Seismic performance evaluation of RC frames with uniform infilled walls based on adaptive CMS

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Abstract. In the development of performance-based seismic engineering, the capacity spectrum method (CMS) has been widely used in seismic performance evaluation because of its merits of clarity in concept and simplicity in computation. The lateral force resistance of nonstructural components and the influence of bidirectional loading are usually neglected in current seismic performance evaluation. Three archetype reinforced concrete (RC) frames were designed according to current Chinese standards and three-dimensional finite element models accounting for infilled walls or not at different modeling fidelity levels were created. Influences of infilled walls and bidirectional loading on seismic performance of RC frames are studied by CMS based on adaptive Pushover analysis. Results show that uniform infilled walls significantly improve seismic performance of RC frames. The bearing capacity under bidirectional loading is less than that under unidirectional loading. And bidirectional loading makes influences of infilled walls become somewhat inefficient.

1. Introduction
As one of the most common forms of structure, the RC frame with infilled walls is a complex composite structure with features of frame structure and masonry structure. On the one hand, infilled walls are nonstructural components in most building design codes [1], so influences of infilled walls on structural seismic performance are neglected. It is obviously not enough to understand actual seismic performance of RC frames with infilled walls. On the other hand, research has indicated that out-of-plane response of infilled walls is different from in-plane response, and the in-plane and out-of-plane seismic performance under bidirectional loading are strongly coupled [2-11]. The objective of this paper is to create three-dimensional finite element models accounting for infilled walls or not by modeling method that is verified by experimental results and study influences of infilled walls and bidirectional loading on seismic performance of RC frames by CMS based on adaptive Pushover analysis.

2. Principle of adaptive capacity spectrum method
Basic theory and analysis process of seismic performance evaluation by nonlinear static analysis is given in ATC-40 (Applied Technology Council, 1996). Based on the basic theory and analysis process, in this paper capacity curve of structure is obtained by adaptive Pushover analysis, which is different from conventional Pushover analysis. It can account for influences of higher modes and progressive stiffness degradation on the distribution of seismic lateral forces. The performance point such as target displacement is calculated by iteration of capacity-spectrum and demand-spectrum. Seismic
performance evaluation is conducted by comparison of deformation limits in design codes with deformation extrema in the case of target displacement. Detailed instructions are as follows.

1. Develop an elastic response spectrum for the corresponding site type with a damping ratio of 5%, and convert it to demand spectrum in form of spectral acceleration - spectral displacement that is shown in Figure 1.

![Figure 1. Transformation from elastic response spectrum into demand spectrum](image)

2. Obtain relationship of base shear force ($V_0$) and top displacement ($\Delta$) by adaptive Pushover analysis, and convert it to capacity spectrum in form of spectral acceleration – top displacement that is shown in Figure 2.

![Figure 2. Transformation from adaptive Pushover curve into capacity spectrum](image)

3. Assume initial performance point ($D_{ij}, A_{ij}$). It could be the end point of capacity spectrum, or it could be calculated by equal displacement method.

4. Convert capacity spectrum into bilinear mode curve using equal energy theory. Calculate spectral reduction coefficient, and perform reduction of demand spectrum.

5. If the spectral displacement ($D_{i}$) at the intersection of the capability spectrum and the demand spectrum satisfies convergence criteria $|D_{ij} - D_{i}|/D_{i} \leq 0.05$, $D_{ij}$ is the target point. Otherwise $D_{ij}$ is the start point, and repeat the step (4) and the step (5) until $D_{ij}$ satisfies convergence criteria.

3. **Seismic performance evaluation of RC frames with uniform infilled walls**

3.1 **Design and modeling**

The height of buildings has an important influence on structural seismic performance. Three archetype RC frame structures in high intensity region were designed to current Chinese standards, and the number of stories of structural models is 3, 5 and 10 respectively with same plane layout, and infilled wall is full layout. The 5-story RC frame structure with infilled masonry walls is shown in Figure 3. Design data of structural models is in References 12.

Finite element analysis is performed using OpenSees platform. And the rationality and reliability of modeling method is verified by comparison of results of pseudo static tests with that of shaking table tests. The three-dimensional finite element model without considering infilled walls of the 5-story RC frame structure with uniform infilled walls is shown in Figure 4. The three-dimensional finite element
model accounting for infilled walls of the 5-story RC frame structure with uniform infilled walls is shown in Figure 5.

![Figure 3. 5-story RC frame structure with infilled walls](image)

![Figure 4. 5-story RC frame model without infilled walls](image)

![Figure 5. 5-story RC frame model with infilled walls](image)

### 3.2 Seismic performance evaluation

Seismic performance evaluation under condition of frequent earthquake and rare earthquake is performed using CMS. And the capacity spectrum curve in forms of base shear force and top displacement is calculated by adaptive Pushover analysis. The iterative process that is used to calculate performance points of 10-story RC frame structure with uniform infilled walls is illustrated in Figure 6.

Analysis results of performance points under frequent earthquake and rare earthquake are illustrated in Table 1. It is shown that comparing with unidirectional loading, bearing capacity corresponding to target displacement in both frequent earthquake and rare earthquake declines 5% under bidirectional loading. Inter-story drift corresponding to target displacement in both frequent earthquake and rare earthquake increases about 15% under bidirectional loading, and the inter-story drift increases 20% for 10-story RC frame. Uniform infilled walls significantly increase bearing capacity of RC frames, average growth of 120% for unidirectional loading and that of 60% for bidirectional loading. Uniform infilled walls significantly decrease inter-story drift of RC frames, average reduction of 70% for unidirectional loading and that of 30% for bidirectional loading. In other words bidirectional loading makes influences of infilled walls become a little less efficient. Comparing with bare RC frame models, influences of bidirectional loading on bearing capacity and inter-story drift of RC frame models accounting for infilled walls are more significant.

![Figure 6. Performance point calculation of 10-story RC space frame with infilled masonry walls](image)
Table 1. Seismic performance points using the adaptive capacity spectrum method.

| Loading Mode | Finite element model | Performance point under frequent earthquake | Performance point under rare earthquake |
|--------------|----------------------|---------------------------------------------|----------------------------------------|
|              |                      | Base shear force/kN | Inter-story drift/% | Base shear force/kN | Inter-story drift/% |
| Unidirectional Loading | 3-story RC frame model without infilled walls | 1623.04 | 0.17 | 4967.56 | 1.47 |
|              | 3-story RC frame model with infilled walls | 3952.45 | 0.05 | 9637.29 | 0.66 |
|              | 5-story RC frame model without infilled walls | 1665.25 | 0.16 | 5719.85 | 1.22 |
|              | 5-story RC frame model with infilled walls | 4442.74 | 0.07 | 9667.77 | 0.87 |
|              | 10-story RC frame model without infilled walls | 2517.01 | 0.17 | 8833.70 | 1.55 |
|              | 10-story RC frame model with infilled walls | 4783.77 | 0.08 | 13227.71 | 0.88 |
| Bidirectional Loading | 3-story RC frame model without infilled walls | 1519.93 | 0.18 | 4785.40 | 1.59 |
|              | 3-story RC frame model with infilled walls | 2251.39 | 0.11 | 7541.99 | 0.43 |
|              | 5-story RC frame model without infilled walls | 1552.50 | 0.18 | 5577.01 | 1.38 |
|              | 5-story RC frame model with infilled walls | 2526.16 | 0.15 | 8756.38 | 1.10 |
|              | 10-story RC frame model without infilled walls | 1808.97 | 0.18 | 8530.79 | 1.85 |
|              | 10-story RC frame model with infilled walls | 3948.52 | 0.12 | 11765.32 | 1.51 |

Results of seismic performance evaluation based on maximum inter-story drift are illustrated in Figure 7. It can be concluded that RC frame structures designed according to the current codes can satisfy the seismic fortification targets of “no damage under frequent earthquake” and “no collapse under the rare earthquake”. Except for 3-story RC frame, the rest of all structures are seriously damaged in rare earthquake. Obviously damage of RC frame models accounting for infilled walls is less severe than that of RC frame models without considering infilled walls. Comparing with unidirectional loading, inter-story drift corresponding to target displacement in rare earthquake increases significantly under bidirectional loading.
4. Conclusion

Seismic performance evaluation of RC frames with uniform infilled walls based on adaptive CMS is analyzed. And conclusions are as follow through Pushover analysis of three-dimensional finite element models accounting for infilled walls or not at different modeling fidelity levels:

(1) Uniform infilled walls significantly improve seismic performance of RC frames. Uniform infilled walls significantly increase bearing capacity of RC frames, and significantly decrease inter-story drift of RC frames.

(2) Comparing with unidirectional loading, the bearing capacity will be reduced because of bidirectional loading, and the inter-story drift corresponding to target displacement will be increased under bidirectional loading in both frequent earthquake and rare earthquake.

(3) Comparing with bare RC frame models, influences of bidirectional loading on bearing capacity and inter-story drift of RC frame models accounting for infilled walls are more significant. Bidirectional loading makes influences of infilled walls become somewhat inefficient.

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