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Pushover Analysis of Unequal Bridge pier

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Abstract— Bridges are one of the critical components of any transport infrastructure network and their serviceability during earthquakes is vital to ensure safety of society. One of the challenges associated with the design of bridges is to synchronize the analysis of piers with unequal height. This paper presents an investigation of the seismic response of few schemes of three span continuous bridge, featuring piers with length by diameter ratio (L/D) as L/D< 12, L/D > 12 and other bridge with piers one <12 and one >12 .Nonlinear static pushover analysis is performed using SAP 2000 .The target is to check the performance of bridge by using ratio of spectral demand to spectral acceleration ratio (Sd/Sa) with in permissible limit as defined by ATC 40. After investigation conclusion is drawn about base shear and deflection with in defined monitored deflection and result is drawn, bridge pier with L/D < 12 reaches its highest value and it is most critical case.

***K*eywords:** Unequal bridge pier, FEMA 356, pushover analysis, SAP 2000, ATC-40, Plastic hinges.

I. INTRODUCTION

A particularly challenging problem worth tackling is the seismic design and response prediction of bridges supported on piers of unequal height – so called *irregular* bridges, a commonly adopted solution when crossing steep-sided river valleys. In case where the cross-sections of the piers are identical, the shorter piers resist higher level of inertia forces than the taller piers. 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 seismic evaluation for an unequal bridge piers using Nonlinear static (pushover) analysis as per ATC 40 is used to verify the results.. The investigation is performed on three-span continuous concrete bridges resting on two unequal piers with relative heights to diameter ratio of less than 12, and more than 12 respectively. Static pushover (under incrementally scaled-up *actual* records) nonlinear inelastic analyses is performed using SAP 2000. The seismic region of greater impact i.e. seismic zone IV and V (IRC:6 and IS:1893) have been considered. The response parameters like base shear and roof displacement for each case are studied. Evaluation of performance point (Sa, Sd) for the given structure is considered as per capacity-demand methodology.

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II. UNEQUAL BRIDGE PIER

One of the challenges associated in predicting the failure of irregular bridges supported by piers of unequal heights, which is not effectively addressed in any code. It currently uses "moment demand-to-moment capacity" ratios to somewhat guarantee simultaneous failure of piers on bridges, In the present work, carried out seismic evaluation for an unequal bridge piers using Nonlinear static (pushover) analysis as per ATC 40 is used to verify the results. It relies on the relative effective stiffness of the piers Evaluation of performance point (Sa, Sd) for the given structure is considered as per capacity-demand methodology ,various irregular bridges will be simulated through a non-linear pushover analysis using shear-critical, fibre-based, beam-column elements. The research will investigate the behaviour of irregular monolithic unequal bridges experiencing different failure modes, and investigate different ways of regularizing the bridge performance to balance damage. The ultimate aim is to obtain a simultaneous or near-simultaneous failure of all unequal piers irrespective of the different heights and failure mode experienced. Case study bridge used is continuous three span bridge with span 30 meters, piers of diameter one meter at spacing of 7.5 m from each end and height of pier varying from 7.5 m to 15 m for different cases. Flat slab deck is used which is integrated with piers using bearings. Bearing of bridge is as per IRC 6, alternative bearings as pinned at one end and free at other end starting from abutment to pier is used.

In first case study pier length to diameter ratio used is l/d >12 as long column.

In second case study pier of unequal length one as short and other as long column is used.

In third case study pier length to diameter ratio used is l/d<12 as short column.

III. NONLINREAR STATIC (PUSHOVER) ANAYSIS

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

This procedure is mainly used to estimate the strength and drift capacity of existing structure and 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) Estimates of force and displacement capacities of the structure. Sequence of the member yielding and the progress of the overall capacity curve.
b) Estimates of force (axial, shear and moment) demands on potentially brittle elements and deformation demands on ductile elements.
c) Estimates 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.

IV. TARGET DISPLACEMENT

Target displacement is the displacement demand for the building at the control node subjected to the ground motion under consideration. This is a very important parameter in pushover analysis because the global and component responses (forces and displacement) of the building at the target displacement are compared with the desired performance limit state to know the building performance. So the success of a pushover analysis largely depends on the accuracy of target displacement. There are two approaches to calculate target displacement:

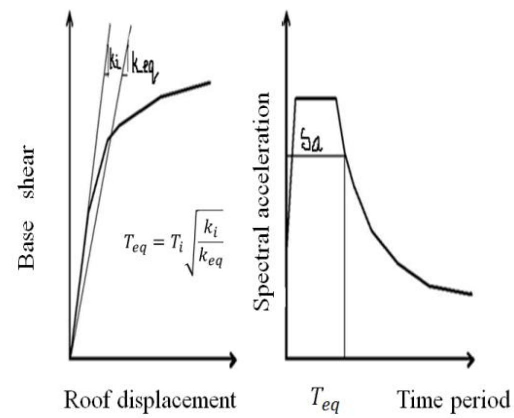
(a) Displacement Coefficient Method (DCM) of FEMA 356 and
(b) Capacity Spectrum Method (CSM) of ATC 40.

Both of these approaches use pushover curve to calculate global displacement demand on the building from the response of an equivalent single-degree-of-freedom (SDOF) system. The only difference in these two methods is the technique used.

V.DISPLACEMENT COEFFICIENT METHOD (FEMA 356)

This method primarily estimates the elastic displacement of an equivalent SDOF system assuming initial linear properties and damping for the ground motion excitation under consideration. Then it estimates the total maximum inelastic displacement response for the building at roof by multiplying with a set of displacement coefficients.

The process begins with the base shear versus roof displacement curve (pushover curve) as shown in Fig.1(a). An equivalent period (*Teq*) is generated from initial period (*Ti*) by graphical procedure. This equivalent period represents the linear stiffness of the equivalent SDOF system. The peak elastic spectral displacement corresponding to this period is calculated directly from the response spectrum representing the seismic ground motion under consideration Fig.1



pushover curve elastic response spectrum

Fig 1 Schematic representation of Dsplacement Coefficient Method (FEMA-356)

$$S_a = \frac{T^2_{eq}}{4\pi^2} S_d$$

(Eq2.1)

Now, the expected maximum roof displacement of the building (target displacement) under the selected seismic ground motion can be expressed as:

$$\delta_t = c_0\ c_1 c_2\ c_3\ S_d = c_0 c_1 c_2\ c_3\ \frac{T^2_{eq}}{4\pi^2} s_d$$

(Eq2.2)

C_o = a shape factor (often taken as the first mode participation factor) to convert the spectral displacement of equivalent SDOF system to the displacement at the roof of the building.

C_1= the ratio of the expected displacement (elastic plus inelastic) for an inelastic system to the displacement of a linear system.

C_2= a factor that accounts for the effect of pinching in load deformation relationship due to strength and stiffness degradation

C_3= a factor to adjust geometry nonlinearity (P-Δ) effects.

These coefficients are derived empirically form statistical studies of the nonlinear response history analyses of SDOF systems of varying periods and strengths and given in FEMA 356

VI. 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"[1] (Fig. 2).

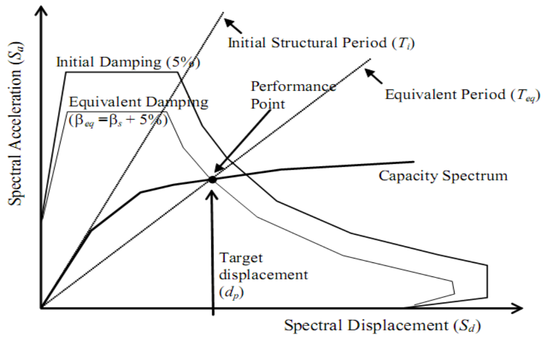


Fig 2. Schematic representation of Capacity Spectrum Method (ATC 40)

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[1] provides the following equations to calculate equivalent time period (Teq) and equivalent damping (βeq).

$$T_{eq} = T_i \sqrt{\frac{\mu}{1+\alpha\mu-\alpha}}$$

$$\beta_{eq} = \beta_i + \kappa \frac{2(\mu-1)(1-\mu)}{\pi u(1+\alpha u-\alpha)} = .05$$

Where α is the post-yield stiffness ratio and $\kappa$is an adjustment factor to approximately account for changes in behaviour in reinforced concrete structures.

VII. PASTIC HINGES

The point of localized damage in structure is often called as hinge. In the implementation of pushover analysis, the model must account for the nonlinear behaviour 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 hinges (FEMA 356 - Auto hinges)[7] is modelled 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 ATC-40[1] and FEMA-273 documents have developed modeling procedures, acceptance criteria and analysis procedures for pushover analysis. These documents define force-deformation criteria for hinges used in pushover analysis. As shown in figure

below, five points labeled A, B, C, D, and E are used to define the force deflection behavior of the hinge and three points labeled IO, LS and CP are used to define the acceptance criteria for the hinge. (IO, LS and CP stand for Immediate Occupancy, Life safety and Collapse Prevention respectively.) The values assigned to each of these points vary depending on the type of member as well as many other parameters defined in theATC-40 and FEMA-273 documents.

The main points in the force-deformation curve shown in the (Fig5) can be defined as follows:

1) Immediate Occupancy (IO): Limited Structure damage with basic Vertical and lateral force resisting system retaining most of their pre earthquake characteristics and capacities. The risk of life-threatening injury as a result of structural damage is very low.

2) Life Safety (LS): Significant damage with some margin against total or partial collapse. Repair may not be economically feasible. Some structural elements and components are severely damaged, but this has not resulted in large falling debris hazards, either within or outside the building. The overall risk of life-threatening injury as a result of structural damage is expected to be low.

3) Collapse Prevention (CP): Significant risk of injury exists. Repair may not be technically or economically feasible. In other word the post-earthquake damage state that includes damage to structural components such that the structure continues to support gravity loads but retains no margin against collapse in compliance with the acceptance criteria specified in this standard for this Structural Performance Level.

Where,

C = Strength Degradation

C-D = Initial failure of the component

D-E = Residual Resistance

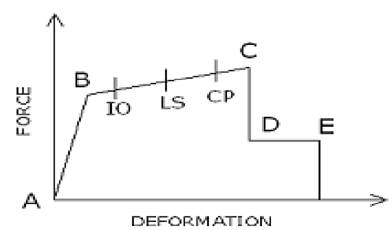


Fig 3.Force deformation for push over Hinges

VIII.RESULTS:

Modelling of size of bridge is done, having 3 spans each with pier height to diameter ratio of l/d <12, l/d >12 and third case having pier size (l/d) one with less than 12 another with l/d> 12 .pushover analysis of bridge is done using SAP 2000 and spectral acceleration to spectral demand curve (Sa/Sd) is studied to evaluate safe performance of bridges and behaviour of bridge pier.

IX. CONCLUSION:

a) Bridges with unequal pier with length to diameter ratio (l/d>12 or l/d<12) have combinations of flexure and shear failure modes. In this case, the shorter piers often result in brittle shear failure and this limits its ductility capacity, while the longer piers are most likely to fail in a ductile flexural mode. As a conclusion, the shorter pier needs to be designed for higher ductility capacity in order to achieve a regularization condition.

b) Spectral acceleration to spectral demand curve resembles to that of standard graph and Sa/Sd ratio is within permissible limit for all cases as limits mentioned in ATC 40 (Sa/Sd should be less than one)

Sa/Sd ratio of bridge with long pier l/d >12 is 0.262 Sa/Sd ratio of bridge with unequal pier l/d <12 and l/d >12 is 0.067

Sa/Sd ratio of bridge with short pier l/d <12 is 0.020.

c) It was found bridge with long pier having monolithic bearing yields to be advantageous as it significantly increases its flexural strength and symmetrical distribution of load on both piers

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