Adaptive Pushover Procedure for Seismic assessment of Shear Wall Structures

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Abstract :

This paper proposes a new adaptive pushover method for the seismic assessment of shear wall structures. The load pattern is defined on the base of the overturning moment that governs the plasticity in the shear wall. After a brief review of the main adaptive pushover procedures, the proposed method is presented as well as its numerical implementation. The predictions of the OMAP method are compared to results derived by other recent adaptive pushover methods and rigorous non linear time history analysis. The results show the efficiency of the proposed OMAP procedure.

Keywords: Adaptive pushover, Overturning moment-based, Shear wall, Plastic hinges

1 Introduction

In recent years, the utilization of the nonlinear static procedure for estimating the response of the inelastic structures has been an efficient tool to assess the seismic demand of structures. It constitutes a reliable alternative of nonlinear time-history analysis in the prediction of the nonlinear seismic response of structures. For tall buildings, the effect of high modes is not negligible, that's why ignoring their effect is one of the main limitations of such approaches. Furthermore, the modes of vibration of the structure can significantly change during strong seismic motion. Several techniques are proposed to integrate the effect of higher modes depending on adaptive pushover procedures that incorporate the progressive variation in dynamic properties associated to structural damages (Gupta and Kunnath 2000 Kalkan and Kunnath 2006), where the applied load is updated at each increment depending on the current dynamic characteristics of the structure, then a static analysis is carried out for each mode independently and the calculated effects are combined with SRSS. But in the inelastic domain, the structural system could not be decomposed into several independent systems, as consequence the application of the modal combination rule in the inelastic domain is no longer valid. In an attempt to avoid the previous inconvenience, single-run adaptive pushover procedures have been proposed by a number of researchers. One of the modal components is chosen as a base for the adaptive pushover procedure.

After a brief description of the principle of single run adaptive pushover procedures, an innovative new single-run adaptive pushover method based on the modal overturning moment storey is developed in this paper. The first part of the paper concerns the background and the implementation of the proposed method. In the second part, the proposed method is applied to a 20 storeys shear wall structure. It will focus on the location of plastic hinges and the seismic induced internal forces. The results of this procedure and other single-run adaptive pushover procedures available in the literature are compared to those obtained by the nonlinear time-history analysis. They show the superiority of the proposed approach and its efficiency in predicting the failure mechanism for shear wall structures.

2 Single-run adaptive pushover procedures

Antoniou and Pinho (2004a) explored the accuracy of force-based adaptive pushover analysis in predicting the horizontal capacity of reinforced concrete buildings. They proposed a force-based adaptive pushover (FAP) which is an extended version of the fully adaptive pushover algorithm proposed by Elnashai (2001). The lateral load distribution is not kept constant but is continuously updated during the process, according to modal shapes and participation factors derived by eigenvalue analysis carried out at each analysis step. The modal floor forces for the interested modes are evaluated at each step according to the instantaneous stiffness matrix and the corresponding elastic spectral accelerations. Then the lateral load pattern is determined by combining the storey forces of each vibration mode. The loads from all modes have been combined by using the SRSS rule. It was concluded that, despite its apparent conceptual superiority, current force-based adaptive pushover shows a relatively minor advantage over its traditional non-adaptive counterpart, mainly for the estimation of deformation patterns of buildings, which are poorly predicted by both types of analysis. Another variant of the method proposed by Antoniou and Pinho (2004b) is the displacement-based adaptive pushover procedure (DAP), whereby a set of laterally applied displacements, rather than forces, is monotonically applied to the structure. In their paper, the authors re-proposed the interstorey drift as a base instead of the displacement and it has been adopted as the standard DAP variant. The DAP procedure proved to provide improved response predictions, throughout the entire deformation range, in comparison to those obtained by force-based methods.

In order to adjust the drawbacks of the FAP procedure, Shakeri et al (2010) proposed a storey shear-based adaptive pushover method (SSAP), where the load pattern is derived from the modal storey shear profile. The SSAP method takes into account the changes in the sign of the storey components along the structure height for higher modes. All the previous methods were mainly applied to estimate the seismic performance of frame structures; that's why it is interesting to investigate their efficiency in the case of shear wall structures.

3 Description of the Overturning Moment-Based Adaptive Pushover Procedure (OMAP)

In nonlinear static pushover analysis the most important issues are: the shape of the external applied load and the target displacement. The scope of the present paper is concerned with the first purpose (load pattern).

The plasticity in shear walls is directly related to the bending moment, that's why in the OMAP method the shape of the applied load is defined on the base of the modal overturning moment. This latter is constantly updated depending on the instantaneous dynamic characteristics of the structure by running an eigenvalue analysis at each load increment, which allows taking into account the structural stiffness state of the building at each step.

The OMAP algorithm is composed of the following basic steps summarized below:

1. Specifying the desirable number of iteration (N) and the corresponding target displacements.
2. Defining the elastic response spectrum with the corresponding damping ratio.
3. Choosing the modal damping ratio of the structure ξ_j , ($1 \le j \le m$) where j is the mode number and m is the desirable number of modes.
4. Performing an eigenvalue analysis of the structure to compute periods (T_j), mode shapes (Φ_{ij}) and modal participation factors (Γ_j) for the (m) modes, where i is the storey number.
5. Computing the spectral accelerations (Saj); if the damping ratio of the jth mode is different from that of the used response spectrum, this latter is adjusted using the following formula (Newmark and Hall, 1982):

$$A_2 = A_1 \frac{(2.31-0.41*\ln D_2)}{(2.31-0.41*\ln D_1)} \quad (1)$$

   where:

   A_1 = acceleration corresponding to damping ratio D_1;

   A_2 = acceleration corresponding to damping ratio D_2;

   $0 < D_1 < 100$ (percentage);

   $0 < D_2 < 100$ (percentage); and

   ln = natural logarithm (base e).

6. Computing the storey force, the storey shear and the overturning moment at each storey level for the (m) modes as follows:

$$F_{ij} = \Gamma_j \Phi_{ij} m_i Sa_j \quad (2)$$

$$SS_{ij} = \sum_{k=i}^{n} F_{kj} \quad (3)$$

$$OM_{ij} = \sum_{k=i}^{n} SS_{kj} * h_k \quad (4)$$

where:

F_{ij} is the lateral storey force at i^{th} storey for j^{th} mode

SS_{ij} is the modal storey shear at i^{th} storey for j^{th} mode

OM_{ij} is the modal overturning moment at i^{th} storey for j^{th} mode

h_i is the height of the i^{th} storey

n is the number of stories.

7. Calculating the combined storey forces to be used in performing the pushover analysis as follows:
   a- Determine the combined overturning moment at each storey associated to all considered modes by quadratic combination rule:

$$OM_i = \sqrt{\sum_{j=1}^{m} OM_{ij}^{2}} \quad (5)$$

   b- Determine the floor force which induces the total overturning moment (eq 5)

$$F_i = \frac{OM_i - OM_{i+1}}{h_i} - \frac{OM_{i+1} - OM_{i+2}}{h_{i+1}} \qquad ; i = 1,2,\dots,(n-1) \quad (6)$$

$$F_n = \frac{OM_n}{h_n} \qquad ; i = n$$

8. Performing the pushover analysis using the shape of the storey forces computed in the previous step together with the target displacement specified in the first step.
9. Returning to step 4 and continuing the process N time.

4 Illustrative example

4.1 Case study

The studied example consists of a shear wall structure designed for a 20 storeys building. The length of the wall is 6 m and the thickness is variable with the height. Table 1 summarizes the shear wall properties, in particular note a capacity ratio taken as a result of a vertical load of 420 kN for each storey. The yield strength of the steel is fy= 345 MPa and the concrete compressive strength is f'c = 28 MPa. The shear reinforcement of wall is 5φ8/m for each face, which is enough to prevent a shear collapse considered undesirable for the design intent. The Imperial Valley (1940), NS is selected in the present study which have a frequency content allowing the higher modes to be excited. The ground motions are scaled in order to obtain an advanced plasticity state in the structure.

Table 1. Shear wall properties

Storey ID	Thickness (cm)	Longitudinal Reinforcement	Capacity Ratio* (Vertical Load)
1→5	28	2φ18/20cm	0.37
6→9	25	2φ14/20cm	0.33
10→11	20	2φ12/20cm	0.35
12→15	18	2φ12/20cm	0.35
16→18	15	2φ10/20cm	0.26
19→20	10	2φ10/20cm	0.33

* The capacity ratio concerns the first storey of each group

4.2 Modeling

The wall is modeled as beam elements. The nonlinear behavior is simulated via discrete hinges defined in the wall at the ends of each storey. The plasticity criterion is based on the interaction of axial force and bending moment. The hinge properties and the modeling parameters are specified according to FEMA-356. A damping ratio of 5% is considered for the first and third mode of vibration, in order to define the Rayleigh damping matrix. The ground motions are incrementally scaled until a full plastic hinge in the structure occurs (SF=1.95).

4.3 Results and Discussion

The pushover analysis is performed using six first modes. Table 3 shows the natural period T, the damping ratio ξ and the spectral acceleration Sa of each mode. Note that zero values of modal participation factors correspond to vertical modes which don't play a role in the computation of the lateral load vector. The proposed "OMAP" procedure is compared with the conventional pushover approach "Mode1", and the above-mentioned FAP, DAP and SSAP procedures.

Table 3. Modal properties.

Mode	T (sec)	ξ%	Sa (g) Imperial Valley
1	2.98	5	0.10
2	0.54	2.6	0.87
3	0.20	5	0.64
4	0.17	5.9	0.70
5	0.11	8.8	0.51
6	0.07	13.5	0.44

a- Plastic Hinge locations:

The locations of plastic hinges are depicted in Figure 1. It can be noted that all methods succeed in predicting the failure mechanism (Full plastic hinges at the base). On the other hand, only the "OMAP" procedure was able to identify most of the plastic hinges resulting from higher modes.

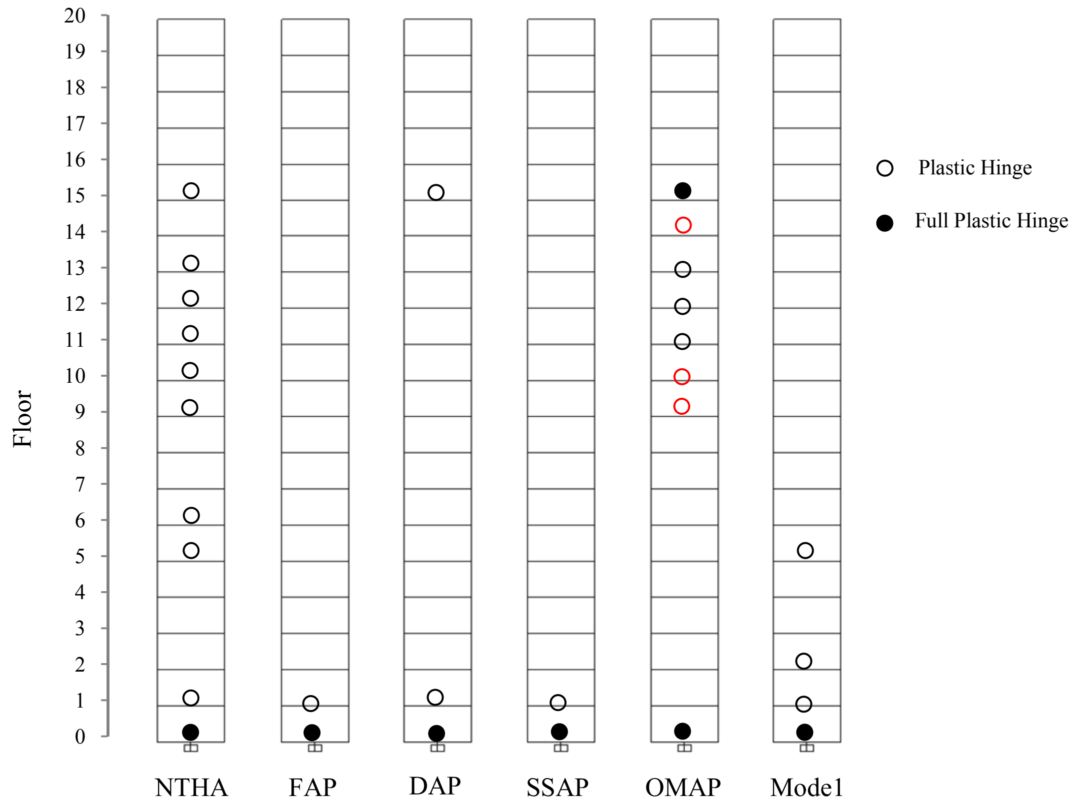

Figure 1. Plastic hinge locations

b- Internal forces:

Flexure hinge properties involve axial force-bending moment interaction as failure envelope. In the present case of shear wall structure, the axial forces remain constant that's why the plastic hinge location is mainly governed by the bending moment. Figure 2 shows the bending moment diagrams obtained by different methods compared to that of NTHA. The efficiency of the proposed method (OMAP) in estimating the flexural moment interprets it's superiority in predicting the plastic hinges.

To investigate the effect of the progressive variation in dynamic and modal properties, linear time history analysis (LTHA) has been compared with NTHA where the maximum moment at the base is scaled to equal to that obtained by the NTHA (see figure 3). On the other hand, the comparison between the results obtained by OMAP and non-adaptive form of OMAP emphasizes the importance of integrating the adaptive feature to the proposed method in order to incorporate the variation in modal properties (see figure 3).

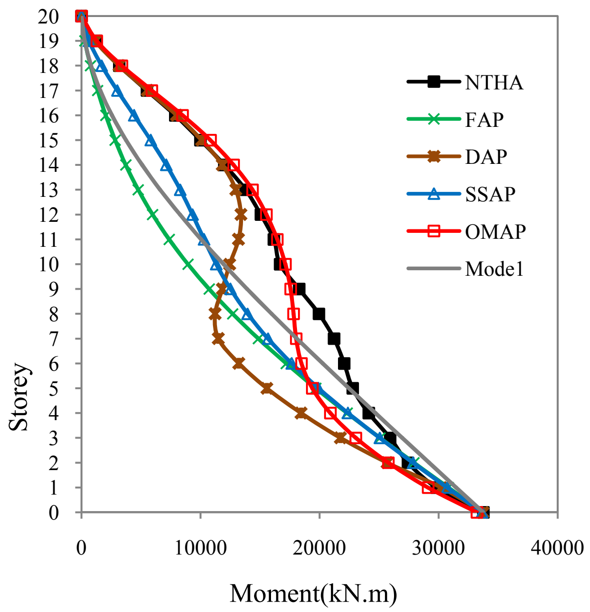

Figure 2. comparative study

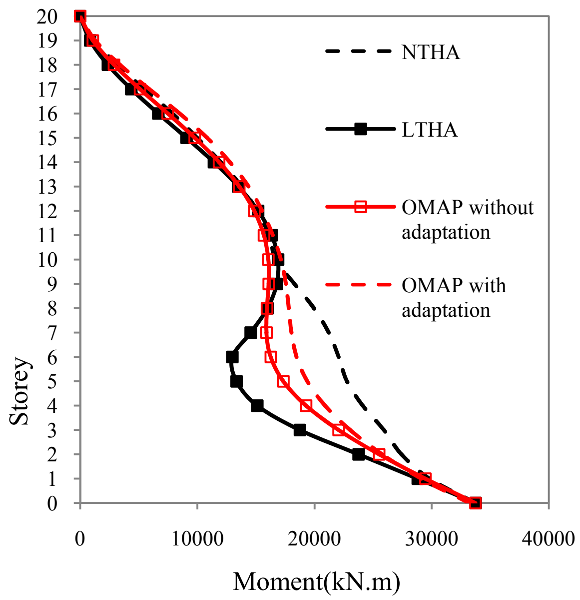

Figure 3. Adaptation effect

5 Conclusion

A new single-run adaptive pushover method "OMAP" is proposed to estimate the seismic response of shear wall structure. The load pattern is derived on the base of the overturning moment as recognition of the evidence that the plasticity in the shear wall is mainly governed by this parameter. The OMAP take into account the progressive changes in the dynamic properties of the structure.

In order to illustrate its potential advantages, the results of the OMAP procedure have been compared to force-based and displacement-based procedures in addition to rigorous non linear time history analysis. The effect of both the base and the adaptation in the single-run adaptive pushover analysis are investigated.

The results indicate that this method could predict the results of the nonlinear time history analysis appropriately. The OMAP method provides an additional advantage in predicting the plastic hinges in shear wall structures relative to higher modes. It is a direct result of a better assessment of the moment in the shear wall using OMAP. The comparison between the non-adaptive form and the adaptive form of the proposed method emphasizes the importance of the adaptive feature to incorporate the progressive variation in dynamic and modal properties.

Future research should focus on the target displacement which is another important aspect of pushover analysis. Additional studies are currently underway on this topic. Preliminary results are very promising.

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