Seismic performance factors of RC frames with infilled walls based on APOA and IDA

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Abstract. Seismic performance factors are important parts of performance-based seismic design, and values of seismic performance factors are directly related to structural safety and economy. Six typical RC structures in high intensity region are designed according to the current Chinese Codes, and finite element models are built on OpenSees platform. The objectivity and accuracy of modeling methods are verified by existing experimental results. Values and rules of seismic performance factors are revealed by adaptive pushover analysis (APOA) and incremental dynamic analysis (IDA). Through comparison with values of design codes, values of the system overstrength factor, the ductility reduction factor, the response modification factor and the deflection amplification factor in this paper is reasonable, and this study provides theoretical reference for Chinese Codes. Analytical methods have important effect on seismic performance factors. Comparing with the IDA method, the APOA method underestimates seismic performance factors. Structural height has significant influence on seismic performance factors. Overstrength factor increases with increase of structural height but ductility reduction factor, response modification factor and deflection amplification factor decrease. Infilled walls increase seismic performance factors of RC frame with infilled walls. The effect of infilled walls on seismic performance factors decreases gradually with increase of structural height.

1. Introduction
At present, most codes for design of structures emphasize design of structural members, and for structural integral safety is mostly qualitative and conceptual description. Ductility of various members and different material is considered by adjustment coefficient of capacity in Chinese Code for seismic design of buildings, but seismic performance factors of structures can’t be estimated. Moreover, determination of seismic performance factors is mainly based on experience in most national design specifications. Many researchers studied seismic performance factors of various structures using methods of experimental tests and numerical simulation [1-11], but systematic studies of seismic performance factors of RC frame with infilled walls are rarely reported. The aim of this paper is to present values and rules of seismic performance factors of RC frame with infilled walls by adaptive pushover analysis (APOA) and incremental dynamic analysis (IDA).

2. Basic concept of seismic performance factors
Seismic performance factors include the response modification coefficient (R factor), the system overstrength factor (Rs), and the deflection amplification factor (Cd) in the FEMA-P695 report [12]. The R factor is structural influencing coefficient (C) and C=1/R in TJ11-74, TJ11-78 and CECS 160: 2004.
2.1. Response modification coefficient
At present, strength-based seismic design is used in major seismic codes. In these codes, \( R \) is used to reflect system overstrength, ductility and dissipation by reducing earthquake action of seismic precautionary intensity. So the value of \( R \) directly affects design seismic force, and establishes relation between the bearing capacity and ductility of structures. The response modification coefficient (\( R \) factor) is a ratio of the maximum base shear of elastic structures under earthquake action of seismic precautionary intensity and the design base shear. The \( R \) factor is a product of \( R_s \) and the structural ductility reduction factor (\( R_\mu \)). It is a basic parameter that defines design seismic force in strength-based seismic design and inelastic response spectra in performance-based seismic design. The system overstrength factor (\( R_s \)) is a ratio of actual strength and design strength, and reflects the strength reserve of structures. Its expression is as follow:

\[
R_s = \frac{V_y}{V_d}
\]

Where,
\( V_y \) is the structural equivalent yield strength.
\( V_d \) is the structural design base shear.

The structural ductility reduction factor (\( R_\mu \)) is a ratio of the maximum base shear of elastic structures under earthquake action of seismic precautionary intensity and the structural equivalent yield strength. Its expression is as follow:

\[
R_\mu = \frac{V_e}{V_y}
\]

Where,
\( V_e \) is the maximum base shear of elastic structures under earthquake action of seismic precautionary intensity.
\( V_y \) is the structural equivalent yield strength.

For intact structures, the expression of \( R \) is as follow:

\[
R = \frac{V_y}{V_d} = \frac{V_e}{V_y} \cdot \frac{V_y}{V_d} = R_s R_\mu
\]

2.2. Deflection amplification factor
Deformation checking is a very important part of serviceability limit state analysis, but bearing capacity in elastic phase is more focused on. The deflection amplification factor (\( C_d \)) is used to simplify calculation of structural maximum displacement in elastic-plastic stage under action of moderate earthquake. The maximum structural elastic-plastic displacement under action of rare earthquake can be obtained by enlarging the design deformation of elastic phase using the factor \( C_d \). The expression of \( C_d \) is as follow:

\[
C_d = \frac{\Delta_{max}}{\Delta_d}
\]

Where,
\( \Delta_{max} \) is the maximum structural displacement.
\( \Delta_d \) is the structural design displacement.

3. Analysis of seismic performance factors
3.1. Analysis of seismic performance factors based on APOA
The classical pushover analysis obtains structural capacity curves under fixed load mode, and cannot consider stiffness degradation and period change due to structural plasticity. So adaptive pushover analysis (APOA) is performed based on OpenSees platform and used to obtain structural capacity curves in this paper. The analysis process of seismic performance factors is as follows:

1. Develop structural capacity curve in form of base shear (\( V_b \)) and top displacement (\( \Delta \)) by APOA.
2) Convert $V_b-\Delta$ curve to bilinear elastic-plastic model based on equal energy theory and solve the structural equivalent yield strength ($V_y$), the structural initial stiffness ($k_0$) and the structural yield displacement ($\Delta_y$).

3) Calculate design base shear ($V_d$) by bottom shear method or spectrum response method.

4) Calculate $R_s$ by formula $R_s=V_y/V_d$.

5) Solve top displacement ($A_e$) corresponding to the maximum inter-story drift ratio of 2% and Calculate $R_\mu$ by formula $R_\mu=V_e/V_y=k_0A_e/V_y$.

6) Calculate $R$ by formula $R=R_s\times R_\mu$.

7) Calculate $C_d$ by formula $C_d=\Delta_{max}/\Delta_d$.

3.2. Analysis of seismic performance factors based on IDA

Incremental dynamic analysis (IDA) in which individual ground motions are scaled to increasing intensities can represent structural performance subjected to one ground motion record of different intensity levels. The analysis of seismic performance factors combine IDA and dynamic time history analysis. The process is as follows:

1) Develop structural dynamic capacity curve in form of base shear ($V_b$) and top displacement ($\Delta$) by IDA, and solve base shear ($V_y$), top displacement ($\Delta_{max}$) and spectral acceleration ($S_{a0.002}$) corresponding to the maximum inter-story drift ratio of 2%.

2) Solve base shear ($V_i$) and top displacement ($\Delta_i$) by linear time history analysis of structures subjected to ground motion records corresponding to spectral acceleration of $S_{a0.002}$.

3) Calculate design base shear ($V_d$) by bottom shear method or spectrum response method.

4) Calculate $R_s$, $R_\mu$, $R$ and $C_d$ by formulas $R_s=V_y/V_d$, $R_\mu=V_e/V_y$, $R=R_s\times R_\mu$ and $C_d=\Delta_{max}/\Delta_d$.

4. Seismic performance factors analysis of RC frame with infilled walls

4.1. Design and analysis of structural models

The height of buildings has an important influence on structural seismic performance. According to the current code, representative RC frames and RC frames with infilled wall in high intensity region are designed. 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 with infilled masonry walls is shown in Figure 1. Design data of structural models is in References 13.

Finite element analysis is performed using OpenSees platform. And the rationality and reliability of numerical analysis is verified by comparison with results of pseudo static tests and shaking table tests [13, 14]. The finite element model of the 5-story RC frame with infilled walls is shown in Figure 2.

4.2. Analysis of seismic performance factors

Table 1 provides values of seismic performance factors of structural models based on APOA and IDA.
Table 1. Seismic performance factors based on APOA and IDA.

| Analysis method | Structural models                  | Number of stories | Seismic performance factors |
|-----------------|------------------------------------|-------------------|-----------------------------|
|                 |                                    |                   | $R_s$ | $R_\mu$ | $R$  | $C_d$ |
| APOA            | RC frames                          | 3                 | 1.12  | 5.14    | 5.76 | 4.18  |
|                 |                                    | 5                 | 1.26  | 3.71    | 4.66 | 3.13  |
|                 |                                    | 10                | 1.52  | 2.87    | 4.35 | 2.95  |
|                 | RC frames with infilled walls      | 3                 | 2.06  | 10.67   | 21.97| 19.74 |
|                 |                                    | 5                 | 2.11  | 5.59    | 11.78| 7.89  |
|                 |                                    | 10                | 2.49  | 3.59    | 8.94 | 3.82  |
|                 |                                    | 3                 | 1.54  | 4.38    | 6.75 | 4.15  |
| IDA             | RC frames                          | 3                 | 1.45  | 4.02    | 5.84 | 3.42  |
|                 |                                    | 5                 | 2.64  | 7.17    | 18.92| 6.13  |
|                 |                                    | 10                | 3.44  | 4.63    | 15.91| 5.69  |
|                 | RC frames with infilled walls      | 3                 | 3.21  | 8.07    | 25.90| 9.26  |
|                 |                                    | 5                 | 2.64  | 7.17    | 18.92| 6.13  |

Values of $R_s$, $R_\mu$, $R$ and $C_d$ of RC frames with infilled walls are greater than those of RC frames. The influence of infilled walls on seismic performance factors diminishes with the increasing structural height. Based on both APOA and IDA values of $R_\mu$, $R$ and $C_d$ increases with the structural height. Values of $R_s$ and $R$ based on IDA is greater than that based on APOA. According to principle of minimum value, Values of $R_s$, $R_\mu$, $R$ and $C_d$ of RC frames is 1.12, 2.40, 4.35 and 2.95, and Values of $R_s$, $R_\mu$, $R$ and $C_d$ of RC frames with infilled walls is 2.11, 3.59, 8.94 and 3.82.

4.3. Comparison of seismic performance factors

Recommended values of seismic performance factors are proposed in design codes by physical tests, numerical simulation analysis, seismic damage investigation and engineering experience. Numerical simulation analysis can develop seismic performance factors of innovative structures and provide reference values to seismic performance factors of general structures. Table 2 compares values of seismic performance factors of this paper with that of different design codes. It is shown that analysis methods and results in this paper of seismic performance factors of RC frames with infilled walls are reasonable and reliable.

Table 2. Comparison of seismic performance factors.

| Country   | Design code | $R_s$ | $R$   | $C_d/R$ |
|-----------|-------------|-------|-------|---------|
| America   | NEHRP       | 3.0   | 1.25-8| 0.5-1.0 |
| America   | UBC         | 2.5   | 4-12  | 0.375   |
| Japan     | BSL 1988    | 1.0-1.8| 1.8-4 | —       |
| Europe    | EC8         | ≥2.0 | 1.5-5.85 | 1.0   |
| New Zealand| NZS4203     | 1.0-1.5| 1.88-9| —       |
| Canada    | NRCC200     | 1.3-1.7| 1.95-6.80| 0.6  |
| China     | GB50011-2010| 1.0  | 2.86  | —       |
| China     | CECS160: 2004| —   | 1.82-4| 0.97-1.76|
| This paper| —           | 1.12-2.11| 4.35-8.94| 0.42-0.68|

5. Conclusion

Seismic performance factors of RC frames with infilled walls based on APOA and IDA is analyzed. And conclusions are as follow through comparative analysis:

(1) The range of $R_s$, $R_\mu$, $R$ and $C_d$ of RC frames with and without infilled walls is 1.12-2.11, 2.40-3.59, 4.35-8.94 and 2.95-3.82. It is shown that analysis methods and results in this paper of seismic performance factors of RC frames with and without infilled walls are reasonable and reliable by comparison.
(2) Seismic performance factors analysis is very sensitive to analysis methods. Comparing to IDA method, estimation of seismic performance factors based on APOA is generally conservative. And comparing to RC frames, RC frames with infilled walls is more sensitive to analysis methods.

(3) Structural height has significant influence on seismic performance factors. $R_s$ increases with increase of structural height but $R_\mu$, $R$ and $C_d$ decrease. Values of $R_s$, $R_\mu$, $R$ and $C_d$ of RC frames with infilled walls is greater than that of RC frames. The influence of infilled walls on seismic performance factors diminishes with the increasing structural height.

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