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Nonlinear Analysis of Existing RC Bridge Using SAP 2000

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Abstract
There are many literatures available on the seismic evaluation procedures of multi-storied buildings using nonlinear static (pushover) analysis. There are presently no comprehensive guidelines to assist the practicing structural engineer to evaluate existing bridges and suggest design and retrofit schemes. In order to address this problem, the aims of the present project was to carry out a seismic evaluation case study for an existing RC bridge using nonlinear static (pushover) analysis. In the present study a 4 Span RC Bridge existed in SH-12 in Karnataka, India, was selected and by defining FEMA 356 Auto hinges conducted Nonlinear Static (Pushover) Analysis using (ATC 40) Capacity Spectrum Method and software SAP2000 was used to analyze the Bridge. The evaluation results presented here shows that the selected bridge does not have the capacity to meet the desired performance level and it requires retrofitting.
Keywords: RC Bridge, FEMA 356, Nonlinear Static (Pushover) Analysis, SAP 2000, ATC 40.

1. Introduction

India has had a number of the world's greatest earthquakes in the last century such as 2001 Gujarat Earthquake and 2005 Kashmir Earthquake etc; there is a nation-wide attention to the seismic vulnerability assessment of existing buildings. The magnitudes of the design seismic forces have been considerably enhanced in general, and the seismic zonation of some regions has also been upgraded. There are many literatures available for seismic evaluation of multi-storied buildings. Where the attention for existing bridges is comparatively less. However, bridges are very important components of transportation network in any country. Therefore, it is very important to evaluate the capacity of existing bridges against seismic force demand. There are presently no comprehensive guidelines to assist the practicing structural engineer to evaluate existing bridges and suggest design and retrofit schemes. In order to address this problem, the present work carried out on the seismic evaluation for an existing RC bridge using Nonlinear static (pushover) analysis as per ATC 40.

2. Loads acting on the Bridge

2.1 Dead load

It is a gravity loading due to the structure simply calculated as the product of volume and material density of the bridge.

2.2 Bridge live load

Road bridge decks have to be designed to withstand the live loads specified by Indian Roads Congress (I.R.C: 6-2010 Section II)

In India, highway bridges are designed in accordance with IRC bridge code. IRC: 6 - 2010 – Section II gives the specifications for the various loads and stresses to be considered in bridge design. There are three types of standard loadings for which the bridges are designed namely, IRC class AA loading, IRC class A loading and IRC class B loading.

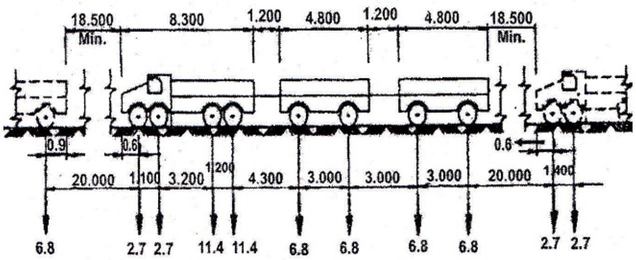


Figure 1. IRC Class A Loading

IRC Class A loading consists of a wheel load train composed of a driving vehicle and two trailers of specified axle spacing (Figure 1). This loading is normally adopted on all roads on which permanent bridges are constructed.

2.3 Impact Load

For I.R.C. class A loading. The impact allowance is expressed as a fraction of the applied live load and is computed by the expression

$$I=4.5/(6+L) \quad \ldots\ldots (1)$$

Where, I=impact factor fraction
L=span in meters.

2.4 Seismic Load

If a bridge is situated in an earthquake prone region, the earthquake or seismic forces are given due consideration in the analysis. An earthquake causes vertical and horizontal forces in the structure that will be proportional to the weight of the structure. IS: 1893 Part-3 may be referred for the actual design loads.

3. Nonlinear Static (Pushover) Analysis

The use of the nonlinear static analysis came in to practice in 1970's but the potential of the pushover analysis has been recognized for last 10-15 years. This procedure is mainly used to estimate the strength and drift capacity of existing structure and the seismic demand for this structure subjected to selected earthquake. This procedure can be used for checking the adequacy of new structural design as well.

Pushover analysis is defined as an analysis wherein a mathematical model directly incorporating the nonlinear load-deformation characteristics of individual components and elements of the structure shall be subjected to monotonically increasing lateral loads representing inertia forces in an earthquake until a 'target displacement' is exceeded. Target displacement is the maximum displacement (elastic plus inelastic) of the structure at top expected under selected earthquake ground motion. Pushover analysis assesses the structural performance by estimating the force and deformation capacity and seismic demand using a nonlinear static analysis algorithm. The seismic demand parameters are global displacements (at roof or any other reference point), storey drifts, storey forces, and component deformation and component forces. The analysis accounts for geometrical nonlinearity, material inelasticity and the redistribution of internal forces. Response characteristics that can be obtained from the pushover analysis are summarized as follows:

a) Estimate of force and displacement capacities of the structure. Sequence of the member yielding and the progress of the overall capacity curve.
b) Estimate of force (axial, shear and moment) demands on potentially brittle elements and deformation demands on ductile elements.
c) Estimate of global displacement demand, corresponding inter-storey drifts and damages on structural and non-structural elements expected under the earthquake ground motion considered.
d) Sequences of the failure of elements and the consequent effect on the overall structural stability.
e) Identification of the critical regions, where the inelastic deformations are expected to be high and identification of strength irregularities (in plan or in elevation) of the building.

3.1 Pushover analysis procedure

Pushover analysis is a static nonlinear procedure in which the magnitude of the lateral load is increased monotonically maintaining a predefined distribution pattern along the height of the Structure. Structure is displaced till the 'control node' reaches 'target displacement' or structure collapses. The sequence of cracking, plastic hinging and failure of the structural components throughout the procedure is observed. The relation between base shear and control node displacement is plotted for all the pushover analysis.

Generation of base shear – control node displacement curve is single most important part of pushover analysis. This curve is conventionally called as pushover curve or capacity curve. The capacity curve is the basis of 'target displacement' estimation. The seismic demands for the selected earthquake are calculated at the target displacement level. The seismic demand is then compared with the corresponding structural capacity or predefined performance limit state to know what performance the structure will exhibit.

3.2 Need for non-linear static (pushover) analysis

Conventionally, seismic assessment and design has relied on linear or equivalent linear (with reduced stiffness) analysis of structural systems. In this approach, simple models are used for various elements of the structure, which are subjected to seismic forces evaluated from elastic or design spectra, and reduced by force reduction (or behavior) factors. This ensures displacements are amplified to account for the reduction of applied forces.

The reduced force-amplified deformation linear elastic approach fails to fit within the principle of failure mode control, which is part of performance based assessment and design. This in turn has led to an increase in the use of inelastic analysis as a more realistic means of assessing deformational state in structures subjected to strong ground motions.

The pushover analysis is a significant step forward by giving consideration to those inelastic response characteristics that will distinguish between good and bad performance in severe earthquakes. The non linear static pushover analysis is a partial and relatively simple immediate solution to the complex problem for predicting forces and deformation demands imposed on the structure and its elements due to ground motions.

The pushover is part of an evaluation process and provides estimates of demands imposed on structures and elements. Hence, there is always a need of a method which is rational and accurate and at the same time able to identify seismic deficiencies correctly and that too in a correct order of vulnerability. Pushover analysis is able to satisfy these criteria satisfactorily and in a convenient way.

3.3 Capacity spectrum method (ATC 40)

In this method the maximum inelastic deformation of a nonlinear SDOF system can be approximated from the maximum deformation of a linear elastic SDOF system with an equivalent period and damping. This procedure uses the estimates of ductility to calculate effective period and damping. This procedure uses the pushover curve in an acceleration-displacement response spectrum (ADRS) format. This can be obtained through simple conversion using the dynamic properties of the system. The pushover curve in an ADRS format is termed a 'capacity spectrum' for the structure. The seismic ground motion is represented by a response spectrum in the same ADRS format and it is termed as demand spectrum (Figure 2).

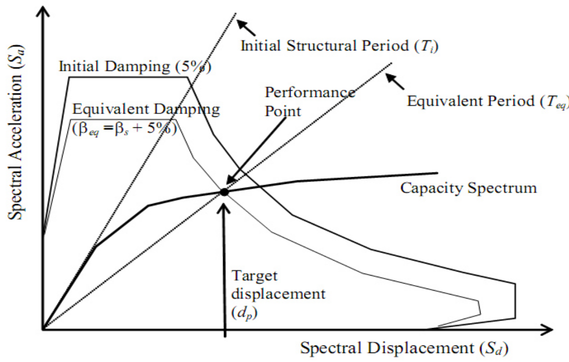


Figure 2. Schematic representation of Capacity Spectrum Method (ATC 40)

The equivalent period (Teq) is computed from the initial period of vibration (Ti) of the nonlinear system and displacement ductility ratio (μ). Similarly, the equivalent damping ratio (βeq) is computed from initial damping ratio and the displacement ductility ratio (μ). ATC 40 provides the following equations to calculate equivalent time period (Teq) and equivalent damping (βeq).

4. Problem definition

This chapter presents a summary of various parameters defining the computational models, the basic assumptions and the bridge geometry considered for this study.

A 4 Span RC Slab Bridge existed at a chainage 12+334 in State Highway (SH-12) from Bijapur-Athani (Karnataka, India) Section across Done River is taken as a case study. The details of the bridge are given in Table 1. The loads and load combinations on the bridge are studied and the same bridge in modeled in SAP 2000 and conducted Linear static analysis to get the maximum bending moments and dynamic properties of the bridge. Afterwards the FEMA 356 Hinges are defined in the model and conducted Nonlinear Static (Pushover) Analysis using ATC-40 to calculate Base Shear vs. Displacements, Effective time, Spectral Displacement Capacity & Spectral Displacement Demand and to find out Performance points of Bridge.

Table 1. Bridge Details

Bridge Details		
Sl.No	Description	
1)	Span of Bridge	4 X 20m
2)	Width of Bridge	8.6m
3)	Number of Lanes	2 Lanes
4)	No. of Main Girders	3 No's
5)	Total depth	2.495m
6)	Slab Thickness (Average)	0.26m
7)	Type of Live load	IRC Class A Train
8)	Load Combination	DL+LL+IL+EQ
9)	Compressive Strength of Concrete (f_{ck})	30000 KN/m^2
10)	Modulus of Elasticity (E)	27386128 KN/m^2
11)	Poisson's Ratio of Concrete	0.18

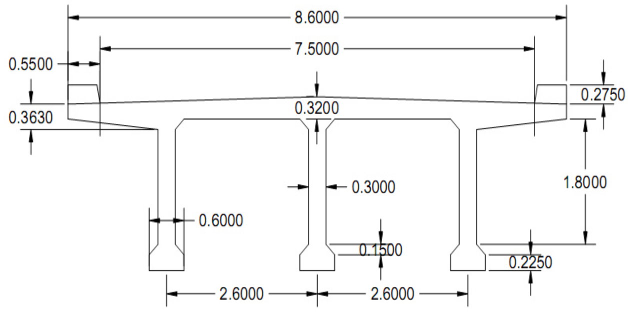


Figure 3. Cross Section of the Bridge

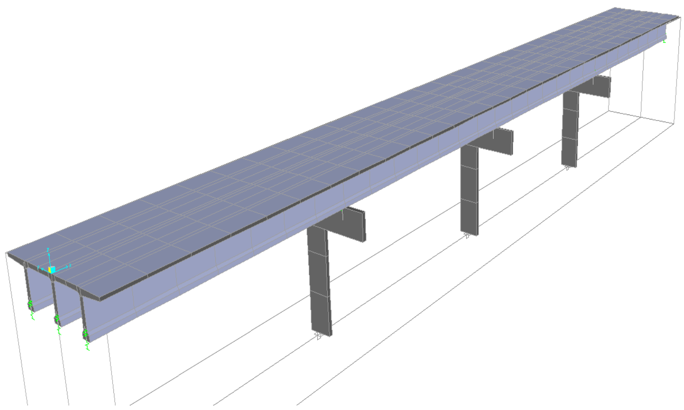


Figure 4. Bridge Model in SAP 2000

Table 2. Input for Nonlinear analysis in SAP 2000

Input Data analysis		
Sl.No	Description	
1)	Density of Reinforced Concrete	25000 KN/m^2
2)	Grade of Concrete	M-30
3)	Type of Live load	IRC Class A Train
4)	Impact factor (i) = 4.5/(6+L)	0.173
5)	Importance factor (I)	1.2
6)	Response reduction factor (R)	3.0
7)	Poisson's ratio of concrete	0.18
8)	Seismic zone	Zone-III
9)	Seismic zone factor (Z)	0.16
10)	Soil type	Type-II (Medium)

4.1 Modeling of Flexural hinges

In the implementation of pushover analysis, the model must account for the nonlinear behavior of the structural elements. In the present study the plastic hinge is assumed to be concentrated at a specific point in the frame member under consideration. In this study flexure (M3) hinges (FEMA 356 - Auto hinges) modeled at possible plastic regions under lateral load. Properties of flexure hinges must simulate the actual response of reinforced concrete components subjected to lateral load. The figure 5, shows the coordinate system of flexural hinges.

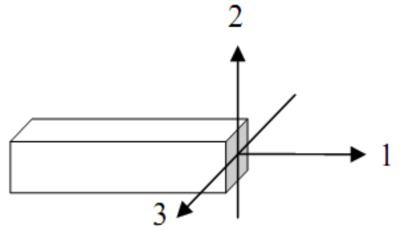


Figure 5. Coordinate system used to define the flexural hinges

4.2 Moment-rotation parameters

Moment-rotation parameters are the actual input for modeling the hinge properties and this can be calculated from the moment-curvature relation. The moment-rotation curve can be idealized as shown in Figure 6, and can be derived from the moment-curvature relation. The main points in the moment-rotation curve shown in the figure can be defined as follows:

1) The point 'A' corresponds to the unloaded condition.
2) The point 'B' corresponds to the nominal yield strength and yield rotation θ_y
3) The point 'C' corresponds to the ultimate strength and ultimate rotation θ_u, following which failure takes place.
4) The point 'D' corresponds to the residual strength, if any, in the member. It is usually limited to 20% of the yield strength, and ultimate rotation, θ_u can be taken with that.
5) The point 'E' defines the maximum deformation capacity and is taken as $15\theta_y$ or θ_u, whichever is greater.

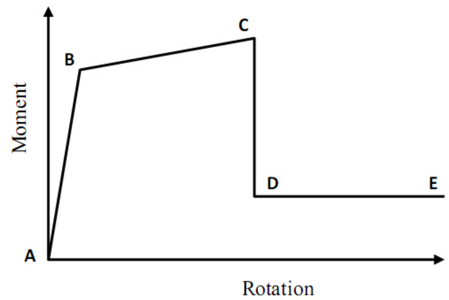


Figure 6. Idealized moment-rotation curve of RC elements

5. Results

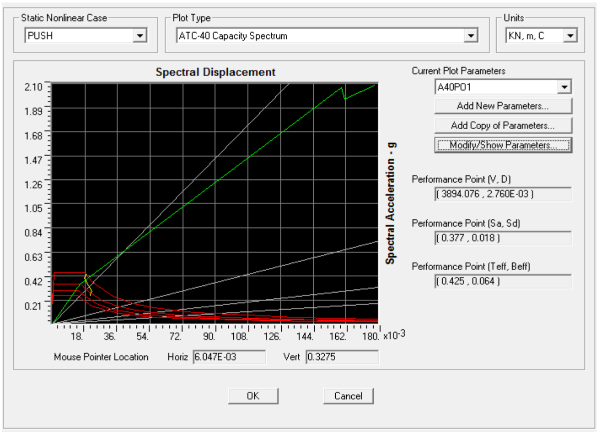
The selected bridge model is analyzed using Nonlinear Static (Pushover) analysis. This chapter presents Pushover analysis results. Pushover analysis (Push Y) was performed first in a load control manner to apply all gravity loads on to the structure (gravity push). Then a lateral pushover analysis in transverse direction (Y-direction) was performed in a displacement control manner starting at the end of gravity push. The results obtained from these analyses are checked by comparing spectral displacement demand and spectral displacement capacity from the pushover curve.

5.1 Nonlinear static (pushover) analysis

Nonlinear Static (Pushover) Analysis permits to identify critical members likely to reach limit states during the earthquake. Nonlinear Static Analysis is carried out after assigning flexural hinges (FEMA 356 Auto hinges) using ATC 40 Capacity Spectrum Method. As a result performance points & levels (IO, LS, and CP) are found in different pushover steps (Fig 7 to Fig 12), Spectral Acceleration vs. Spectral Displacement Graph (Graph 1) is drawn and Spectral Displacement Demand & Spectral Displacement Capacity is calculated.

Table 3. Pushover Demand Capacity (ATC 40)

Pushover Curve Demand Capacity - ATC40 – PUSH				
Step	T_{eff}	B_{eff}	S_d Capacity (m)	S_d Demand (m)
1	0.414959	0.05	0	0.018554
2	0.414959	0.05	0.012881	0.018554
3	0.422873	0.063618	0.015547	0.017778
4	0.557828	0.081033	0.15941	0.021952
5	0.574937	0.108421	0.161382	0.020765
6	0.585788	0.114581	0.178023	0.020797



Graph 1. Pushover Demand Capacity Curve (ATC 40)

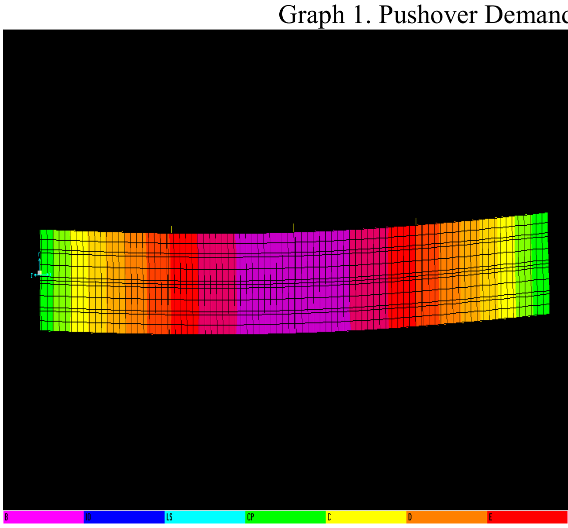


Figure 7. Pushover Step 1

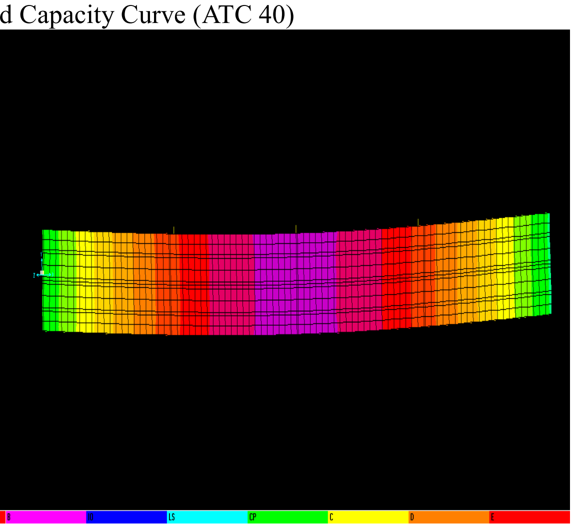


Figure 8. Pushover Step 2

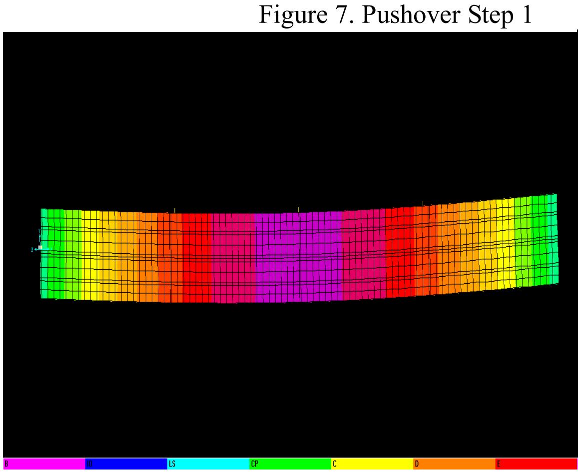


Figure 9. Pushover Step 3

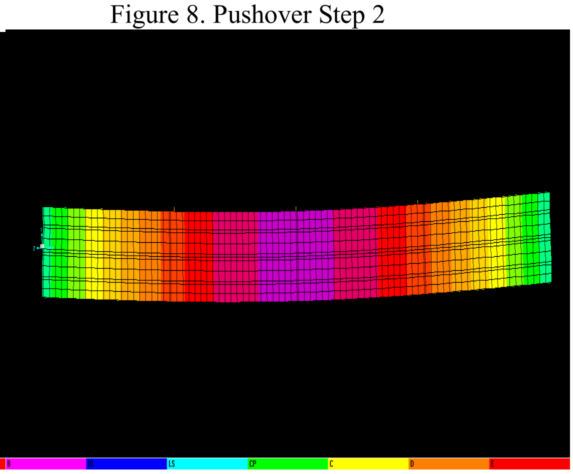


Figure 10. Pushover Step 4

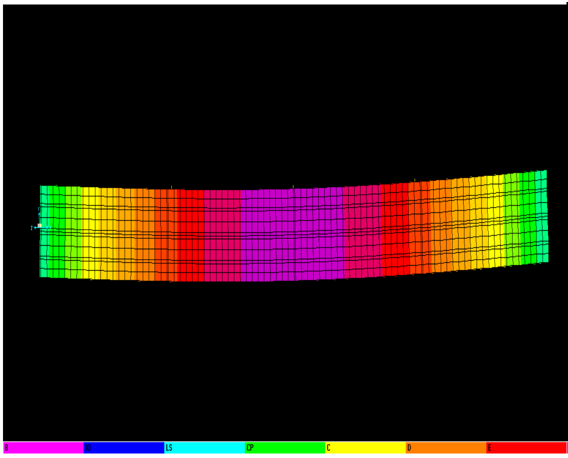


Figure 11. Pushover Step 5

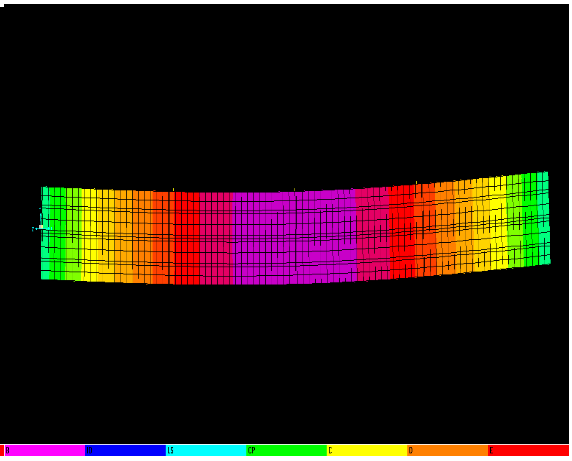
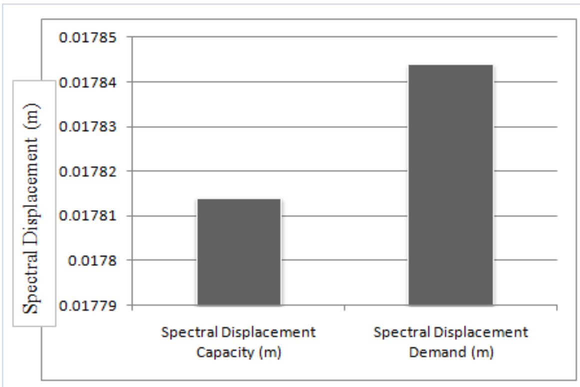


Figure 12. Pushover Step 6

The effective time is 0.425; it is in between pushover step 3 and step 4. At effective time the Spectral Displacement Capacity (m) and Spectral Displacement Demand (m) is calculated by interpolating values in the Table 3. Table 4 shows the Spectral Displacement Capacity and Spectral Displacement Demand values according to Capacity Spectrum Method ATC 40 at effective time 0.425 sec's.

Table 4. Comparison between Capacity & Demand (ATC 40)

Pushover Step	Effective Time, T_{eff} (Sec)	Spectral Displacement Capacity (m)	Spectral Displacement Demand (m)
Between 3 & 4	0.425	0.017814	0.017844



Graph 2. Comparison between S_d Capacity & S_d Demand

6. Conclusion

From the Pushover Analysis the performance levels of bridge are studied. From the Analysis it is evident that Spectral Displacement Demand is more than the Spectral Displacement Capacity (Graph 2) in the analyzed Bridge. So the analyzed bridge requires retrofitting.

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