**PGA (g) From Base Shear Capacity**		**Damage State**
	SCB	**MCB**	**SCB**	**MCB**	**SCB**	**MCB**	
1	24784.545	13147.981	27.965	42.626	1.3	0.73	Immediate occupancy
2	28790.687	15851.286	41.211	61.809	1.5	0.88	Life safety
3	30754.036	17588.692	52.783	90.678	1.7	0.97	Collapse prevention
4	32717.369	18316.816	64.354	110.338	1.81	1.0	Damage
5	34712.447	18703.914	76.506	127.187	1.92	1.0	Complete collapse

At the completion of the analysis phase, the pushover curve is obtained, as shown in Figure 3 and 4, where the total base shear and displacement capacity of the bridge are determined. A quick check of the base shear values should be conducted to verify the results of the pushover analysis using seismic design codes.

D. Nonlinear Transient Analysis

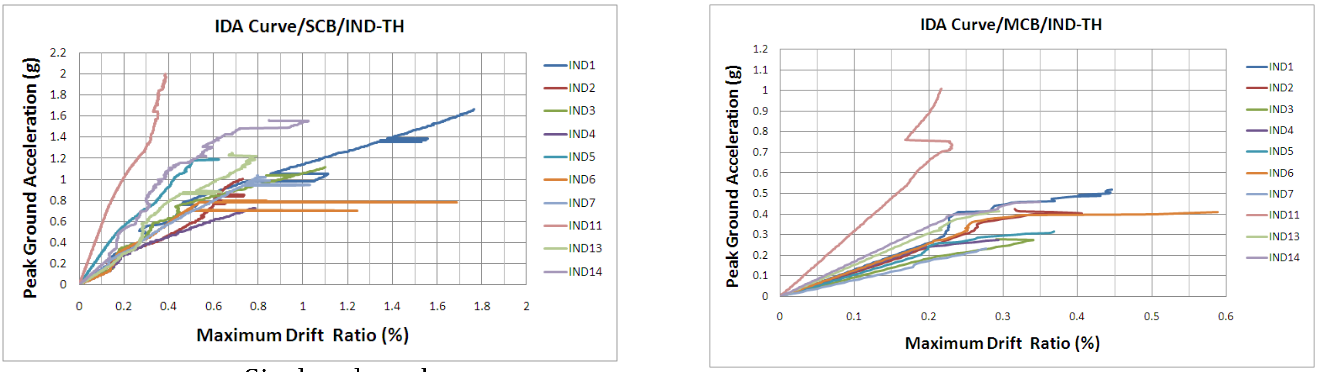
This research adopts nonlinear transient (time-history) analysis to simulate the earthquake loads acting on the analytical bridge model. As said before, the sources of nonlinearity were the nonlinear materials and bridge components behaviors. The ground motions were applied at the nodes representing 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 [5], the seismic capacity performance level is reached on the IDA curve where the local tangent reaches 20% of the elastic slope.

E. Incremental dynamic analysis results for transverse directions

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 [10]. IDA results are tabulated in Table 5. Figure 5 shows the developed IDA curves for bridge components.



a. Single column bent

b. Multi column bent

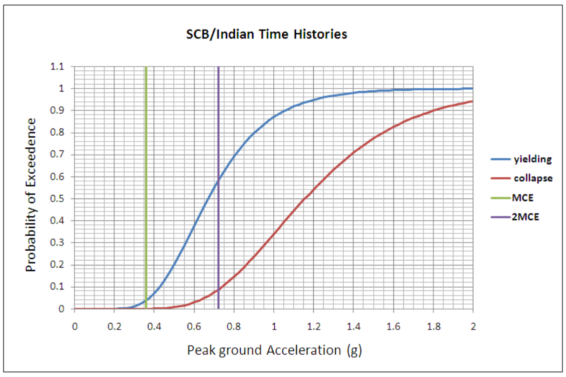
Figure 5. IDA curves

Table 5. IDA Result Summary for Set 1 Time Histories

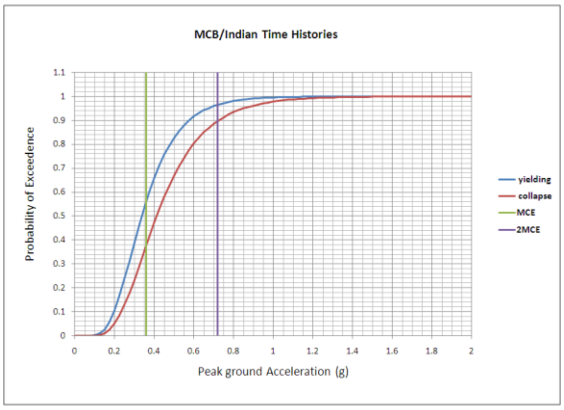
Degradation Condition	Damage States	Single-column bent (SCB)		Multi-column bent (MCB)	
		Range of PGA(g)	Range of % Drift Ratio	Range of PGA(g)	Range of % Drift Ratio
Moderate	At-Yield	0.455 to 1.34	0.254 to 1.243	0.19 to 0.74	0.176 to 0.293
	At-Collapse	0.73 to 2.0	0.385 to 1.767	0.235 to 1.01	0. 217 to 0.588

F. Fragility results for transverse directions

Fragility curves can be used for evaluating the total risk of infrastructures [11]. 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 for the single column and multicolumn bents are constructed as shown in Fig. 6. The results are tabulated in Table 6.



a. Single column bent



b. Multi column bent

Figure 6. Fragility Curves

Table 6. Fragility Results for Set 1 Time Histories

Degradation Condition	Type of Earthquake	PGA(g) of Earthquake	Probability of Damage (%)			
			At Yield		At Collapse	
			SCB	MCB	SCB	MCB
Moderate	MCE	0.36	4	56	0	38
	2MCE	0.72	58	96	8	90

IV. DISCUSSION OF RESULTS

From pushover analysis results, it is observed that six span bridges are safe in both directions whereas both column bent has over strength in both directions as indicated by demand-capacity ratio. Displacement ductility is adequate for both the column bent in longitudinal direction whereas for single column bent displacement ductility is not adequate in transverse direction. Results shows bridges are vulnerable in transverse direction only and range of vulnerable PGA(g) for collapse prevention 0.45 to 0.59 is low. 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).

A methodology based on IDA is developed to determine the structural performance, damage levels, fragility and hazard-survival probability of the representative box-girder bridge. The seismic performance of the sample bridge is quantified in terms of yield and collapse capacities in terms of various ground motion indices, which are derived from IDA curves. The yield capacity of the structure is defined as the level of PGA(g) (i.e. *Intensity Measure)* at which the IDA curve leaves the linear path. Similarly, the collapse capacity is defined as the PGA(g) level at which the IDA curve becomes horizontal. Results of IDA with the 10 ground motion records are used to assess the record-to-record randomness of response. Fragility curves defined as the probability of exceeding a damage level (yielding/collapse) at various levels of PGA(g) are then plotted for these two damage levels. The fragility curves for yielding and collapse damage levels are developed by statistically interpreting the results of the time-history analyses. Hazard-survival curves are generated by changing the horizontal axis of the fragility curves from ground motion intensities to their annual probability of exceedance using the log-log linear ground motion hazard model.

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

- ✓ From IDA results, it is observed that the drift capacities are low for Box girder bridges designed as per Indian seismic code.
- ✓ The hazard survival curve clearly shows the acceptable performance level against SE (Serviceability Earthquake) and DBE (Design Base Earthquake) as per Indian seismic code.
- ✓ There exists 44% probability of survival against yield and 66% probability of survival against collapse under MCE levels which is very low.
- ✓ From this study, it is observed that time period of the column bents 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 and for lower value multicolumn bents are more vulnerable.
- ✓ These results show inadequacy of Indian seismic design code as recent earthquakes experienced worldwide has intensity range of 2MCE.

V. 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 a typical Box girder concrete highway bridge designed as per Indian Standards is evaluated through a probabilistic method as well as nonlinear static analysis (pushover analysis) for substructure type of single-column and multi-column bents separately. Fragility curves are developed and used for evaluation purposes. These fragility curves represent the probability of structural damage due to various ground shakings. They describe a relationship between ground motion and level of damage. This paper presents the method as well as the results in the form of vulnerability and structural reliability relations based on two damage functions. 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 Box-girder concrete bridges.

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