Different levels seismic capacity identification method of reinforced concrete frame structures

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Abstract

Identification of seismic capacity of existing reinforced concrete structures before earthquakes is the significant basis for effective earthquake disaster mitigation, which is also practically valuable to reduce the damage of this kind of structures in earthquake. In the framework of seismic capacity index method for reinforced concrete buildings, which is given the current national Standard for seismic appraisal of buildings (GB50023-2009), the seismic capacity coefficient method was proposed. However, there is no seismic capacity identification method for different levels of intensity corresponding to the Chinese code for seismic design of buildings. For this purpose, according to the seismic hazard curve formula of design acceleration Amax and earthquake influence coefficient α_{max} with the seismic hazard curve of intensity, combining a variety of ground motion parameters with the standard for seismic appraiser of building, seismic capacity identification method for different levels of intensity is proposed. Using this method to identify the reinforced concrete buildings damaged by actual earthquake for three levels of intensity, the goal is achieved, and it is easy to predict whether the building is “not damaged under small earthquakes, repairable under moderate earthquakes, not collapsed under large earthquakes”. And that the results are consistent with the actual earthquake damage. The feasibility and effectiveness of the method are verified, and it can be concluded that the method is practical for the identification of the seismic capacity of the buildings designed for different seismic fortification levels. What is more, this method can be effectively applied to engineering practice with less structural messages of reinforced concrete.

Keywords: reinforced concrete frame buildings, seismic design levels, seismic capacity, identification method

1 Introduction

In China, the RC frame structure is one of the main structural types of existing low - rise buildings with good seismic capacity and flexible space layout. In previous earthquakes, some RC frame structures local damaged and even collapsed. As we know, earthquake is random and uncertain, and the RC frames in different earthquake regions should meet different seismic standards. Therefore, it is necessary to appraise the seismic capacity of existing RC frame structures, to make accurate and efficient measures for disaster prevention and reinforcement.

Existing buildings with continuous seismic working life of 30 years, 40 years, or 50 years are defined as Category A, Category B, or Category C respectively, according to the Chinese Standard for Seismic Appraisal of Buildings (GB50023-2009) (hereafter referred to as "the Standard")[1]. For RC frame structures, the seismic capacity identification for Category A- buildings should be divided into two grades. The first one is to check the structural system, materials, configurations, and local connections. The second one adopts the Compound Seismic Capacity Index Method (CSCIM), and the calculated index can estimate whether the seismic capacity is satisfied or not. The seismic capacity identification for Category B buildings either need to check the available capacity of components; or use the CSCIM. However, the former way only focuses on the components neglecting the whole structure, consequently, the CSCIM is more reasonable to all categories. The Chinese current Code for Seismic Design of Buildings (GB50011-2010)[2], presents three seismic capacity levels, which are not damaged under small earthquakes, repairable under moderate earthquakes, and not collapsed under large earthquakes. However, the CSCIM method is only applicable for the second level, instead of the other two. However, the seismic capacity index is calculated by earthquake influence coefficient in "the Standard", regardless of the effect of buildings' continuous seismic service life, which means that ground motion parameters are constant for selection.

A new three level seismic capacity identification method for existing RC frame structures is proposed in this study, based on ground motion parameters and the seismic intensity, which is on the basis of the CSCIM method with consideration of building continuous seismic service life and three seismic capacity levels.

2 Seismic capacity index method

The building seismic capacity index should be calculated at least in two main axis directions respectively according to "the Standard", which is calculated as follows:

$$\beta=\psi_1\psi_2\xi_y \tag{1}$$

In the equation, β denotes the compound seismic capacity index which is unsatisfied if $\beta<1$, ψ_1 and ψ_2 denote the geometry and the local influence coefficient respectively, and ξ_y denotes the story yield strength coefficient.

Moreover ψ_1 is the compound result of the structural system, hoops of beam and column, axial compression ratio and so on. The value of ψ_1 will be more than one, if all configurations meet the Code for Seismic Design of Buildings(GB50011-2010) or Category A buildings conform to requirements of the Category B. That is to say, the story seismic capacity would be strengthened by ψ_1 when existing buildings meet higher requirement. Otherwise, it would be weakened, as buildings were designed without seismic fortification or being local destruction. ψ_2 is to reduce the seismic capacity on account of the connection between frame and the infill or masonry.

The story yield strength coefficient can be calculated as follows:

$$\xi_y = V_y / V_e \quad (2)$$

In the equation, V_y and V_e respectively denote the story shear bearing capacity and the story elastic earthquake shear force.

A new method presented in this paper refer to the proportion of V_y and V_e, and the calculation will be introduced in details as follows.

2.1 Elastic earthquake shear force

When influenced by the torsion effect of irregular structures, the story elastic earthquake shear force can be calculated by the Code for Seismic Design of Buildings (GB50011-2010), and if for structures with regular shapes or with uniform mass and stiffness distribution along the height, it can be calculated by the "base shear method". The corresponding calculation formula is as follows:

$$F_{\mathrm{EK}} = \alpha_{\max} G_{\mathrm{eq}} \quad (3)$$

$$F_i = \frac{G_i H_i}{\sum_{j=1}^{n} G_j H_j} F_{\mathrm{EK}} \quad (4)$$

In the equation, F_{EK} and F_{i} respectively denote the standard value of the total horizontal earthquake action of a structure and at the i_{t} mass, $\alpha_{\max}$ denotes the maximum of the horizontal seismic influence coefficient, G_{eq} and G_i respectively denote the total equivalent gravity load of a structure and the representative values of the gravity at the i_{th} mass, H_i denotes the calculated height of the i_{th} mass.

2.2 Story shear capacity

The story shear capacity can be calculated by "the Standard" as follows:

$$V_y = \sum V_{cy} + 0.7 \sum V_{my} \quad (5)$$

In the equation, V_y denotes available story shear capacity, V_{cy} and V_{my} respectively denote sum of available story shear capacity of frame column and of infill.

The available story shear capacity of rectangular RC column can be taken as the minimum between the following two formulas:

$$V_{cy} = \frac{M_{cy}^{u} + M_{cy}^{L}}{H_n} \quad (6)$$

$$V_{cy} = \frac{0.16}{\lambda + 1.5} f_{ck} b h_0 + f_{yvk} \frac{A_{sv}}{s} h_0 + 0.056 N \quad (7)$$

In the equation, M_{cy}^{u} and M_{cy}^{L} respectively denote the available bending bearing capacity at the upper and lower end of the column, and H_n denotes the net height of the column. λ denotes the calculated shear span ratio, as $\lambda = H_n / 2h_0$. N denotes the axial force according to the representative values of the gravity, which is taken not more than $0.3 f_{ck} bh$. A_{sv} denotes the sum of hoop areas in the same section. According to "the Standard", f_{yvk} and f_{ck} respectively denote the tensile strength standard value of the hoop and the compressive strength standard value of the concrete. s denotes the spacing of hoops. b and h_o respectively denote the section width and effective column height.

Moreover, the moment capacity of rectangular RC column eccentrically compressed with symmetrical reinforcement can be calculated as follows:

$$M_{cy} = f_{yk} A_s \left(h_0 - a_s^{'}\right) + 0.5Nh\left(1 - N / f_{cmk} bh\right) \qquad (N \le \xi_{bk} f_{cmk} bh_0) \tag{8}$$

$$M_{cy} = f_{yk} A_s \left(h_0 - a_s^{'}\right) + \xi\left(1 - 0.5\xi\right) f_{cmk} bh_0^2 - N\left(0.5h - a_s^{'}\right) \qquad (N > \xi_{bk} f_{cmk} bh_0) \tag{9}$$

$$\xi = \left[\left(\xi_{bk} - 0.8\right) N - \xi_{bk} f_{yk} A_s\right] / \left[\left(\xi_{bk} - 0.8\right) f_{cmk} bh_0 - f_{yk} A_s\right] \tag{10}$$

In the equation, A_s denotes the available cross-sectional areas. According to “the Standard”, f_{yk} and f_{cmk} respectively denote the tensile strength standard value of the longitudinal reinforcement and the compressive strength standard value of the concrete. ξ_{bk} denotes the relative height of compression zone, which can be taken as 0.6 for HPB steel or as 0.55 for HRB.

The story shear capacity of existing RC frame with infill can be calculated as follows:

$$V_{my} = \sum\left(M_{cy}^{u} + M_{cy}^{L}\right) / H_0 + f_{VEk} A_m \tag{11}$$

$$f_{vEk} = \zeta_N f_{vk} \tag{12}$$

In the equation, ζ_N denotes normal stress influence coefficient of masonry strength, f_{vk} denotes the shear strength standard value of the masonry wall, A_m denotes the total areas of the horizontal section.

3 Three-level ground motion parameters based on the intensity for existing buildings

The earthquakes are classified in the three levels as small, moderate, and large, according to the Code for Seismic Design of Buildings (GB50011-2010), which are respectively defined as the exceedance probability of the buildings suffering earthquake in 50 years being, and the corresponding value are 63%, 10% , and 2%-3%. The intensity corresponding to three earthquake levels mentioned above are defined as Level 1 intensity, Level 2 intensity and Level 3 intensity in sequence.

3.1 Three-levels of seismic fortification objective for existing buildings

Existing buildings with continuous seismic working life of 30 years, 40 years, or 50 years are defined as Category A, Category B ,or Category C respectively, according to “the Standard. For the three - categories buildings, in order to realize the same seismic fortification objectives as the Code for Seismic Design of Buildings (GB50011-2010), the three-levels of seismic fortification objectives for existing buildings should adopt continuous seismic working life to calculate the exceedance probability, shown below:

Table 1. Return period of three-level earthquake for different continuous seismic working life (Unit: year).

Seismic capacity level	Continuous seismic working life of existing buildings		
Level 1(Not damaged under small earthquakes)	30	40	50
Level 2(Repairable under moderate earthquakes)	285	380	475
Level 3(Not collapsed under large earthquakes)	985-1485	1314-1980	1462-2475

Results of seismic identification will be more reasonable and applicable, when taking different continuous seismic working life of all categories existing buildings into consideration.

3.2 Three-level parameters of ground motion based on intensity for different continuous seismic working life

The relationship between the exceedance probability and the intensity has been fit by results of seismic hazard analysis in Chinese cities and towns [4]. For random variables x, the relationship between probability distribution function $F(x)$ and probability of exceedance $P(X \ge x)$ is:

$$F(x) = 1 - P(X \ge x) \tag{13}$$

In addition, the distribution of seismic intensity is shown as follows:

$$F(i)=1-P(I\geq i)=\exp\left[-\left(\frac{\omega-i}{\omega-\varepsilon}\right)^k\right]\quad(i<\omega) \tag{14}$$

In the equation, i denotes the seismic intensity, ω denotes the upper limit of intensity, which can be taken as 12, ε denotes the Level 1 intensity, and k denotes the shape parameter.

Natural logarithm and common logarithm are respectively taken on both sides of the eq. (14), and i is given the value of the Level 2 intensity I_0. Consequently, the intensity curve of seismic hazard can be expressed as follows:

$$\lg\{-\ln[1-P(I\geq i)]\}+0.9773=k\lg\left(\frac{\omega-i}{\omega-I_0}\right) \tag{15}$$

According to the Code for Seismic Design of Buildings (GB50011-2010), horizontal seismic influence coefficient $\alpha_{\max}$ and seismic acceleration $A_{\max}$ can be calculated as follows:

$$\lg\alpha_{\max}=0.3i-2.75 \tag{16}$$

$$\lg A_{\max}=0.3i-2.1 \tag{17}$$

Furthermore, the expression of intensity curve of seismic hazard about horizontal seismic influence coefficient and seismic acceleration is:

$$\lg\{-\ln[1-P(I\geq i)]\}+0.9773=k\lg\left(\frac{0.85-\lg\alpha_{\max}}{0.85-\lg\alpha_{\max}^{10}}\right) \tag{18}$$

$$\lg\{-\ln[1-P(I\geq i)]\}+0.9773=k\lg\left(\frac{1.5-\lg A_{\max}}{1.5-\lg A_{\max}^{10}}\right) \tag{19}$$

In the equation, $\alpha_{\max}^{10}$ and $A_{\max}^{10}$ respectively denote the value of $\alpha_{\max}$ and $A_{\max}$ in the moderate earthquakes.

From the above, seismic intensity i with a 10% exceedance probability in 50 years, horizontal seismic influence coefficient $\alpha_{\max}$, and seismic acceleration $A_{\max}$ can be obtained by the equation (15), (18), and (19), by using the I_0, $\alpha_{\max}^{10}$, $A_{\max}^{10}$, and the shape parameter k that is shown as Table 2.

Table 2. The shape parameter values of current Code

Fortification intensity	6	7	8	9
Shape parameter k	9.79	8.33	6.87	5.40

The exceedance probability of different levels in t years can be converted via equal (20) as in 50 years [4].

$$P=1-(1-P')^{t/50} \tag{20}$$

In the equation, t denotes continuous seismic working life, P' denotes exceedance probability of continuous seismic working life corresponding to three seismic capacity levels, P denotes the relative exceedance probability which is in 50 years.

By taking the relative exceedance probability into equation (18) and (19), horizontal seismic influence coefficient $\alpha_{\max}$ and seismic acceleration $A_{\max}$ for three seismic capacity levels with continuous working life t years can be calculated as Table 3 [3].

Table 3. Horizontal seismic influence coefficient $\alpha_{\max}$ for different continuous working life (unit: year)

Continuous working life	Seismic capacity level	Fortification intensity			
		6	7	8	9
30	Level 1(Not damaged under small earthquakes)	0.029	0.060	0.115	0.227
	Level 2(Repairable under moderate earthquakes)	0.090	0.185	0.364	0.734

	Level 3(Not collapsed under large earthquakes)	0.207	0.415	0.755	1.168
	Level 1(Not damaged under small earthquakes)	0.034	0.070	0.136	0.272
40	Level 2(Repairable under moderate earthquakes)	0.102	0.210	0.411	0.825
	Level 3(Not collapsed under large earthquakes)	0.230	0.457	0.828	1.283
	Level 1(Not damaged under small earthquakes)	0.040	0.080	0.160	0.320
50	Level 2(Repairable under moderate earthquakes)	0.112	0.230	0.450	0.900
	Level 3(Not collapsed under large earthquakes)	0.250	0.500	0.900	1.400

Table 4. Seismic acceleration A_{max} for different continuous working life (unit: cm/s^2)

Continuous working life	Seismic capacity level	Fortification intensity			
		6	7	8	9
	Level 1(Not damaged under small earthquakes)	13	26	51	101
30	Level 2(Repairable under moderate earthquakes)	40	80	162	326
	Level 3(Not collapsed under large earthquakes)	93	181	336	519
	Level 1(Not damaged under small earthquakes)	15	30	60	120
40	Level 2(Repairable under moderate earthquakes)	45	91	183	367
	Level 3(Not collapsed under large earthquakes)	103	200	368	570
	Level 1(Not damaged under small earthquakes)	18	35	70	140
50	Level 2(Repairable under moderate earthquakes)	50	100	200	400
	Level 3(Not collapsed under large earthquakes)	/	220	400	620

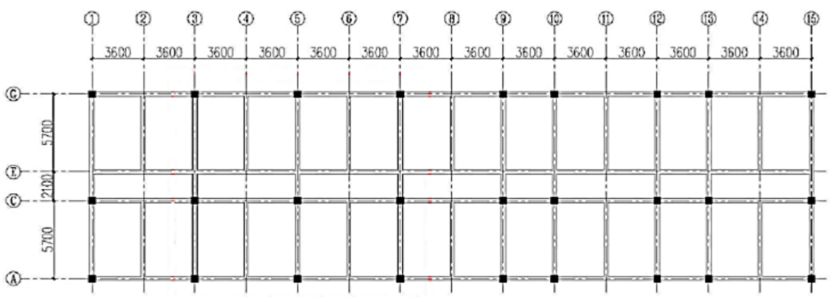
Therefore, the new three level seismic capacity identification method for existing RC frame structures is based on the equal probability principle. Moreover, ground motion parameters are obtained by the way that different continuous seismic working life of existing buildings for requirement of three levels are converted as the new building.

4 Example

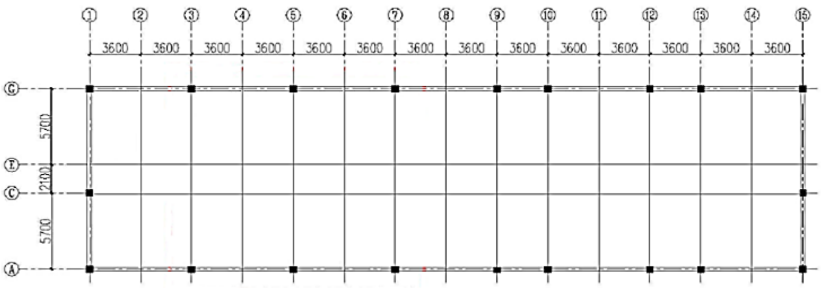
Take a damaged RC frame structure for appraisal using the new identification method proposed in this paper. The building suffered Yu Shu earthquake with magnitude 7.1 in China on April 14, 2010.

4.1 Building configurations and damage description

The RC frame structure is in intensity Ⅸ, which was built in 2009 with four stories, and the seismic design acceleration was 0.15g. The plan of the 4-story frame is shown in Fig.1. The story height is 3.6m. The concrete used for beam and column is C30. Steel bars are HPB300. The cross sections of columns are listed in Table 5, and the cross sectional configurations are shown in Fig. 2.



(1) Story 1~3



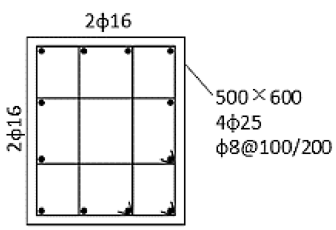
(2) Story 4

Figure 1. Standard plan of the RC frame structure (Unit: mm)

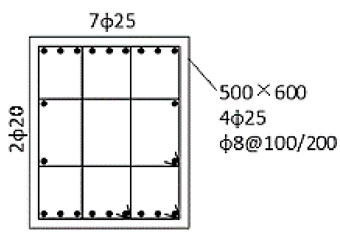
Table 5. Cross sections of all columns

Story	Location	Transverse number	Cross section number
4	Side column	1 & 15	CS-D
		2 - 14	CS-B
	Middle column	1 & 15	CS-D
		2 - 14	×
3	Side column	1 & 15	CS-D
		2 - 14	CS-B
	Middle column	1 & 15	CS-D
		2 - 14	CS-E
2	Side column	1 & 15	CS-D
		2 - 14	CS-A
	Middle column	1 & 15	CS-D
		2 - 14	CS-E
1	Side column	1 & 15	CS-D
		2 - 14	CS-A
	Middle column	1 & 15	CS-D
		2 - 14	CS-C

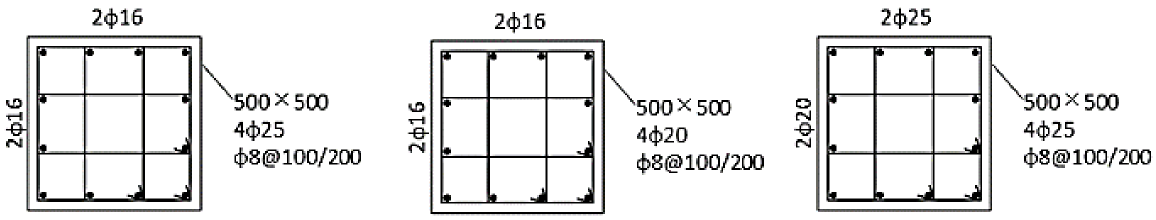
Note: CS-A represents cross section A whose detail is in Fig. 2-1, and × represents no column.



(1) Section A



(2) Section B



(3) Section C (4) Section D (5) Section E

Figure 2. Cross sectional configurations of columns (unit: mm)

According to the investigation [6], lots of plastic hinge appeared in the RC frame structure, and the concrete of column was crushed in first story with longitudinal reinforcement buckling, and that story drift was significant, the earthquake damage is shown in Fig. 3. Moreover, this failure mechanism consumes a lot of energy so that the upper three stories damage slightly.


(a) The overall view (b) The local failure

Figure 3. Damage view of the RC frame structure

4.2 Seismic capacity identification for existing RC frame

The building was classified into Category B according to the completion time. In addition, take it for appraisal using the new identification method proposed in this paper. The values of three-level compound seismic capacity index are listed in Table 6.

Table 6. The values of three-level compound seismic capacity index β

Appraisal location		Not damaged under small earthquakes				Repairable under moderate earthquakes				Not collapsed under large earthquakes			
Story	Direction	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅵ	Ⅶ	Ⅷ	Ⅸ
4	L	34.31	16.67	8.58	4.29	11.44	5.56	2.84	1.41	5.07	2.55	1.41	0.91
	T	27.30	13.26	6.82	3.41	9.10	4.42	2.26	1.13	4.04	2.03	1.12	0.72
3	L	69.38	33.70	17.35	8.67	23.13	11.23	5.74	2.86	10.26	5.16	2.85	1.84
	T	21.72	10.55	5.43	2.71	7.24	3.52	1.80	0.90	3.21	1.62	0.89	0.58
2	L	63.13	30.66	15.78	7.89	21.04	10.22	5.22	2.60	9.33	4.70	2.59	1.67
	T	14.94	7.26	3.73	1.87	4.98	2.42	1.24	0.62	2.21	1.11	0.61	0.40
1	L	60.04	29.16	15.01	7.51	20.01	9.72	4.97	2.47	8.88	4.47	2.47	1.59
	T	11.38	5.53	2.85	1.42	3.79	1.84	0.94	0.47	1.68	0.85	0.47	0.30

Note: L and T respectively represent the longitudinal and transverse direction.

Because of the large length-width ratio of the structure, and because of the larger column space in the transverse direction, all longitudinal index values are more than the transverse direction, as shown in Table 6. In this earthquake, the structure was located on the Ⅸ intensity area, with fortification intensity Ⅶ. As shown in Table 6, the upper three stores values of β in transverse direction on the moderate earthquake level are all less than one, which is not satisfied for the requirement of "Repairable". As the result of the least β value, the first story damaged severely. In contrast, the third and fourth story suffered slight damage, and the corresponding β value are 0.9 and 1.13, which are closed to one or more than one. Consequently, the results of the new identification method proposed in this paper are consistent with the actual earthquake damage. Furthermore, the shear force obtained by equation (6) more than the result calculated by equation (7), which means the column capacity of bending is stronger than that of shear, consequently, the design can't satisfy the requirements. Meanwhile, the β values of Ⅵ intensity in the transverse direction are all less than one, so that the goal "Not collapsed under large earthquakes" is not achieved. As shown in Fig. 3, the structure is on the verge of collapse in the transverse direction, according with the appraisal result using the new identification method proposed in this paper.

5 Summary and conclusions

According to the seismic hazard curve formula of design acceleration Amax and earthquake influence coefficient α_{max} with the seismic hazard curve of intensity, combining a serious of ground motion parameters with the Chinese Standard for Seismic Appraisal of Buildings (GB50023-2009), seismic capacity identification method for different levels of intensity is proposed. Considering of the earthquake uncertainty and randomness, whether structures satisfy the design requirements on different levels of intensity is easy to identify. Using this method to identify the reinforced concrete buildings damaged by actual earthquake for three levels of intensity, the goal is achieved. In addition, it can be predicted whether the building is "not damaged under small earthquakes, repairable under moderate earthquakes, not collapsed under large earthquakes". Moreover, the results are consistent with the actual earthquake damage. The feasibility and effectiveness of the method are verified, and it can be concluded that the method is practical for the identification of the seismic capacity of the buildings designed for different seismic fortification levels.

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