Seismic preliminary evaluation of low-rise residential buildings in Taiwan

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ABSTRACT

On 6 February 2016, Meinong Earthquake with M_L 6.4 attacked the south part of Taiwan. Many low-rise residential buildings were collapsed due to soft story and eccentricity. In order to exam seismic capacity of the existing low-rise residential buildings, Taiwan government decides to implement a project of seismic evaluation for the existing low-rise residential buildings. However, a number of low-rise reinforced concrete (RC) buildings in Taiwan is huge. A seismic preliminary evaluation can provide a pre-screen of seismic capacity for the huge number of low rise reinforced RC buildings. The buildings that have seismic doubts screened by preliminary evaluation need to implement detailing evaluation to conform the seismic capacity. National Center for Research on Earthquake Engineering (NCREE) developed a seismic preliminary evaluation method by the seismic detailing evaluation data bank of the school buildings in Taiwan. The performance ground acceleration of each school building should be related to the total floor area, column section area, and wall section area of each school building by statistical regression. In the other words, the performance ground acceleration of a low-rise RC building can be preliminary evaluated by the ratio of column section area to floor area of the building. Modified factors of soft story and eccentricity of a low-rise RC building were provided to reflect the effect on performance ground acceleration of the building. The seismic preliminary evaluation method has been verified by the other data bank of earthquake reconnaissance. Verification results show that the preliminary assessment of the buildings with moderate or serious seismic damage has seismic capacity doubts. Meanwhile, for the buildings with slight seismic damage, the preliminary evaluating results show partially having seismic capacity doubts. Consequently, the preliminary evaluation method is conservative but without loss the capability on screening seismic capacity of the existing low-rise RC buildings.

Keywords: seismic evaluation; preliminary evaluation; reinforced concrete; low-rise; existing building; Meinong Earthquake

1. Introduction

The recent Kaohsiung Meinong Earthquake on February 6, 2016 (local time) affected several categories of building, which include concrete framed buildings, high rise steel office buildings, street houses and individual single-family homes, and school buildings. The majority of housing in Taiwan consists of “street houses” particularly in urban areas. Seismic reconnaissance of Meinong Earthquake shows that many street houses were severely damaged in the ground floor due to soften story structural system (Figure 1) and additional penthouse on the roof (Figure 2).   Moreover, many masonry infills along the corridor direction of a street house were collapsed as shown in Figure 3. The recon teams found that many street houses in the street corner were with full openings on both faces of the buildings, which induced significantly eccentric effect of the structural system (Figure 4). Most of these traditional street houses were insufficient ductility due to with non-ductile detailing design in 1980s to 1990s (Figure5). Besides, shear failure of the extremely short column effect was found in a 3- story commercial building as shown in Figure 6. Shear failure of captive columns were also recorded in many public buildings (Figure 7). From the lesson of the Kaohsiung Meinong Earthquake, the major failure features of the low-rise RC buildings summarized soften story, seismic weak direction along the corridor direction, eccentrically torsion effect, non-ductile detailing, and short column effect.

To avoid the disaster from happening again, it is necessary to conduct a comprehensive health check on existing reinforced concrete buildings and to retrofit buildings with inadequate seismic capacity. To efficiently assess the seismic capacity of a large number of street houses, National Center for Research on Earthquake Engineering (NCREE) utilized a database of school buildings to develop a preliminary seismic assessment method for low-rise reinforced concrete structures.

According to the summary of the seismic damage of street houses and public buildings, this type of low-rise reinforced concrete buildings often experience severe damage or collapse in the bottom floor, with only minor damages above the second floor. Therefore, the lateral strength of members in the bottom level primarily controls the seismic capacity of these structures. In other words, a structure’s seismic capacity can be estimated if the strength of the members in its bottom floor is known. The principle of preliminary evaluation of seismic capacity of street houses is to estimate the seismic capacity based on the amount of columns and walls on the ground floor of such low-rise RC buildings. NCREE used the database of detailing seismic evaluation of school buildings to derive a relationship between seismic capacity and column and wall areas on the ground floor of low-rise RC buildings. On the basis of this relationship, a quick assessment method for seismic capacity of low-rise RC buildings is developed.

This study selects school buildings for detailed assessment using Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA) as objects. This means that the preliminary assessment method applies only to RC or confined masonry (CM) buildings with less than six levels (inclusive) and having rigid floor panels. This paper first introduces the underlying principle of the proposed method, followed by validation of this method using RC building seismic database that was set up from past reconnaissance reports by NCREE. It can be seen that the proposed method has screening function. Finally, the proposed method is applied to the NCREE database of typical street house buildings in Taiwan.

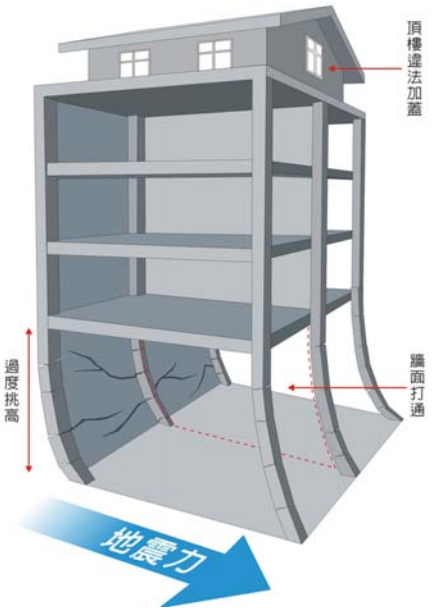

Figure 1. A shear building with soften story due to the partition wall demolished.


Figure 2. A street house with the penthouse on the roof.


Figure 3. Shear failure of a masonry infill adjacent to the staircase along the corridor direction of a street house.

Figure 4. A street house in the street corner with full openings on both faces of the building.


Figure 5. A corridor column with non-ductile detailing.

Figure 6. Shear failure and gravity resistance lose of an extremely short column.

Figure 7. Shear failure of captive columns.

2. Seismic preliminary evaluation

Song et al. [1] chose 1,187 school buildings with bare frames in the longitudinal direction from the school building seismic database set up by NCREE to perform statistical analysis. The database contains information on the total floor area, column area and the performance ground acceleration A_p derived from the pushover analysis. From this information, a relationship between the column to floor ratio and the associated seismic performance, A_p, can be derived through regression analysis. The relationship is as shown in Equation (1).

$$\begin{cases} A_p = \dfrac{100CFR - 0.4 + 0.05N_f}{1.62 - 0.24N_f}, CFR \geq (0.4 - 0.05N_f)\% \\ A_p = 0, CFR < (0.4 - 0.05N_f)\% \end{cases} \tag{1}$$

in which A_p is the performance ground acceleration derived from the pushover analysis; N_f is the number of levels in the building, for a five-level or six-level building, N_f should be taken as 4 to produce conservative assessment results; CFR is the column area to floor area ratio, which can be calculated from Equation (2) as

$$CFR = \frac{\sum A_C}{\sum A_f} \tag{2}$$

where $\sum A_C$ is the total column area on the ground floor and $\sum A_f$ is the total floor area on and above the second floor. If there is an additional penthouse on the top floor of the RC structure, the entire additional floor area is accounted for in the calculation of the total floor area; if the additional penthouse is lightweight material such as steel and wood, half of its area is included in the calculation of the total floor area.

Song et al. [1] summarized the detailed assessment results for the bare frames of school buildings and proposed the average ultimate shear strength of column is 7.95 kgf/cm^2. Chiou et al. [2] proposed lateral shear strength for masonry infill and RC wall in accordance with experimental verification and theoretical formulas. The lateral strength of major members for low-rise RC buildings is listed in Table 1, which is in good agreement with the results of other studies in the past, as shown in Table 1.

Therefore, using the in-plane lateral strength for various types of walls (as shown in Table 1) and a lateral strength per unit column area of $7.95 kgf/cm^2$, the equivalent conversion coefficient for different types of walls can be derived. First, for brick walls confined on three sides, Equation (3) can be used for the conversion into equivalent column area.

$$\tau_c \sum A_c = \tau_{bw3} \sum A_{bw3} \tag{3}$$

where τ_{bw3} is the average ultimate shear strength of brick walls confined on three sides, and $\sum A_{bw3}$ is the sum of the cross-sectional area of brick walls confined on three sides on the ground floor. Substituting $\tau_c = 7.95$ and $\tau_{bw3} = 3.2$ in Equation (3), we get the conversion coefficient for converting brick walls confined on three sides into equivalent column area, as shown in Equation (4).

$$\sum A_{c,eq} = \frac{3.2}{7.95} \sum A_{bw3} = 0.403 \sum A_{bw3} \tag{4}$$

where $\sum A_{c,eq}$ represents the equivalent column area. Similarly, the conversion coefficient for brick walls confined on four sides can be derived on the basis of Table 1. It is given as Equation (5).

$$\sum A_{c,eq} = \frac{4.0}{7.95} \sum A_{bw4} = 0.503 \sum A_{bw4} \tag{5}$$

where $\sum A_{bw4}$ is the sum of the cross-sectional area of brick walls confined on four sides on the ground floor. The conversion coefficient for converting RC walls confined on three sides into the equivalent column area is given in Equation (6).

$$\sum A_{c,eq} = \frac{12}{7.95} \sum A_{rcw3} = 1.509 \sum A_{rcw3} \tag{6}$$

where $\sum A_{rcw3}$ is the sum of the cross-sectional area of brick walls confined on three sides on the ground floor. The conversion coefficient for RC walls confined on four sides is given in Equation (7).

$$\sum A_{c,eq} = \frac{21}{7.95} \sum A_{rcw4} = 2.642 \sum A_{rcw4} \tag{7}$$

where $\sum A_{rcw4}$ is the sum of the cross-sectional area of the ground floor's RC walls that are confined on four sides.

Consequently, brick walls and RC walls are included in the ratio of equivalent column to floor, as given in Equation (8).

$$\begin{aligned} CFR_{eq} &= \frac{\sum A_C}{\sum A_f} + \beta\left(0.403\frac{\sum A_{bw3}}{\sum A_f} + 0.503\frac{\sum A_{bw4}}{\sum A_f} + 1.509\frac{\sum A_{rcw3}}{\sum A_f} + 2.642\frac{\sum A_{rcw4}}{\sum A_f}\right) \\ &= \frac{\sum A_C + 0.36\sum A_{bw4} + 0.45\sum A_{bw4} + 1.36\sum A_{rcw3} + 2.38\sum A_{rcw4}}{\sum A_f} \end{aligned} \tag{8}$$

where CFR_{eq} is the equivalent column to floor ratio, β is the reduction factor on the ultimate strength. Since the ultimate strength of the various members of the structure will not occur simultaneously, a value of 0.9 is adopted based on Su's suggestion [3]. Substituting the equivalent column to floor ratio for the directions parallel and perpendicular to the street, CFR_{eqx} and CFR_{eqy}, in Equation (1), the performance ground acceleration in the two directions, A_{px} and A_{py}, can be obtained. The seismic capacity of a building is the lesser of the two, as shown in Equation (9).

$$A_p = \min(A_{px}, A_{py}) \tag{9}$$

Since the proposed method aims at low-rise buildings, the seismic demand A_T can be determined on the basis of the seismic design code. The short-term horizontal acceleration coefficient, S_S^D, of the building (based on its location), the near-fault correction coefficient, N_A, and the magnification coefficient, F_a, for industrial sites can be looked up in the seismic design code. The short-term design horizontal acceleration coefficient, S_{DS}, can be then obtained. The seismic demand A_T is calculated by

$$A_T = 0.4 S_{DS} \tag{10}$$

The ratio of the seismic capacity to the seismic requirement is given as

$$E = \frac{A_P}{A_T} \tag{11}$$

This study proposes that modification factors should include the construction year (q_1), eccentricity effect (q_2), effect of a weak story (q_3), and effect of short columns (q_4). According to the evolution of seismic design code, construction year is divided into four periods. For buildings constructed before 1974, the modification factor for construction time q_1 is 0.9, for between 1975 and 1983, q_1 is 0.95; for between 1983 and 1999, q_1 is 1.0; and for buildings constructed after 2000, q_1 is 1.05. The reconnaissance on 0206 Meinong Earthquake in Taiwan, 2016, shows that buildings at the corner of intersections exhibit apparent eccentric rotation, as shown in Figure 8. Therefore, the eccentricity effect is chosen as modification factor q_2. For buildings with corridors on both sides, q_2 is 0.9, and for those with a corridor on only one side, q_2 is 1.0. Removal of some walls in the bottom floor of buildings may cause collapse, as shown in Figure 1. Therefore, the effect of a weak story is taken as a modification factor q_3. If any wall in the building frame is removed, q_3 is 0.9; otherwise, q_3 is 1.0. The effect of a short column is a modification factor q_4. When the net height of column (H_n) is less than or equal to twice the depth in the loaded lateral direction (2D) (i.e., height-to-depth ratio $H_n/D \le 2$), the column is defined as a short column. It is found in the 0206 Meinong Earthquake reconnaissance that many short window columns tend to experience shear failure, as shown in Figure 9. The modification factor for short columns q_4 can be calculated according to the following equation and it should not be less than 0.5.

$$q4 = (1 - \text{ratio of area of short columns to the total column area}) \ge 0.5 \tag{12}$$

The fundamental seismic capacity modification factor Q can be calculated as

$$Q = q1 \times q2 \times q3 \times q4 \tag{13}$$

The preliminary evaluation index for building seismic capacity I_s is

$$I_S = E \times Q \tag{14}$$

If $I_s < 1.0$, there is a concern over the building’s seismic capacity, while if $I_s \ge 1.0$, there is no concern.

Table 1 – Recommended lateral strength of various members

Unit: kgf/cm^2		Japan [4]	Kuo [5]	Sheu [6]	Chiou [2]
Column	Short column	15	14.1	7.92	7.95
	Window column	10	9.9		
	Long column	7	5.4		
RC wall	Confined on four sides	30	28.6	10.37	21
	Confined on three sides	20	20		12
	Confined on two sides	10	11.2		-
Brick wall	Confined on four sides	-	3.9	3.37	4.0
	Confined on three sides	-	1.6		3.2

Figure 8. Buildings at the corner of an intersection collapsed in 0206 Meinong Earthquake, owing to eccentric rotation

Figure 9. Shear failure of short columns in high windows

3. Verification

In this study, basic information, such as dimensions and damages, of 59 low-rise RC buildings, including street houses and school buildings, is collected from NCREE's reconnaissance report which including 921 Chi Chi Earthquake, 0304 Jiaxian Earthquake, 0602 Nantou Earthquake etc. With the information on stories, total floor areas, column dimensions and quantities, and number of brick walls in the direction along the corridor (X direction) and perpendicular to the corridor (Y direction), the seismic capacity of various buildings can be estimated using the proposed preliminary assessment equations. Assessment results are compared with the actual seismic records on these buildings to validate the screening of the proposed method.

Applying the preliminary assessment method to the 59 buildings, their equivalent column to floor ratios, CFR_{eq}, as well as the seismic performance, A_p, can be derived. The seismic performance, A_p, is divided by the peak ground acceleration recorded in the earthquake, A_{rec}. If the value is greater than 1, it means the building should have no safety concern in the earthquake, and the seismic damage should be minor or slight; if the value is less than 1, the building may be damaged in this earthquake and the extent should be moderate or severe, or the building may collapse. Figure 10 presents the assessment results versus the level of damage buildings experienced in the earthquake.

Figure 10 shows that the results of preliminary assessment are less than 1 for majority of buildings with moderate, severe, or collapse damage. This indicates that the assessment results are in agreement with the actual level of seismic damage. The preliminary assessment results are greater than 1 for most buildings with minor or slight damage. However, some of the buildings with minor or slight damage have a result of less than 1, demonstrating that the results of the preliminary assessment are conservative.

If the seismic performance obtained from the preliminary assessment, A_p, is taken as the seismic capacity and $A_T = 0.4S_{DS}$ from the seismic design code as the seismic demand, the ratio between the two is the ratio of seismic capacity to seismic demand. This ratio is plotted with the actual seismic damage in Figure 11. The average is 1.4 for minor damage, 1.06 for slight damage, 0.89 for moderate damage, 0.68 for severe damage, and 0.34 for collapse. This matches with the trend that lower capacity/demand ratio means greater damage level. The fact that the average of A_p/A_T is less than 1 for collapse, severe, and moderate damage confirms that the proposed preliminary assessment method has an effective screening function.

To understand the actual effect of the preliminary assessment method, this study utilized the database of typical street house buildings in Taiwan, set up by NCREE [3], to conduct trials. This database contains structural data on 145 street house buildings. Information such as location, total floor area, stories, column area on the ground floor, wall area in the parallel and perpendicular direction to the corridor is included in the database. Moreover, it contains information on street house buildings in Taipei City, New Taipei City, Taichung City, Changhua County, Nantou County, Tainan City, and Kaohsiung City. The types of street house buildings include terraced townhouses, condo-type street houses, and free-standing townhouses. It is a comprehensive database, covering all existing representative types of street house buildings in Taiwan.

The 145 buildings are assessed using the proposed method. The assessment result, the performance ground acceleration, A_p, represents the seismic capacity. Depending on the location of the building, the seismic design ground acceleration, A_T, is looked up in the design code and taken as the seismic demand. The ratio of capacity to demand gives the seismic index *Is*. An *Is* of less than 1 indicates that the building's seismic capacity is of concern, while that of greater than 1 indicates that there is no concern. Figure 12 shows the preliminary assessment results for the 145 street house buildings. Among them, 56 buildings have $Is < 1$, which is 38.6% of the total sample buildings (Figure 13). This means that by using this proposed preliminary assessment method to assess all the street houses in Taiwan, about 38% of them require a more detailed assessment of the seismic capacity.

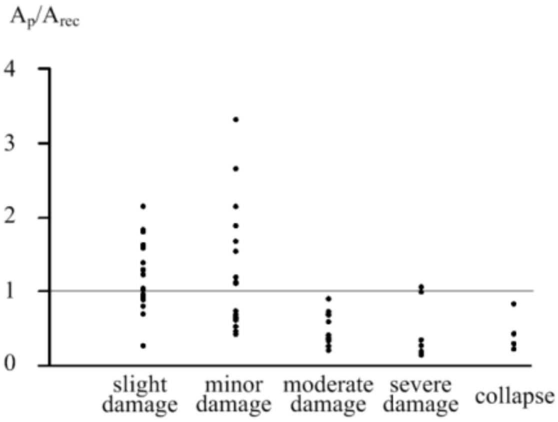

Figure 10. Ratio of preliminary assessment results to recorded acceleration versus actual seismic damage level

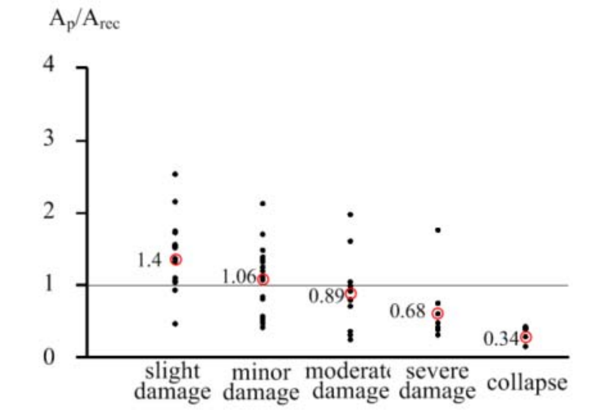

Figure 11. Ratio of preliminary assessment results to design acceleration versus actual seismic damage level

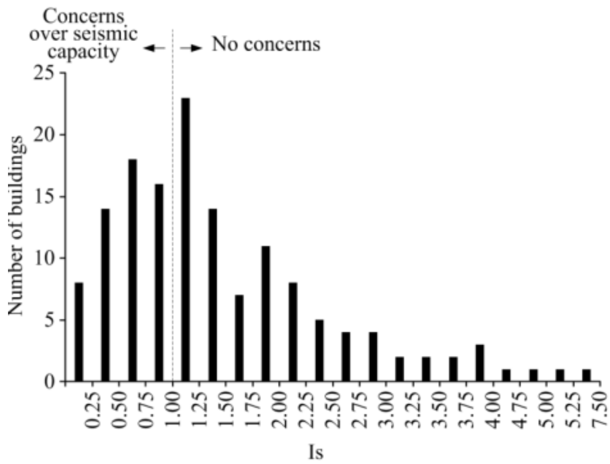

Figure 12. Results of preliminary assessment of the seismic capacity of typical street house buildings in Taiwan

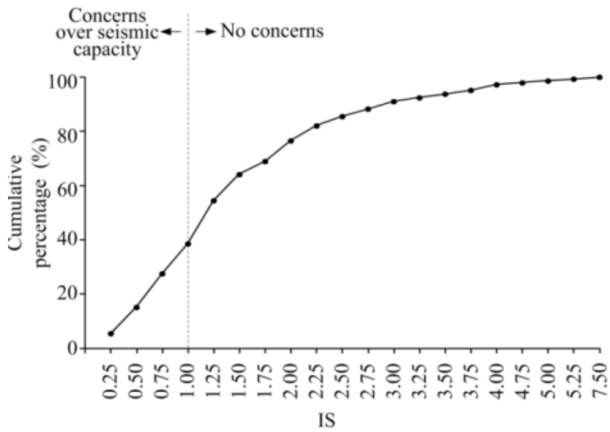

Figure 13. Results of preliminary assessment of the seismic capacity of typical street house buildings in Taiwan (accumulative percentage)

4. Conclusion

This study utilized seismic database of school buildings to derive a relationship between the parameters of bare frames and the seismic capacity through a regression analysis. Based on the area of the column and wall members, their strength is converted into equivalent column area. Modification factors relevant to the seismic characteristics of low-rise buildings are chosen, and a preliminary assessment method for the seismic capacity of low-rise RC buildings is developed. The proposed method is applicable to RC or brick infill buildings up to six stories with rigid floor panels. Through validation using the seismic damage database of low-rise RC buildings, this method is verified to be conservative and able to serve as a screening tool. It can be used in the preliminary screening of a large number of street house buildings according to their seismic capacity.

5. References

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