Assessment of Seismic Fragility of RC Fram Based on Different Methods for Selecting Index Threshold

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Abstract. In the current structure damage assessment process, different methods of selecting damage index threshold will significantly affect assessment results. OpenSees finite element software is used to build a 6-story RC frame structure model. Then, the inter-story drift and residual inter-story drift are used as single and double indices to calculate threshold values using the code method and the incremental dynamic analysis method. Evaluation results vary more significantly when the damage is evaluated using a single index. When the threshold is selected based using the code method with a double index, the results are more conservative. The stronger the correlation between the inter-story drift and residual inter-story drift is, the more conservative the results are.

1. Introduction
Seismic fragility is one method of structural seismic reliability assessment. The damage level of a structure under different ground motion intensity can be evaluated according to the varying threshold of the structure under different performance states. If the structural damage index selects a single index and does not completely reflect the seismic performance of the structure, the structural damage index is transformed from a single index to a multiple index [1].

Most structural damage assessment research uses the inter-story drift as the damage index; however, after an earthquake the residual drift has a non-negligible influence on the seismic performance evaluation of the structure [2]. Christopoulos et al. used the double index of maximum displacement and residual displacement of the structure to evaluate the structural damage for different performance states [3, 4]. For the first time, Uma jointly used the inter-story drift and the residual inter-story drift and proposed a structural performance target matrix to seismic design and evaluate of the structure [5].

Previous studies have focused on analyzing structural fragility using various damage indices [6], but there is no comparative analysis of methods for selecting threshold values. Since there are different methods for selecting threshold values under different performance states, structural seismic reliability assessments may have certain variations. In this paper, the inter-story drift and residual inter-story drift are used as indicators for selecting different structural threshold values using the code and IDA methods. The influence of different methods of threshold value selection on the structural fragility analysis is analyzed, and the seismic reliability of the structure is evaluated.

2. Plane structure fragility analysis method

2.1. Single index structure fragility analysis equation
The structural fragility equation can be expressed by Eq. (1) when using a single index:

$$
	ext{fragility} = f(x, \theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{1}{\sigma_x} e^{-\frac{(x-\theta)^2}{2\sigma_x^2}} dx
$$

where $x$ is the damage index, $\theta$ is the threshold, and $\sigma_x$ is the standard deviation of the damage index.
Where $\theta$ is the structural response; $\theta_{LSi}$ is the structural response threshold at the $i$-th performance state.

When the structure is in different performance states, the structural response is a random variable, and when the structural damage limit value is fixed, the structural exceeding probability can be calculated using Eq. (2):

$$ F = \Phi \left( \frac{\ln(\mu_{\theta}) - \ln(\theta_{LSi})}{\sigma_{\ln \theta}} \right) $$

Where $\mu_{\theta}$ is the mean structural response; $\sigma_{\ln \theta}$ is the logarithmic standard deviation of the structural response.

2.2. Double index structure fragility analysis equation

When multidimensional performance indicators are used as structural performance evaluation indicators, the structural fragility equation can be expressed by Eq. (3):

$$ F = P \left\{ \bigg( \bigcup_{i=1}^{n} (R_i \geq [R]_{LSi}) \bigg) \right\} $$

Where, $R_i$ is the structural response value; $[R]_{LSi}$ is the response limit value of the structure under a certain limit state; $I$ is the ground motion intensity.

In this paper, the inter-story drift and the residual inter-story drift are jointly considered as the index of structural seismic performance evaluation. Structural fragility Eq. (4) is expressed as:

$$ F = P \left\{ (\theta \geq \theta_{LSi}) \bigcup (\theta_r \geq \theta_{rLSi}) \right\} $$

Where $\theta_r$ is the residual inter-story drift response of the structure; $\theta_{rLSi}$ is the residual inter-story drift threshold value of the structure at the $i$-th performance level.

When $\theta_{LSi}$ and $\theta_{rLSi}$ are fixed values, $\theta \geq \theta_{LSi}$ and $\theta_r \geq \theta_{rLSi}$ are two independent events.

According to Eq. (2) the exceeding probability can be expressed by Eq. (5):

$$ F = \Phi \left( \frac{\ln(\mu_{\theta}) - \ln(\theta_{LSi})}{\sigma_{\ln \theta}} \right) + \Phi \left( \frac{\ln(\mu_{\theta}) - \ln(\theta_{rLSi})}{\sigma_{\ln \theta}} \right) - \Phi \left( \frac{\ln(\mu_{\theta}) - \ln(\theta_{LSi})}{\sigma_{\ln \theta}} \right) * \Phi \left( \frac{\ln(\mu_{\theta}) - \ln(\theta_{rLSi})}{\sigma_{\ln \theta}} \right) $$

Cimellaro G P proposed that the inter-story drift and residual inter-story drift are not independent variables, and there is a certain correlation between the two [7]. When the performance limit states of the structure are related, the multi-dimensional performance limit state function is given by Eq. (6):

$$ \frac{\theta_i}{\theta_{LSi}} + \left( \frac{\theta_{ri}}{\theta_{rLSi}} \right)^N - 1 \leq 0 $$

Where $\theta_i$ and $\theta_{ri}$ are the inter-story drift and the residual inter-story drift response, respectively. $\theta_{LSi}$ and $\theta_{rLSi}$ are the inter-story drift and the residual inter-story drift threshold values of the structure at the $i$-th performance state. $N$ is the coefficient that affects the correlation between the inter-story drift and the residual inter-story drift. When $N=1$, the inter-story drift and residual inter-story drift are linearly related, when $N$ approaches infinity, the two are independent of each other.
3. Earthquake record selection, adjustment and structural model establishment

3.1. Earthquake record selection

According to the conditional spectrum method proposed by Baker [8], 40 sets of ground motion records were selected from the Pacific Earthquake Engineering Research Center (PEER) seismic record database. Each group of ground motion records includes two horizontal seismic records of the same earthquake and one vertical ground motion record. 40 ground motion records are randomly selected from the horizontal ground motion records (Table 1).

| NO. | Earthquake name | Magnitude | Time | Station | Earthquake component |
|-----|-----------------|-----------|------|---------|----------------------|
| Eq.1 | El Alamo        | 6.8       | 1956 | El Centro Array #9 | ELALAMO/ELC180       |
| Eq.2 | San Fernando    | 6.6       | 1971 | Santa Felita Dam   | SFERN/FSF262          |
| Eq.3 | Friuli          | 6.5       | 1976 | Codroipo           | FRIULI/A-COD270       |
| Eq.4 | Friuli          | 5.9       | 1976 | Codroipo           | FRIULI/B-COD270       |
| Eq.5 | Imperial        | 6.5       | 1979 | Plaster City       | IMPVALL/H-PLS135      |
| Eq.6 | Imperial        | 6.5       | 1979 | Superstition Mtn Camera | IMPVALL/H-SUP045     |
| Eq.7 | Livermore       | 5.8       | 1980 | San Ramon/Eastman Kodak | LIVERMOR/A-KOD180    |
| Eq.8 | Livermore       | 5.8       | 1980 | Sewage Treatm Plant | LIVERMOR/A-STD183     |
| Eq.9 | Mammoth Lakes   | 5.9       | 1980 | Paradise Lodge     | MAMMOTH/LBPL160       |
| Eq.10| Victoria        | 6.3       | 1980 | SAHOP Casa Flores  | VICT/SHP010           |
| Eq.11| Coalinga        | 6.4       | 1983 | Cholame 3W        | COALINGA/H-C03000     |
| Eq.12| Coalinga        | 6.4       | 1983 | Fault Zone 16     | COALINGA/H-Z16000     |
| Eq.13| Coalinga        | 6.4       | 1983 | Stone Corral 3E    | COALINGA/H-SC0300     |
| Eq.14| Morgan Hill     | 6.2       | 1984 | Gilroy Array #2    | MORGAN/G02090         |
| Eq.15| Morgan Hill     | 6.2       | 1984 | Gilroy Array #7    | MORGAN/GMR000         |
| Eq.16| Morgan Hill     | 6.2       | 1984 | San Juan Bautista/24 Polk St | MORGAN/SJB213     |
| Eq.17| N. Palm Springs | 6.1       | 1986 | Indio             | PALMSPR/INO315        |
| Eq.18| N. Palm Springs | 6.1       | 1986 | Valley Cemetery   | PALMSPR/H06270        |
| Eq.19| Chalfant Valley | 6.2       | 1986 | Shehorn Res       | CHALFANT/A-SHE099     |
| Eq.20| Whittier Narrows| 6.0       | 1987 | Topanga Can       | WHITTIER/A-CNP196     |
| Eq.21| Whittier Narrows| 6.0       | 1987 | S Grnd            | WHITTIER/A-NOR090     |
| Eq.22| Whittier Narrows| 6.0       | 1987 | S Orange Ave      | WHITTIER/A-SOR225     |
| Eq.23| Loma Prieta     | 6.9       | 1989 | Dumbarton Bridge West End FF | LOMAP/DUMB267 |
| Eq.24| Loma Prieta     | 6.9       | 1989 | Emerson Court     | LOMAP/FMS180          |
| Eq.25| Loma Prieta     | 6.9       | 1989 | Mission San Jose  | LOMAP/FRE000          |
| Eq.26| Big Bear        | 6.5       | 1992 | Lake Cachulla     | BGBEAR/LA0094         |
| Eq.27| Big Bear        | 6.5       | 1992 | Salton Sea Pk HQ  | BGBEAR/SS090          |
| Eq.28| Big Bear        | 6.5       | 1992 | Office Bldg       | BGBEAR/SEA000         |
| Eq.29| Big Bear        | 6.5       | 1992 | Snow Creek        | BGBEAR/SNC180         |
| Eq.30| Northridge      | 6.7       | 1994 | Jabonera          | NORTHR/JAB030         |
| Eq.31| Northridge      | 6.7       | 1994 | Castlegate St     | NORTHR/CAS270         |
| Eq.32| Northridge      | 6.7       | 1994 | Elizabeth Lake    | NORTHR/ELL180         |
| Eq.33| Northwest China | 5.9       | 1997 | Jiashi            | NWCHINA2/JA000        |
| Eq.34| CA/Baja Border  | 5.3       | 2002 | Calexico Fire Station | CABA/JA090          |
| Eq.35| CA/Baja Border  | 5.3       | 2002 | El Centro Array #7 | CABAJA/E07090        |
| Eq.36| CA/Baja Border  | 5.3       | 2002 | Holtville Post Office | CABA/JA090          |
| Eq.37| Chi-Chi         | 6.2       | 1999 | CHY034            | CHICHI.03/CHY034N     |
| Eq.38| Chi-Chi         | 6.2       | 1999 | CHY047            | CHICHI.03/CHY047W     |
| Eq.39| Chi-Chi         | 6.2       | 1999 | TCU145            | CHICHI.03/TCU145W     |
| Eq.40| Chi-Chi         | 6.3       | 1999 | CHY036            | CHICHI.06/CHY036E     |
The acceleration response spectra of the original ground motion records in Table 1 are shown in Figure 1. In this paper, the acceleration spectrum $S_a(T_1, 5\%)$ corresponds to the fundamental period $T_1$ of the structure with a damping ratio of 5% as the ground motion intensity index, and a series of adjustments are made to the seismic record. Taking $S_a(T_1, 5\%)=0.4g$ as an example, the adjusted acceleration response spectrum is shown in Figure 2.

3.2. Structural model
In this contribution, the seismic design of structures is carried out according to the *Code for Seismic Design of Buildings* (GB 50011-2010). The structural model is a 6-story RC frame with a bottom story height of 3.9 m and 2-6 story height of 3.6m (Figure 3). The floor slab is made of 250mm thick hollow slabs, and the strength of the frame columns, beams, and slabs from the base top up to 7.7m high is C35. Above 7.7m, the strength grade of the frame columns, beams, and slabs is C30. The main ribs of beams and columns are made of HRB400 and HRB335 steel bars, and the hoops are made of HPB300 steel bars.

4. Probabilistic seismic demand analysis of planar RC frame structures
Incremental dynamic analysis (IDA) [9] of structures was completed using the finite element software OpenSees. The acceleration spectrum value $S_a(T_1, 5\%)$ corresponding to the fundamental period $T_1$ of the structure with a damping ratio of 5% is the ground motion intensity index, and an elastoplastic time history analysis is performed on the structure. In order to obtain the final residual inter-story drift response for the structure, 20s of zero-intensity time is added to the end of seismic record for
time-history analysis of the structure. The inter-story drift $\theta$ and residual inter-story drift $\theta_r$ of the structure under different ground motion intensities are obtained (Figure 4 and Figure 5).

The scatter point data are the structural responses, and the dotted lines are the structural response threshold values of the structure in different performance states (Figure 4 and Figure 5). Uma [5] proposed that the structure is either fully operational, operational, life safety, or near collapse under the four different performance states. The corresponding maximum inter-story drift and residual inter-story drift threshold are hereinafter referred to as code method (Table 2).

| Performance          | Fully Operational | Operational | Life Safety | Near Collapse |
|----------------------|-------------------|-------------|-------------|---------------|
| Inter-story drift    | 0.5%              | 1.0%        | 2.0%        | 4.0%          |
| Residual inter-story drift | 0.2%       | 0.4%        | 0.6%        | 1.0%          |

5. **Fragility analysis of RC frame based on an IDA single-index and code threshold**

The acceleration spectrum value $S_a(T,5\%)$ is used as the ground motion intensity index. The structural inter-story drift and residual inter-story drift response are used as damage indicators. (Figure 6 and Figure 7).

The IDA curve shows an obvious reentry point, indicating that greater local vibration intensity corresponds to a smaller structural response. Taking the starting point of the return curve as the extreme structural response point of the IDA analysis method (IDA method), the inter-story drift response threshold value is taken as 5.32%, and the residual inter-story drift response threshold value...
is 0.772% (Figure 6 and Figure 7).

When the structure is subjected to fragility analysis using either the inter-story drift or residual inter-story drift as an index in a near-collapse state, the inter-story drift and residual inter-story drift limit obtained using the IDA method are 5.32%, 0.772%, respectively. The inter-story drift and residual inter-story drift limit used in the code method are 4.0%, 1.0%, respectively. According to Eq. (2), the exceeding probability is calculated, and the structural fragility curves with inter-story drift and residual inter-story drift as single indexes can be respectively plotted under different threshold values obtained using different methods (Figure 8 and Figure 9).

The exceeding probability of the inter-story drift threshold value selected by the IDA method is lower than that selected by the code method (Figure 8). The maximum difference is 0.39, indicating the exceeding probability is more conservative when the structure is subjected to fragility analysis using the code method. The exceeding probability calculated by the residual inter-story drift threshold value selected by the IDA method is the same as the code method, and the difference is 0.14 (Figure 9). The exceeding probability is slightly conservative when the fragility analysis is carried out using the IDA method.

6. Fragility analysis of RC frame based on an IDA double-index and code threshold

The structure model is under a near collapse limit state, considering the selection of different evaluation index thresholds based on different methods and the fragility analysis between the inter-story drift and residual inter-story drift as a double index. It is assumed that the inter-story drift response and the residual inter-story drift response are independent variables, and the double-index exceeding probability can be calculated using Eq. (5). When the ground motion intensity is the same, the structure is characterized by the inter-story drift and residual drift as a single index, and both can be taken as joint indicators of the exceeding probability of a structure in the near collapse performance level.

| Table 3 Exceeding probabilities of structures under different ground motion intensities |
|---------------------------------|---|---|---|---|---|---|---|---|
|                                | $S_a(T_1,5\%)$ (g) | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 |
| Code method                    | $\theta$          | 0   | 0   | 0.01 | 0.33 | 0.69 | 0.83 | 0.89 | 0.97 |
|                                | $\theta_r$        | 0   | 0   | 0    | 0.04 | 0.28 | 0.40 | 0.33 | 0.28 |
| Double-index                   |                | 0   | 0   | 0    | 0.01 | 0.36 | 0.78 | 0.90 | 0.92 |
| IDA method                     | $\theta$         | 0   | 0   | 0    | 0.05 | 0.31 | 0.50 | 0.50 | 0.60 |
|                                | $\theta_r$       | 0   | 0   | 0    | 0.09 | 0.39 | 0.50 | 0.47 | 0.42 |
| Double-index                   |                | 0   | 0   | 0    | 0.14 | 0.58 | 0.75 | 0.73 | 0.77 |
When the inter-story drift is used in the code method, the maximum exceeding probability is 0.97. When the residual inter-story drift is used, the maximum exceeding probability is 0.40. When the code method is used to evaluate the seismic performance of the structure using different evaluation indicators, the difference is large. When the inter-story drift is used in the IDA method, the maximum exceeding probability is 0.60. When the residual inter-story drift is used, the maximum exceeding probability is 0.50. When the IDA method is used to evaluate seismic performance of the structure using different evaluation indicators, the difference is small. The structural exceeding probability calculated using the double index is greater than the exceeding probability calculated using the single index regardless of the method used, indicating that the seismic performance evaluation of the structure with double indicators is more conservative. When using a double index for the same ground motion intensity, the structural exceeding probability calculated using the code method is larger than the structure exceeding probability calculated using the IDA method. The exceeding probability is more conservative when the structural seismic performance evaluation is carried out using the code method threshold value.

Threshold values of different evaluation indicators are selected based on the single- and double-index methods. When the single-index method is used to analyze the fragility of the structure, the difference is large and the results are not uniform. Assume that the structural inter-story drift and the residual inter-story drift response are independent of each other. When the threshold values are used in the different methods, the structural fragility curve is taken as the joint index of the inter-story drift and residual inter-story drift (Figure 10).

![Figure 10. Different methods for considering the impact of double indicators on fragility](image)

The inter-story drift and residual inter-story drift are considered as double indexes (Figure 10). When analyzing the seismic performance of the structure, the exceeding probability calculated by the threshold value selected based on the IDA method is lower than that of the code method. The maximum deviation of the structural exceeding probability calculated by selecting the threshold values of the inter-story drift and residual inter-story drift is 0.23. When the fragility of the structure is analyzed using the code method with the inter-story drift and the residual inter-story drift threshold values, the calculation results are conservative.

If we consider the influence of correlation between indicators on structural fragility analysis and evaluation, the influence of correlation coefficient $N$ in Eq. (6) on the multi-dimensional threshold limit state can be determined (Figure 11).
residual inter-story drift

Operational
Life safety
Near collapse
Fully operational

Figure 11. Effect of coefficient $N$ on multi-dimensional threshold limit state: (a) $N=1$; (b) $N=3$; (c) $N=5$; and (d) $N=15$.

The exceeding probability of the structure is obtained using Eq. (6) (Figure 12 and Figure 13).

Figure 12. Selecting thresholds according to the code method

Figure 13. Selecting thresholds according to the IDA method
Correlation of the indices has a significant influence on the seismic performance of the structure, and a change in $N$ has a more significant influence on the structural exceeding probability calculated using the threshold value selected by the IDA method (Figure 12 and Figure 13). When $N$ is held constant, the threshold value obtained using the code method is larger than that obtained using the IDA method, and the result is more conservative. When $N$ increases, that is, when the two indicators tend to be independent of each other, the calculated structural exceeding probability decreases. When $N=1$, that is, when the two indicators are linearly correlated, the calculated structural exceeding probability is largest, and the structural performance is more conservative.

7. Conclusion
- When fragility is analyzed using the inter-story drift as a single index, the code method is more conservative than the IDA method for selecting a threshold value. When the residual inter-story drift is used as a single index, the IDA method is more conservative than the code method for selecting a threshold value.
  - If the inter-story drift and residual inter-story drift are assumed to be independent of each other, the code method is more conservative than the IDA method.
  - When the correlation between the two indicators is stronger, the calculation result is more conservative.

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