A SPECTRA-BASED MULTI MODAL ADAPTIVE PUSHOVER PROCEDURE FOR SEISMIC ASSESSMENT OF BUILDINGS

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ABSTRACT :

Since the conventional pushover analyses are unable to consider the effect of the higher modes and progressive variation in dynamic attribute of structure in inelastic phase, during the recent years, some advanced multi modal and also adaptive pushover procedures have been proposed. However they are not complete and suffer from some drawbacks explained in this paper. In order to remedy these drawbacks, an advanced spectra-based multi modal adaptive (MMA) procedure is proposed. This method incorporates the adaptive method in multi modal pushover analysis while in consecutive steps the effects of the yielding in one mode are reflected in the stiffness matrix of the other modes, whereas the capacity curve and seismic demand are derived for each mode individually. The total seismic demands are estimated by combining the modal demands due to some selected number of modes.

KEYWORDS: Seismic demands, nonlinear analysis, pushover, adaptive, multi modal

1. INTRODUCTION

Regarding the inelastic behaviour of structures at low performance levels and the complexity associated with the nonlinear time history analysis, in recent years nonlinear static procedure (NSP) as a simple tool has been developed for estimating seismic demands in the inelastic structure. Therefore the NSP so-called pushover analysis has played an important role in the development of performance-based earthquake engineering concepts in guideline documents and codes (e.g. ATC-40, 1996; FEMA-356, 2000; Erocode-8, 2002).

In the conventional pushover analysis, the nonlinear properties of the structural materials are directly involved in the structural model. Then an invariant lateral force pattern incrementally is applied to the structural model until its displacement reaches some predetermined limit (target displacement). Definition of the lateral load pattern is based on the assumed fundamental mode shape and the response of a multi degree of freedom (MDOF) system is directly related to the response of an equivalent single degree of freedom (SDOF) system with a fundamental mode shape assumed to be constant in the elastic and inelastic deformation.

In regular and low-rise buildings in which the response is governed primarily by fundamental mode, this procedure provides a good estimation of the global deformation response (Saiidi and Sozen 1981, Fajfar and Gaspersic 1996, Gupta and Krawinkler 2000). While in the irregular or high-rise buildings, the structural behaviour is affected by the higher modes as well as the fundamental mode and the buildings modal attributes are changed by yielding during the nonlinear time history procedure; consequently, the pushover procedure is flawed (Lawson et al. 1994, Krawinkler and Seneviratna 1998, Kim and D’Amore 1999, Mwafy and Elnashai 2001, FEMA 440 2004).

2. ADVANCED PUSHOVER ANALYSIS

The major drawback of conventional pushover is that it is basically restricted to a single-mode response, and cannot account for the contributions of the higher modes and the progressive change in the modes shape because of structural yielding.

For the purpose of considering higher modes effects recently some enhanced pushover procedures based on the modal combination concept are developed while the simplicity of the conventional methods is kept (Paret et al. 1996; Sasaki et al. 1998; Moghadam 2002; Chopra and Goel 2002; Shakeri et al. 2006). In the most well-known modal pushover analysis (MPA) proposed by Chopra and Goel (2002), multiple pushover analyses with lateral load corresponding to the considered elastic mode shapes are conducted separately, and then the total seismic response is estimated by combining the responses due to each modal load. In fact the total seismic response of the multi degree of freedom system is estimated by combining the responses of multiple single degree freedom system. However the performance of the MPA procedure is better than the traditional pushover analysis, but it suffer from some drawbacks. The load pattern in each modal pushover analysis is still invariant and the variation of the modal properties during the procedure is not considered. The pushover analysis are ran for each mode independently therefore the stiffness matrix in sequence steps is obtained based on the yielding of the structure only due to applied load in this mode and the softening effects of yielding in one modes are not considered in others modes and just as modal analysis in elastic phase, interaction between modes is neglected.

On the other hands in order to consider the effect of progressive changes in the dynamic attributes of structure in the inelastic phase recently, some researchers have developed adaptive modal methods (e.g. Gupta and Kunnath 2000, Elnashai 2001, Antounio and Pinho 2004a, 2004b, Shakeri and Shayanfar 2008) whereby, in each step, the load patterns are updated with respect to progressive changes in the structural properties. These methods, conceptually have a strong background compared to the conventional pushover and considers the effects of the higher modes, interaction between modes, progressive changes in structural dynamic properties, stiffness degradation and the frequency content of a design or particular response spectra. However, the main problem in these adaptive methods is that the peak response of the structure (target displacement) is estimated inevitably through a single equivalent pushover curve of the equivalent SDOF system. It seems improbable that the peak response quantities associated with the multi-mode effects can be correctly predicted with a conversion technique based on a single-mode response (Aydinoglu 2003).

Aydinoglu (2003) has proposed an advanced displacement-based adaptive method, which use inelastic spectral displacement associated with the instantaneous configuration of the system in every step to define the profile of the incremental displacement for each mode. Then they are combined with SRSS rule and considered as an applied load pattern. The load pattern is scaled based on the minimum value, which cause to a yielding hinge in any of potential hinge locations. Therefore the consecutive hinge take palace at the end of each step and within every step the structural behavior is linear. The procedure is continued where any of the modal displacement exceeds the estimated inelastic spectral displacement. In the last step the scale factor of the load pattern is selected unit. This method theoretically is rigorous and in derivation of the modal ADSR curve the inelastic softening effects of one mode are considered in the stiffness of other modes. However the target displacement cannot to be defined for each mode independently and upon any of the modes reach peak displacement, the procedure is terminate and assume that the all other modes reach their peak displacement simultaneous with this mode.

Recently an adaptive modal combination (AMC) procedure was proposed by Kalkan and Kunnath(2006) which try to consider the variation of modal shapes during the MPA procedure and incorporate the adaptive method in MPA procedure. Since the procedure is conducted independently for each mode, the main drawback of the MPA procedure has remained and the softening effects of yielding in one mode are not considered in others modes. Therefore the stiffness matrix obtained in each step consequently computed modal shapes and load pattern are not based on the actual state of the structure. Also the resulting capacity curves do not depend to spectra acceleration (load patch) which is not consistent with structural behavior in inelastic phase. Another aspect of this method is that the loads are applied based on displacement. Application of displacement based loads lead to incur a constant deformation shape to the structure in each step that it may lead to conceal structural characteristics within steps.

3. PROPOSED PROCEDURE

Since the conventional pushover analysis are unable to consider the effect of the higher modes and progressive variation in dynamic attribute of structure in inelastic phase, during the resent years some advanced multi modal and adaptive pushover procedure have been proposed. However they couldn't overcome all problems completely and suffer from some drawback explained in this paper.

In order to eliminate the drawbacks of the mentioned methods and integrate the advantage of the different methods, herein is developed an advanced spectra-based multi modal adaptive (MMA) procedure which, incorporate the adaptive method in multi modal pushover analysis while in consecutive steps the effects of the yielding in one mode are reflected in the stiffness matrix of the other modes whereas the capacity curve and seismic demand are derived individually for each mode and a MDOF system is decoupled to some SDOF systems. The peak response quantities associated with the multi-mode effects predicted with a conversion technique based on multi single-mode response. The total seismic demands are estimated through combining the modal demand due to some interested number of modes.

During the procedure the applied load pattern for each mode in consecutive steps are adapted based on the instantaneous dynamic attribute due to all considered modes. Then the values of the load patterns are scaled based on the corresponding spectra acceleration. Therefore the resulting capacity curves depend to spectra acceleration (load patch) which is according to the structural behavior facts in inelastic phase. In the end of the each step the increased storey drifts, resulting from each mode are combined by SSRS rule and applied as a displacement load to the system. Then perform an eigenvalue analysis to define the instantaneous natural frequencies and modal shapes due to changing in all considered modes.

The proposed procedure is summarized in a sequence of basic stage as follow:

1. Create a structural model incorporated nonlinear material characteristics.

2. Perform an eigenvalue analysis to compute the instantaneous natural frequencies, ωj and mode shapes, Øj.

3. For a selected number of first modes to be considered, compute the storey forces at the each level by the Eqn. 3.1.

$$F_{ij} = \Gamma_j \varnothing_{ij} m_i S_a(j) \tag{3.1}$$

Where, i and j indicate the storey level and mode number respectively

Γ_j : modal participation factor for j th mode
Øij : the i th component of the j th modal eigenvector (modal shape)
mi : the mass of the i th storey
Sa(j) : Spectral acceleration corresponding to j th mode

4. Calculate modal base shears (Vj) and combine them using SRSS to compute the building base shear (V).

$$V_j = \sum_{i=1}^{N} F_{ij} \qquad V = \sqrt{\sum_{j=1}^{n} V_j^2} \tag{3.2}$$

Where, N : number of storey
n : number of selected mode

5. The storey forces computed in stage 2 are uniformly scaled using the scaling factor Sn indicated below:

$$\overline{V_j} = S_n V_j \qquad S_n = \frac{\Delta V_b}{V} \tag{3.3}$$

6. Apply the scaled forces (stage 5) for each mode independently to a structural model which their stiffness matrix is consistence with the instantaneous dynamic attribute in inelastic phase due to all considered modes (In the first step it is same as the elastic structural model and for the next steps it is defined in the stage 7 of the previous step) and compute the increment of the displacement, element force, storey drift, etc. then add them directly to the corresponding values of the stage 6 in previous steps (cycles) to compute the instantaneous total values individually for each mode.

7. Compute the total increased story drifts due to all modes in the current step by an SRSS combination of the quantities resulting from each mode. Then apply them to the structural model and return to step 2.

8. Repeat the process until the supposed maximum base shear (a extreme value) is reached

9. Using the result of the stage 6 in consecutive steps to develop a capacity curve (i.e. spectral acceleration, Sa versus spectral displacement, Sd) for each mode.

10. Idealize the Sa- Sd as a bilinear backbone curve for equivalent SDOF systems resulting from each mode with unit mass.

11. Perform NTHA to estimate the maximum displacement of the equivalent SDOF systems.

12. Point the maximum displacement in the Sa- Sd curve and determine the corresponding step, np associated with each mode.

13. determine the interested demands (e.g. drift story, displacement, element force, etc.) associated with the npth step in each mode and combine them by SRSS rule to calculate the total demands

4. CONCLUSION

In order to integrate the advantage of the different advanced pushover methods, herein is developed an advanced spectra-based multi modal adaptive (MMA) procedure which, incorporate the adaptive method in multi modal pushover analysis while in consecutive steps the effects of the yielding in one mode are reflected in the stiffness matrix of the other modes whereas the capacity curve and seismic demand are derived individually for each mode and a MDOF system is decoupled to some SDOF systems. The resulting capacity curves depend to spectra acceleration (load patch) which is according to the structural behavior facts in inelastic phase. It is expected that the proposed method predict the seismic response accurately in the inelastic structures.

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