Inherent Strength-based Approach for Collapse Seismic Assessment of Low-rise Masonry Buildings


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ABSTRACT: Confined masonry structures are a widely applied structural system in China. In the Great 512 Wenchuan Earthquake, buildings in the affected areas were subjected to seismic intensities as high as three to five times the design intensity; numerous confined masonry buildings collapsed, while many others suffered damage. The subsequent comprehensive investigation together with the post-earthquake field studies undertaken by the authors revealed that, inherent strength rather than ductility protected confined masonry buildings from collapse or serious damage, a simple calculation of the inherent strength of masonry buildings is given in this paper. The shortcoming of ductility design approach for low-rise masonry buildings is discussed. It is believed by the authors that the ductility design approach is mistakenly adopted by the Chinese Seismic Design Codes for design of low-rise masonry buildings. Hence, a new assessment and design approach, namely, the inherent strength-based approach is introduced.

1 INTRODUCTION

In the Great Wenchuan Earthquake that occurred on 12 May 2008 in China, more than 216,000 buildings collapsed, including 6898 schools, and countless buildings were damaged to different extents. The total amount of death and missing reached more than 80,000. The recorded peak ground acceleration (PGA) was as high as three to five times the design basic PGA according to the rare earthquake scenario of Chinese seismic design code GB 50011-2001 (National Standard of PRC 2001a).

Confined masonry structures are widely applied in China, especially in the construction of low-rise residential buildings and schools. Although since the 1976 Great Tangshan Earthquake in China, confined masonry structures have been extensively studied, they still suffered widespread collapse or severe damage and cause a huge number of casualties. In Dujiangyan, about 51 % and 18 % of masonry buildings without and with earthquake resistant designs, respectively, collapsed or were seriously damaged (China Earthquake Administration 2008).

In June 2008, the authors reached the affected areas and conducted two post-earthquake field investigations with special attentions paid to the causes of failure of masonry buildings. In this paper, different causes of collapse of masonry buildings are briefly discussed. Most importantly we explain how sufficient lateral strength protected masonry buildings and why ductility failed to protect masonry buildings when the lateral strength was insufficient. The conception of inherent strength is introduced in this paper to represent the actual lateral strength of a building, and a simple calculation of the inherent strength of masonry buildings is given. The inherent strength-based design approach is suggested for seismic design and assessment of low-rise masonry buildings against the rare earthquake.

2 TYPICAL CONFINED MASONRY STRUCTURE

According to the Chinese seismic design code, masonry brickwork is required to be restrained by cast in-situ reinforced concrete (RC) tie-beams and tie-columns. The minimum sizes of the tie-columns and
tie-beams are 240 mm x 180 mm and 120 mm x 180 mm (b x d), respectively. The beams and columns are required to be reinforced by only four longitudinal steel bars (nominal yield strength $f_y \geq 335$ MPa) with diameters of 12 mm. The concrete used should have a cube compressive strength of at least 20 MPa. A typical construction detail of the brick walls, tie-beams, and tie-columns is shown in Figure 1. Horizontal tie-bars (two 6 mm diameter bars, 1 m long at 500 mm vertical spacing) are used to improve the structural integrity between the tie-columns and the brickwork. To further enhance the bonding between the tie-system and the masonry walls, the tie-columns and beams have to be cast after laying the adjacent brickwork.

![Figure 1. A typical construction detail of confined masonry structures.](image)

Various types of brickwork, such as fired clay bricks, fired clay perforated bricks, and small hollow concrete blocks, are commonly used in building construction. The minimum compressive strengths of clay bricks and mortar are 10 MPa and 5 MPa respectively. The floor slab could be cast-in-situ RC slab or precast RC slab.

For a typical confined masonry structure in China, brick walls resist most of the gravity and earthquake loads. Tie-beams and tie-columns are used to enhance the integrity of the structure. To enhance the confinement effect, the Chinese seismic design code requires certain amount of tie-columns to be provided at several important positions as defined in Clauses 7.3 to 7.5, for example, at the four corners of the exterior walls, at intersections of the transverse wall and the exterior longitudinal wall, at both sides of large openings, at the four corners of the staircases and elevator shafts, and so on. Furthermore, the quality of the connections between precast RC structural members is very important to ensure good integrity of the structure, the relevant design requirements are defined in Clause 3.5.5. In this paper, “seismic measures in the Chinese seismic design code” refers to all these requirements for design and construction of confined masonry buildings.

3 CAUSES OF COLLAPSE OF MASONRY BUILDINGS

3.1 Under-prediction of the basic design PGA and under-design of strength

The primary reason for serious damage and widespread collapse of buildings is the substantial under-prediction of the basic design PGA. The basic design PGA and the characteristic period of the affected areas, from the Chinese Seismic Zoning Maps GB18306-2001 (National Standard of PRC 2001b) are shown in Figures 2(a) and 2(b). The PGA values recorded by the China Earthquake Data Centre (http://www.smsd-iem.net.cn/) and Wang (2008a) are shown in Figure 3(a). The recorded PGA in the affected areas ranged from 1.02 m/s$^2$ to 9.57 m/s$^2$.

The inaccuracy of the prediction of the basic design PGA resulted in substantial under-design of the lateral strength of structures. The following discussion will demonstrate that, the inherent strength of the masonry buildings can explain the overall damage of masonry buildings in different regions.
Figure 2. Distributions of (a) basic design PGA and (b) characteristic period in the earthquake affected areas.

Figure 3. Recorded PGA map of the Wenchuan Earthquake.
3.2 **Failing to comply with the seismic measures of the design code**

The field investigations revealed that many precast slabs were directly seated on tie-beams without any mechanical connections. Many buildings constructed in this way suffered extensive damage during the earthquake (see Figures 4). In contrast, many masonry buildings designed and constructed in accordance with the Chinese design code survived in the earthquake, which are evidenced by our field investigations and many other field studies (e.g. Wang 2008b). This contrast shows the effectiveness and importance of the seismic measures in the Chinese seismic design code.

![Figure 4. Building damage (a) collapse of hollow precast slabs and (b) soft-storey failure of masonry building (China Academy of Building Research 2008)](image)

4 **SOME MISUNDERSTANDINGS IN THE DESIGN OF MASONRY BUILDINGS**

4.1 **Typical soft-storey failure mode of masonry buildings**

Previous earthquakes and extensive research (e.g. Fajfar et al. 1997; Dolšek and Fajfar 2000; Su et al. 2008a) have revealed that masonry buildings, even for those designed with high ductility and uniform storey stiffness, create a soft storey at the bottom of the building if the ground motion was strong enough (see Figure 4b). When the strength is inadequate, the deformation of the building will concentrate in the weakest storey and will increase rapidly. Dolšek and Fajfar (2000) demonstrated that, the PGA increasing ratio from the beginning of formation of soft storey to collapse of the structure is very small (e.g. 1.1), which is much smaller than the strength reduction factor \( R \) in a typical ductility design sense. Although it is difficult to determine accurately when a structure collapses, the structure with a soft storey is dangerous enough in a normal design sense. Hence, the non-collapse design of low-rise masonry buildings should make sure that the structure has sufficient lateral strength.

Conversely, a typical ductility failure mode with plastic hinges formed at the beam ends as shown in Figure 5(a) was rarely seen in the earthquake affected areas. In real construction of masonry buildings, beams are often strengthened and stiffened by the adjacent slabs, masonry walls, and other non-structural components. The principle of strong column-weak beam is hard to be implemented in real masonry building constructions. If ductility design is difficult to implement, shall we look for an alternative, such as strength design?

It is well known that strong earthquake loads would generate very high loading and displacement demands on a building. To ensure the building could survive during strong shakings, it should have sufficient lateral strength and lateral deformability. To utilize the entire building to resist the seismic induced loading, a good structural integrity is vitally important. As premature failure (e.g. failures of tie-beams and floor diaphragms as well as out-of-plane dislocation failure of load-bearing masonry walls) occurred before global swaying (see Figure 5b) would lead to brittle partial collapse of buildings, maintaining adequate integrity for masonry buildings are very important in seismic design.
Figure 5. Building deformations (a) a typical ductility failure mode and (b) deformation of a low-rise building

4.2 Multiple seismic defence lines

The effectiveness and importance of the seismic measures in the Chinese seismic design code have been evidenced in the Wenchuan earthquake. However, there are different understandings regarding the real effect of the seismic measures. It was reported by Wang (2008b) that, for masonry structures designed and constructed in accordance with the Chinese design code, tie-columns and tie-beams succeeded acting as the second defence line after the damage of masonry walls. However, one may argue why so many buildings had brittle failure in Dujiangyan and Yingxiu. How could the tie-columns and tie-beams act as the second defence line? The small tie-beams and tie-columns might be too weak to contribute to the resistance of gravity and earthquake loads. We believe that the real effect of the tie-columns and tie-beams system is for restraining infill walls and resisting the tensions generated in the global lateral load structural systems. The tie-system can enhance the integrity of the entire building and effectively avoided brittle or premature failures under cyclic earthquake loads. The restraining frame of tie-columns and tie-beams cannot be considered as the second defence line. Sufficient strength rather than ductility should be considered of the decisive factor in the design of masonry buildings.

5 SEISMIC ASSESSMENT OF CONFINED MASONRY BUILDINGS

5.1 Yield rotation and inherent strength

Given that the building can be deformed globally and premature failures are controlled, the inherent lateral strength of a building is defined as the actual lateral strength which has considered the strengths contributed from both non-structural and structural components. The inherent strength can be calculated at peak loading (or yielding) status of a masonry building. For comparison purposes, response spectral acceleration (RSA) demand and spectrum acceleration capacity $S_a$ of a building which is directly proportional to the inherent lateral strength will be calculated.

Considering a first-mode dominant confined masonry building under seismic attack (See Figure 5b), the structure can be conveniently represented as a single degree of freedom (SDOF) system. For a SDOF structure, the spectral acceleration capacity $S_a$ can be calculated using Equation 1:

$$ S_a = S_d \cdot \left(\frac{2\pi}{T}\right)^2 $$

where $S_d$ is the spectral displacement at peak load of the structure. As the vibration shapes of different first-mode dominant low-rise buildings are very similar under earthquake loads, $S_d$ can be related to the maximum inter-storey drift ratio $\theta_{\text{max}}$ by Equation 2.

$$ S_d = \frac{H_b \theta_{\text{max}}}{\lambda} $$
where $H_b$ is the height of the building and $\lambda$ is the drift factor which has been found to range from 1.6 to 2.9 (Zhu et al. 2007) and may be conservatively taken as 2.5 for seismic assessment purposes.

By substituting Equation 2 into Equation 1, we get Equation 3:

$$S_a = \frac{H_b \cdot \theta_{\text{max}}}{\lambda} \cdot \left(\frac{2\pi}{T}\right)^2$$

(3)

At peak loading condition, $\theta_{\text{max}}$ is just equal to the yield inter-story drift ratio $\theta_y$.

Liang and Chen (2006) reported that the structural period $T$ of masonry structures may be obtained by Equation 4:

$$T = 0.0463\beta H_b / \sqrt{B}$$

(4)

where $B$ is the depth of the building and $\beta$ is the period shift factor which accounts for the effect of period lengthening under strong shakings. As the structural period can be related to the structural stiffness through the well-known relationship ($T = 2\pi\sqrt{M/K}$), the period shift factor can be obtained from the stiffness degradation factors.

There have been extensive experimental studies (e.g. Kwan & Xia 1996; Jin et al. 2001; Zheng et al. 2004; Gao 2007) of the lateral resistance performance of concrete walls with different sizes, configurations and construction measures in China. According to these studies, the yield drift ratio $\theta_y$ is typically ranging from 0.5% to 0.9%, the period shift factor ($\beta$) is found to vary from 1.6 to 2.3.

Assuming $B=12m$, storey height = 4m at ground floor and 2.8m for all other floors, and $\beta=1.9$, the structural period and spectral acceleration capacity of multi-storey buildings were calculated in Table 1. Figure 7 shows the comparison between the inherent strengths, design capacity and the estimated seismic loads (all in terms of spectral accelerations). The design capacity was calculated according to the Chinese seismic design code Clause 5.1.4 and 5.1.5. The results show that, buildings generally have sufficient inherent strength in Chengdu, Deyang and Mianyang while buildings with 3 to 7 storeys in Dujiangyan, Mianzhu and Yingxiu could have insufficient inherent strength.

<table>
<thead>
<tr>
<th>Number of Storeys</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_b$ (m)</td>
<td>6.8</td>
<td>9.6</td>
<td>12.4</td>
<td>15.2</td>
<td>18</td>
<td>20.8</td>
</tr>
<tr>
<td>$T$ (sec)</td>
<td>0.102</td>
<td>0.173</td>
<td>0.245</td>
<td>0.316</td>
<td>0.387</td>
<td>0.458</td>
</tr>
<tr>
<td>$\theta_y=0.5%$</td>
<td>17.9</td>
<td>12.7</td>
<td>9.8</td>
<td>8.0</td>
<td>6.8</td>
<td>5.8</td>
</tr>
<tr>
<td>$\theta_y=0.8%$</td>
<td>28.6</td>
<td>20.2</td>
<td>15.7</td>
<td>12.7</td>
<td>10.8</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Table 1. Evaluation of inherent strength

Figure 6. A comparison between the inherent strengths, design capacity and estimated seismic loads

\[ \text{Figure 6. A comparison between the inherent strengths, design capacity and estimated seismic loads} \]
5.2 Field observations

In our post-earthquake field investigations, we visited the Chengdu and Mianyang urban areas, as well as the Dujiangyan and Yingxiu cities. Our observations broadly agreed with the predicted results. We found that

1) No collapse of buildings were observed in the Chengdu urban area;
2) Only one partial collapse of a 6-storey building was found at Mianyang city;
3) Numerous partial or total collapses of 5- to 6-storey buildings in Dujiangyan; and
4) Widespread collapse of buildings at Yingxiu.

As illustrated in Figure 6, the inherent strength calculations explain our field observations very well. The inherent strength, rather than ductility, protected confined masonry buildings from collapse or serious damage.

5.3 Inherent strength-based design approach

Through the above simple analysis, it is found that inherent strength is vitally important in protecting confined masonry buildings against rare earthquake loads. A new design approach, namely, the inherent strength-based design is introduced for design low-rise confined masonry buildings.

As a new design approach, several major factors influencing the inherent strength are to be further studied. Some general suggestions are given here:

1) Rare earthquake loads should be used to the non-collapse design of low-rise masonry buildings. According to the comparison between inherent strength and the rare earthquake loads, this will not cause too much increase in the construction costs of masonry buildings.

2) Use strong bricks for constructing masonry walls. Accord to the previous studies (e.g. Dolšek and Fajfar 2000), masonry walls contribute much to the strength and stiffness of a structure; change of construction materials of the walls can change the seismic response of the structure to a large extent. By doing so the yield drift ratio of the building can be increased.

3) The seismic measures defined in the Chinese seismic design code are quite effective in ascertaining the required integrity, but not the ductility, of a structure. Nonetheless, tie-column and tie-ring beam systems, and other ductile detailing requirements are still considered to be of vital importance of increasing the yield rotations and hence the inherent strength of a building.

4) Increase the initial stiffness (or reduce the initial period) of buildings by increasing the size of structural members. Compared to Eurocode 8, the minimum sizes of tie-columns and tie-beams specified in the Chinese seismic design code are relatively small.

5) Reduce the period shift factor. This could be achieved by improving the structural integrity and preventing premature failures.

6) Avoid having structural irregularities.

6 CONCLUSIONS

Based on the field studies of the Great Wenchuan Earthquake and the subsequent seismic assessments of masonry buildings, the major findings are summarised as the following:

1) The substantial under-design of strength is the primary reason for the widespread collapse of masonry buildings. For those masonry buildings survived in this earthquake, their inherent strength, rather than their ductility, protected them from collapse.

2) The inherent strength-based approach should be used in the design of low-rise masonry buildings. The ductility design approach is preferable to be used in the design of medium and high-rise buildings.

3) Rare earthquake loads should be used directly in the design of masonry buildings to achieve the objective of “no collapse in rare earthquakes”. As the inherent strength of the buildings constructed
according to the current Chinese seismic code has already been very high, the increase in construction costs is insignificant.

4) The seismic measures stipulated in the Chinese seismic design code are very effective in increasing the strength and integrity of structures and should be strictly followed during design and construction.

5) The major factors influencing the inherent strength and preventing premature failures warrant further studies.

7 ACKNOWLEDGEMENTS

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