Seismic Evaluation of Buildings using Adaptive Force-Based Multimode Pushover Analysis

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Abstract. The conventional pushover method has 2 major drawbacks, it cannot account for the higher mode effect and do not consider the change in lateral load pattern when the structure reaches its inelastic phase. To overcome those limitations, in this research will present the Adaptive Force-Based Multimode Pushover Analysis (AFMP) method. In this method the higher mode effect, and the change in lateral load pattern have already been considered. This research will compare the result of evaluation using triangular and uniform load pattern with the AFMP load pattern using 1, 2, and 3 modal pairs towards its effects on non linear seismic behaviour of a building with the first mode being not dominant. The analysis resulted that using the AFMP method yields to a higher seismic response on the upper floors, caused by the higher being considered in the analysis. The triangular load pattern, resulted in smaller seismic response on all stories than the AFMP method, while the uniform load pattern tends to overestimate the response on the lower floors. Based on the performance criteria of FEMA 356, the conventional pushover resulted in Life safety performance level, while the AFMP also resulted in Life safety performance level.

1. Introduction
Pushover analysis procedure can be viewed as a method that account for redistribution of member forces of a structure subjected to inertial force that no longer can be resisted by the elastic behavior of the building. Pushover analysis started to become popular as a method to evaluate buildings since 1996-1997, since the ATC-40, and FEMA 273& FEMA 274 was published. Pushover analysis as its name stated is a proses of pushing a structure horizontally, with a particular load pattern, gradually, until the structure reached its limit state [1].

The pushover analysis, has two major drawbacks, it cannot account for the higher mode effect so that when used for building with the first mode being not dominant, it yields to an inaccurate result [2][3] and do not consider the change in lateral load pattern when the structure reaches its inelastic phase [4].

To overcome these limitation Amini and Poursha [5], proposed the adaptive force based multimode pushover analysis (AFMP) which will be presented in this paper. In this method the higher modes effect and the change of modal properties when the structure reached its inelastic phase, so that the change in the lateral load pattern can be accouted.

1.1. Pushover analysis
Pushover analysis as its name stated is a proses of pushing a structure horizontally, with a particular load pattern, gradually, until the structure reached its limit state [1]. The purpose of the pushover analysis
is to evaluate the performance of a structure by estimating the strength demand and deformation demand caused by a design earthquake using inelastic analysis, and comparing these demands with the available capacity [2].

1.2. Displacement coefficient method [6]

In this method the linear elastic response of an equivalent single degree of freedom system is modified by the factor C0, until C3 to obtain maximum displacement of the structure (the target displacement).

The target displacement is calculated by the equation below:

\[ \delta_t = C_0 C_1 C_2 C_3 S_a T_e \frac{T_i^2}{4\pi^2} g \]  

Where, \( C_0 \) = shape factor, to modify the spectral displacement of the equivalent SDOF into the roof displacement; \( C_1 \) = modification factor, to correlate the inelastic maximum displacement with the linear elastic response; \( C_2 \) = coefficient to account for the effect of pinching from the load deformation relation caused by degradation of stiffness and strength; \( C_3 \) = coefficient to account for lateral deflection amplification by the P-delta effect; \( T_e \) = effective period of building, \( T_i \sqrt{\frac{K_i}{K_e}} \), \( S_a \) = spectral acceleration at the effective period, \( g \) = gravitational acceleration.

1.3. Adaptive force based multimode pushover analysis

In the AFMP method, the change of modal properties when structure reached the inelastic region, and the higher modes effect simultaneously included in the analysis. In this procedure, the modal load vector of the n-th mode, at each steps is calculated using the equation below:

\[ f_n = \alpha_n m \Phi_n S_a(T_n, \zeta_n) \]  

Where, \( f_n \) = load vector; \( \Phi_n \) = mode shape of the n-th mode; \( S_a \) = pseudo-acceleration as a function of building period, \( T_n \), dan and damping ratio \( \zeta_n \), from the n-th mode caused by earthquake ground motion.

The thing to be considered is that the value from equation (2), must be updated at each steps of the analysis using the appropriate modal property of the structure. The sum of the effective modal mass participating ratio for every mode equal to unity, thus the effective modal mass participating ratio give a more accurate lateral load pattern than the modal participation factor [7]. To overcome the short of the CQC[8] rules and reflected the sign reversal of the story shear at the higher modes, Amini and Poursha [5] suggested that the lateral load can be calculated by adding the modal story forces algebraically using following equation:

\[ F_k = \sum_{i=1}^{k} f_i = \sum_{i=1}^{k} \beta_i m \Phi_i S_a(T_i, \zeta_i) \]  

Where, \( F_k \) = lateral load vector; \( k \) = the sum of vibration mode included in the analysis; and the factor \( \beta_i \) calculated using the following equation:

\[ \beta_i = \alpha_i \quad i \leq k - 1 \]  

\[ \beta_i = 1 - \sum_{i=1}^{k-1} \alpha_i \quad i = k \]  

**Figure 1** The lateral force of the AFMP method using : (a) 1 mode; (b) 2 modes; dan (c) and 3 modes [5]

In the AFMP procedure, at each steps of the analysis, the lateral load distribution should be updated using the immediate dynamic properties of the structure. To update the lateral load, there are 2 options:
using total updating, and incremental updating method. At the total updating algorithm the load pattern at each step is substituted by the load pattern calculated using equation (3). Even if the total updating the proper method to account for the change in modal properties of structure at the inelastic region, several numerical instability has been reported by past investigation by Antoniou and Pinhou [9], [10]. The numerical instability caused by sudden change in story shear force when the structure experienced extensive inelastic deformation. Therefore, the total updating algorithm is exchanged with the more stable incremental updating algorithm, where the lateral force at a step is defined by the load pattern from previous step using a load factor.

\[ P_t = P_{t-1} + \Delta P_t \]  \hspace{1cm} (6)

Where, \( P_{t-1} \) = load pattern from previous step, \( P_t \) = load pattern from current step.

The increas in load vector, \( \Delta P_t \), calculated by multiplying the load vector from equation (3) with a load factor [10]

\[ \Delta P_t = \mu F_t \]  \hspace{1cm} (7)

Where, \( F_t \) = load vector from equation (3), \( \mu = \) load factor.

Amini and Poursha [5] sugested the load factor of 0.1, because the use of the factor \( \mu \) that is too small, will cause the participation of the load vector \( F_t \), that is calculated using equation (3) too small compared the the load pattern from the previous step, \( P_{t-1} \).

2. Research methodology
The building that will be analyzed was a building with the height of 23 floors which functions as educational facility, office, and a hall. The analysis model generated using 3D finite element-based program, with the structural system of beam, column, and shear wall. The calculation, of the design earthquake force was done using the design spectra of SNI 1726:2012 [11] “Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Non Gedung”. The analysis using the AFMP method, was done using 1, 2, and 3 modal pairs, and the results were compared with those calculated using the conventional pushover method.

![Figure 2 3D view of the building model](image)

3. Results and discussion

3.1. Target displacement
The target displacement was calculated using the coefficient of displacement method [6]. In calculating the target displacement, the conventional pushover was done using the FEMA load pattern, and based on the generated capacity curve the target displacement was obtain for each loading directions
Table 1 Target displacement

| Model | X direction (Triangular) | X direction (Uniform) | Y direction (Triangular) | Y direction (Uniform) |
|-------|-------------------------|-----------------------|-------------------------|-----------------------|
| Te (sec) | 1.5904 | 1.5878 | 3.0263 | 3.0261 |
| Sa (g) | 0.3508 | 0.3513 | 0.1843 | 0.1843 |
| C0 | 1.3 | 1.2 | 1.3 | 1.2 |
| C1 | 1 | 1 | 1 | 1 |
| C2 | 1 | 1 | 1 | 1 |
| C3 | 1 | 1 | 1 | 1 |
| δt (m) | 0.2866 | 0.2641 | 0.5454 | 0.5034 |

3.2. Adaptive force-based multimode pushover analysis
When analyzing the lateral load pattern, first we should do a modal analysis to get the natural period and mode shape of the structure. The modal analysis was done using an eigen value analysis. The natural period and the effective modal participating mass ratio presented at the table below.

Table 2 Natural period and the effective modal participating mass ratio of the elastic condition

| Mode | Period (sec) | UX | UY | RZ |
|------|-------------|----|----|----|
| 1    | 2.99        | 0.001 | 0.6084 | 0.0001 |
| 2    | 2.238       | 0.1181 | 0.0001 | 0.4448 |
| 3    | 1.579       | 0.6382 | 0.0015 | 0.1229 |
| 4    | 0.851       | 0.0004 | 0.1509 | 0.0005 |
| 5    | 0.794       | 0.0249 | 0.0001 | 0.1382 |
| 6    | 0.612       | 0.044 | 0.0003 | 0.0245 |
| 7    | 0.465       | 0.0003 | 0.0006 | 0.103 |
| 8    | 0.419       | 0.0001 | 0.0656 | 0.0032 |
| 9    | 0.365       | 0.0059 | 8.13E-06 | 0 |

After that, the load pattern at each step was calculated using equation (3), the distribution of the story acceleration at each steps was presented at the figure below.
Figure 3 Distribution of story lateral acceleration of the AFMP method for the X direction using 1 modal pair (a), 2 modal pairs (b) and 3 modal pairs, and the Y direction using 1 modal pair, 2 modal pairs, and 3 modal pairs.

3.3. Seismic response
The adaptive procedure was done until the structure reach the predefined target displacement, and then was checked for the seismic response. The seismic result discussed in this paper are inter-story drift and plastic hinge rotation.

Figure 4 inter-story drift in X direction (a) and Y direction (b)

Figure 5 Plastic hinge rotation as a result of pushover in X direction (a) and Y direction (b)

3.4. Performance Level
The performance level obtained by comparing the maximum seismic response with the acceptance criteria of FEMA 356[7]

Table 3 Performance level based on the rotation of pastic hinges

| Load Pattern     | rotation of pastic hinges (Radian) | Performance level          |
|------------------|------------------------------------|----------------------------|
| X direction      |                                     |                            |
| Triangular Load  | 0.0132                              | Life Safety                |
| Uniform Load     | 0.0175                              | Life Safety                |
| AFMP             | 0.0174                              | Life Safety                |
| Y direction      |                                     |                            |
| Triangular Load  | 0.0061                              | Immediate Occupancy        |
| Uniform Load     | 0.0187                              | Life Safety                |
| AFMP             | 0.018                               | Life Safety                |
Table 4 Performance level based on inter-story drift

| Load Pattern | Maximum Drift Ratio | Performance level |
|--------------|---------------------|-------------------|
| X direction  |                     |                   |
| Triangular Load | 0.6527%              | Immadiate Occupancy |
| Uniform Load | 0.8162 %             | Immadiate Occupancy |
| AFMP         | 0.719%               | Immadiate Occupancy |
| Y direction  |                     |                   |
| Triangular Load | 0.826 %              | Immadiate Occupancy |
| Uniform Load | 0.834 %              | Immadiate Occupancy |
| AFMP         | 1.393 %              | Life Safety       |

4. Conclusion
Based on the analysis done we can conclude that using the adaptive load pattern showed that when the structure reached its inelastic region, there will be a change in the base shear value of the building. We can see that the base shear value lessens at each analysis steps, along with the reduction of its stiffness that caused the period of the building increased. When the AFMP procedure done using 2 and 3 modal pairs, at each steps of the analysis the negative acceleration due to sign inversion of the higher modes increases, this shows that the participation of the higher modes increase as the structure reached its inelastic region.

The conventional pushover tends to underestimate the seismic responds at the upper stories. This shows that the seismic response at the upper stories is determined by higher modes effect. The triangular load pattern tends to underestimate seismic response at all stories, while the uniform load pattern tends to overestimate seismic response at lower stories. Based on the FEMA 356 criteria, the AFMP and the conventional pushover yields in life safety performance level. The life safety performance level depicted with intermediate damage when the building subjected to strong earthquake, but the force resisting elements still have its residual strength and stiffness, the building expected not to collapse when strong earthquake occurs.

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