Comparative study nonlinear static pushover analysis and displacement based adaptive pushover analysis method

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Abstract: A major challenge in performance-based earthquake engineering is to develop simple and practical methods for estimating the capacity level and seismic demand on structures by taking into account their inelastic behaviour instead of complicated nonlinear time history analysis. However, in nonlinear static procedure, both predetermined target displacement and force distribution pattern are based on a false assumption that the structural behaviour and its responses are dominated by the fundamental vibration modes. Displacement-based adaptive pushover analysis (DAP) is one of the performance assessment tools for improving the accuracy of the obtained results of the nonlinear static analysis in estimating the seismic demands of structures. The paper attempts to use DAP method to evaluate the performance of 6, 9, 12 and 15 storey RC moment resisting frame, analysed for seismic Zone V and designed as per provisions of IS codes. It is observed from the study that DAP analysis shows better results compared to static pushover analysis.

Keywords: moment resisting frame; nonlinear static pushover analysis; DAP; displacement based adaptive pushover analysis; IDA; incremental dynamic analysis.


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1 Introduction

The elastic analysis gives a good indication of the elastic capacity of the overall structure and indicates where first yielding occurs, it cannot predict failure mechanisms and account for redistribution of forces during progressive yielding. The elastic analysis is insufficient because they cannot predict the force and deformation distributions after the initiation of damage in the building. In performance-based design, the response of structure is considered beyond the elastic limit. Inelastic analysis procedures help to understand that how the building really works by identifying modes of failure and the potential of progressive collapse. The static non-linear analysis is one of the analysis techniques used for performance-based design.

In the nonlinear static procedure, the structural model is subjected to an incremental lateral load whose distribution represents the inertia forces expected during ground shaking. The lateral load is applied until the imposed displacements reach the so-called ‘target displacement’ which represents the displacement demand that the earthquake ground motions would impose on the structure. Once loaded to the target displacement, the demand parameters for the structural components are compared with the respective acceptance criteria for the desired performance state. System-level demand parameters, such as story drifts and base shears, may also be checked.

The nonlinear static procedure is applicable to low-rise regular buildings, where the response is dominated by the fundamental sway mode of vibration. It is less suitable for taller, slender, or irregular buildings, where multiple vibration modes affect the behaviour.

Alternative pushover procedures (Rovithakis et al., 2002) have been proposed based on adaptive load patterns after recognising the fact that conventional pushover methods suffer from some limitations due to implementation of fixed load distributions, that are not consistent with the progressive structural yielding of the elements, and neglecting effects of higher and torsional modes. In adaptive pushover procedure. The story forces are obtained at each modal pushover step applying the interested mode shapes according to the instantaneous stiffness matrix and corresponding elastic spectral Pseudo accelerations. Then lateral force distribution is computed by combing the storey forces with a modal combination statistical rule and applied through a single-run pushover analysis.

Displacement-based Adaptive Pushover (DAP) technique has been proposed by Antoniou and Pinho (2004a, 2004b), in which a set of lateral displacements (rather than forces) is monotonically applied to the structure. The displacement pattern is updated at each step of the analysis, based on the current dynamic characteristics of the structure.
2 Displacement-based adaptive pushover analysis method

Antoniou and Pinho have proposed a displacement-based adaptive pushover analysis (DAP) in 2004 to take into account the updated loading vector at each analysis step according to current dynamic characteristics of the building. The aim of adaptive pushover analysis is to evaluate the seismic performance of the structure by predicting seismic demands and capacity of a building and considering its dynamic response characteristics includes the effect of the frequency content and deformation of input motion (Antoniou and Pinho, 2004b).

The lateral load distribution in the adaptive pushover method, continuously updated during the analysis, depending on modal shapes and participation factors obtained by performing eigenvalue analysis at each step of the analysis. DAP is a fully multi-modal method that takes into account the modification of the inertia forces, the structural stiffness softening, and its period elongation due to spectral amplification (Antoniou and Pinho, 2004a).

It has the capability to update and change the horizontal load distributions based on the constantly changing modal properties of the structure and solves the drawback of fixed-load pattern of the pushover analysis, providing a more accurate tool for assessing structural performance and better response estimator than conventional pushover methods, particularly, in structures that the effects of higher modes play a major role in its dynamic structural response.

2.1 Methodology

The analysis stages of the displacement-based adaptive pushover method, described in greater detail are as follows:

- **Step 1**: The gravity loads are applied in a single step.

- **Step 2**: With its current initial stiffness, the structure has been subjected to an eigenvalue analysis and the modal properties are determined.

- **Step 3**: Modal participation factor are calculated.
• **Step 4**: Define initial nominal displacement load vector \((U_0)\) which is uniform distribution shape in height.

\[
U = \lambda \times U_0. \quad (1)
\]

The load vector is automatically increased, by means of a (a) load control or (b) response control.

• **Step 5**: Computation of load factor

The magnitude of the loading vector \(U\) at any given analysis step is obtained by the product of its nominal load vector and the load factor \(\lambda\) at that step.

\[
U = \lambda \times U_0. \quad (1)
\]

The load vector is automatically increased, by means of a (a) load control or (b) response control.

• **Step 6**: Calculation of normalised scaling vector

The normalised modal scaling vector \(\bar{D}\) determines the shape of the load vector

\[
\bar{D}_i = \frac{D_i}{\max D_j}, \quad (2)
\]

where \(D_i = \sum_{i=1}^l \Delta_i\) with \(\Delta_i \geq \left\{ \begin{array}{ll} \text{SRSS}(\Delta_i) \\ \text{CQC}(\Delta_i) \end{array} \right. \)

\[
\Delta_i = S_{d,j} \Gamma_j (\phi_{i,j} - \phi_{i-1,j}),
\]

where

- \(\Delta_i\): interstorey drift
- \(\Gamma_j\): modal participation factor
- \(S_{d,j}\): displacement response spectrum ordinate corresponding to the period of vibration of the \(j\)th mode.
Comparative study nonlinear static pushover analysis

Time history data generated by Kumar (2004) compatible with IS code response spectra is considered for adaptive pushover analysis as shown in Figures 1 and 2.

- Step 7: Using statistical rules method (SRSS or CQC) to combine the lateral load profiles of the modes.

- Step 8: Increase the load factor $\lambda$ to scaled-up story loads. The story forces are obtained by the nominal load at that story, updated load factor and the displacement pattern calculated above (typically, the nominal loads are equivalent at all stories). Incremental scaling can also be employed, whereby only the load increment is updated and added to the load already applied to structure throughout the last increments

$$U_t = U_{t-1} + \Delta \lambda \delta U_o.$$  \hspace{1cm} (3)

- Step 9: Apply the newly obtained loads to the structure and then determine the response of the structure by solving the system of equations at the new equilibrium state.

- Step 10: Update and compute the matrix of the tangent stiffness of the system and return to the first stage of the algorithm, for the next increment of the DAP.

3 Member properties and design data of frames

RC moment resisting frames of 6, 9, 12 and 15 storeys with 3 bays in each direction were considered for this work. The frames were symmetrical with three bays of 6.0 m width, storey heights of 3.2 m and the ground storey height of 4.0 m. It was located in Zone-V and assumed to be constructed on medium soil condition. All RC sections have distributed reinforcing steel around the perimeter and Longitudinal reinforcing ratios varied from 2% to 4% in columns. Response Reduction factor (R) of 5 was used for the design of special RC moment-frames. The loading considered was self-weight of beams, columns and slabs, floor finish and live load on slabs. The frames were analysed using Staad Pro v8i software and designed as per the provisions of IS 456:2000 (2000). The design acceleration and displacement response spectrum were used, which corresponds to
IS 1893 (Part 1):2002 (2002) for medium soil for 5% damping. The percentage of steel and sizes of beams and columns of a 6-storey frame designed are presented in Tables 1 and 2, respectively.

**Figure 1** Acceleration response spectrum (see online version for colours)

**Figure 2** Displacement response spectrum (see online version for colours)
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Table 1  Reinforcement percentage for beams: 6-storey frame

<table>
<thead>
<tr>
<th>Storey</th>
<th>Size (mm)</th>
<th>$P_t$ (%)</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bot.</td>
<td>Top</td>
</tr>
<tr>
<td>1</td>
<td>300 × 650</td>
<td>1.20</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>300 × 650</td>
<td>1.20</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td>3</td>
<td>300 × 650</td>
<td>1.20</td>
<td>1.88</td>
<td>1.88</td>
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<tr>
<td>4</td>
<td>300 × 550</td>
<td>1.02</td>
<td>1.93</td>
<td>1.93</td>
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<tr>
<td>5</td>
<td>300 × 500</td>
<td>0.91</td>
<td>1.75</td>
<td>1.75</td>
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<tr>
<td>6</td>
<td>300 × 350</td>
<td>1.01</td>
<td>1.69</td>
<td>1.69</td>
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</tbody>
</table>

Table 2  Reinforcement percentage for columns: 6-storey frame

<table>
<thead>
<tr>
<th>Storey</th>
<th>Exterior column</th>
<th>$P_t$ (%)</th>
<th>Interior column</th>
<th>$P_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size (mm)</td>
<td></td>
<td>Size (mm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>550 × 550</td>
<td>3.25</td>
<td>650 × 650</td>
<td>3.09</td>
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<tr>
<td>2</td>
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<td>550 × 550</td>
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<td>550 × 450</td>
<td>2.83</td>
</tr>
<tr>
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<td>3.45</td>
<td>450 × 450</td>
<td>2.83</td>
</tr>
<tr>
<td>5</td>
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<td>450 × 450</td>
<td>2.83</td>
</tr>
<tr>
<td>6</td>
<td>400 × 400</td>
<td>3.14</td>
<td>450 × 450</td>
<td>2.83</td>
</tr>
</tbody>
</table>

4  Results and comparison

This section presents the results of nonlinear static pushover analysis and nonlinear static displacement based adaptive pushover analysis using Seismostruct. The results are presented in terms of capacity curve and compared with incremental dynamic analysis (IDA). Performance evaluation of frames is carried out in terms of interstorey drift ratio (IDR) for Nonlinear Static Pushover Analysis and DAP analysis.

4.1  Base shear vs. roof displacement curves (capacity curve)

One of the most important steps in post-processing of nonlinear structural analysis is to obtain the capacity curve (base shear vs. roof displacement). The capacity curve can reveal important features of structural response, includes yield displacement, total strength and initial stiffness estimation of the structure. Thus, it is important to compare the new approaches of pushover analysis to nonlinear dynamic analysis envelopes in terms of the base shear vs. roof displacement curve. The aim of comparing different analyses method is to identify and understand the differences in the results achieved by different approaches, and verify their accuracy compared to dynamic and static analyses. The result is plotted in terms of Capacity Curve for Static Pushover Analysis and DAP
and compared with IDA for 3% of Total Drift. The results of capacity curves obtained by different nonlinear analyses are shown in Figure 3.

**Figure 3** Capacity curves for RC frames (see online version for colours)

![Capacity curves for RC frames](image)

### 4.2 Interstorey drift ratio profile (%)

The performance evaluation is carried in terms of IDR (%) for Static Pushover Analysis and Displacement Based Adaptive Pushover Analysis of 6, 9, 12 and 15 storey frames. For all frames, IDR profile is plotted for 2% of total drift ratio. The plots of IDR profile are shown in Figure 4. The maximum value of IDR (%) for all frames corresponding to total drift ratio of 2% is shown in Table 3.

**Table 3** Maximum interstorey drift ratio

<table>
<thead>
<tr>
<th></th>
<th>Static pushover</th>
<th>DAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.18</td>
<td>2.31</td>
</tr>
<tr>
<td>9</td>
<td>3.65</td>
<td>2.52</td>
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<tr>
<td>12</td>
<td>3.17</td>
<td>3.12</td>
</tr>
<tr>
<td>15</td>
<td>3.40</td>
<td>3.30</td>
</tr>
</tbody>
</table>
5 Conclusion

The 6, 9, 12 and 15 Storey RC moment resisting frames are evaluated using static pushover and DAP analysis and results are compared in terms of the capacity curve and IDR profile. Based on study presented, following conclusion can be drawn:

It is observed from the results that Static Pushover analysis shows less capacity compared to DAP and results of DAP are much closer to the IDA. Further, it is observed that the peak interstorey drift for Nonlinear Static Pushover Analysis is higher compared to DAP for all frames. Hence it can be said that Static Pushover Analysis underestimates the performance of frames. The better performance of Displacement Based Adaptive Pushover Analysis procedure can be attributed to the consideration of higher mode effects, lateral load continuously updated according to the modal shapes and participation factors derived by eigenvalue analysis carried out at the current step and accounts for period elongation, spectral amplification.
References

Bibliography