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Simplified density indexes of walls and tie-columns for confined masonry buildings in seismic zones

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Abstract

This paper discusses and quantifies the minimum requirements of walls and tie-columns in confined masonry (CM) buildings located in earthquake-prone regions. A research database including 238 damaged CM buildings obtained from the 2008 Wenchuan earthquake survey is established and comprehensively examined. The requirements of masonry walls in CM buildings are discussed, and a simplified tie-column density index is proposed for evaluating the potential damage of the structures. Besides, the minimum requirements of reinforced concrete (RC) tie-columns and their maximum allowable spacing in CM buildings at different seismic intensity zones are discussed.

Keywords: Confined masonry; Simplified indexes; Seismic assessment; Design requirements; Wall density; Spacing of tie-columns; Database of damaged buildings;

1 Introduction

Confined masonry (CM) buildings commonly consist of masonry walls as well as horizontal and vertical reinforced concrete (RC) confining elements, which are widely applied in multi-storey buildings such as inhabitant apartments. The RC confining elements in CM structures are usually constructed after all masonry walls located at the same floor are completed. The most important construction aspect is that the interface edges between masonry wall and tie-column are usually toothed – the so-called “Horse-tooth” in China, as shown in Fig.1. According to the construction experiences in China, and comparing with RC and steel structures, CM is an economical structural type for low-rise buildings and has been widely applied and practiced in other seismic active regions such as Mediterranean Europe, Latin American and Asia for over five decades. Since the RC confining elements can improve the structural ductility and integrity simultaneously, a well-designed and constructed CM building can survive and resist effectively the total collapse of the structure during an earthquake. Figs. 2 and 3 show some representative CM buildings damaged without collapse during the 2008 Wenchuan earthquake.

In China, the first field investigation on the seismic-resistant performance of CM buildings has been reported for the 1966 XingTai earthquake (Richter magnitude scale, Ms=6.8). All inspected CM buildings survived the earthquake without collapse while all inspected unreinforced masonry (URM) buildings had been partially or entirely collapsed. Since that earthquake, CM structures have been increasingly applied in China and their effectiveness in subsequent several large earthquakes such as the 1976 Tangshan earthquake (Ms =7.8) and, more recently the 2008 Wenchuan earthquake (Ms =8.0) and the 2013 Lushan earthquake (Ms =7.0) has been verified (Wei and Xie 1989; Zhang and Sun 1999; Li and Zhao 2008). According to the field survey performed by one of the authors, almost all low-rise CM buildings resisted effectively their collapse during the 2008 Wenchuan earthquake, therefore offered an effective protection for the users and their possessions. On the other hand, the demolition of buildings with severe damage or the alternative of strengthening and rehabilitation after an earthquake is strongly associated with the available time and cost. Therefore, the method to effectively reduce the heavy damage of masonry structures during an earthquake becomes an important challenge nowadays, in particular as the residential demands and construction costs of buildings (and land) increase.

Up to date, the seismic behaviour of confined masonry walls/structures has been widely studied (e.g., Franch et al. 2008, Marques and Lourenço 2013, 2014; Ghorbani et al. 2015; Perez et al. 2015; Medeiros et al. 2013;

Janaraj and Dhanasekar 2014). The wall density significantly affects the seismic performance of masonry structuressuch as in terms of their seismic damage degree and ultimate failure mode. According to previous studies, the wall density of masonry structures positioned in the dominant earthquake direction has been considered as one of the key parameters influencing the seismic performance of CM buildings during an earthquake (e.g., Lourenço and Roque 2006). The index is determined as the total area of masonry walls in the direction divided by the whole floor area. It is accepted that the damage of masonry structures with a higher wall density could be well controlled. Consequently, the provisions regarding the minimum requirements of masonry walls in detail have been specified in various national seismic design codes (e.g., CEN 2005; NCH 2123 2003; GB 50003-2011 2011; NIIT 1991; EEAC 2010; NERERC 2003; NTE E.070 2006). The confining elements in CM buildings and in particular RC tie-columns influence significantly the ductility and structural integrity of masonry structures as well as restrict cracking development and extensive damage to masonry walls. However, due to the fact that confining columns are not typically designed through detailed structural calculations, the details of the elements (i.e., their spacing and arrangement) are dependent on engineers' skills and experiences. As a consequence, a potential risk exists in the CM structures although a good seismic performance is expected. Therefore, it is essential to specify a reasonable spacing of such confining elements in CM structures during a design practice.

To this end, this study discusses the relationship between the actual damage and the density of masonry walls and tie-columns in CM buildings located at Modified Mercalli Intensity Scale (hereafter, seismic intensity) zones VIII to X during the 2008 Wenchuan earthquake. Based on this, the minimum requirements of wall density and design details of RC tie-columns in CM structures are quantified and modelled through a comprehensive analysis of 238 masonry buildings damaged during the earthquake. In addition, a new simplified design parameter for describing the relationship between the used amount of RC tie-columns in CM buildings and their damage degree, called tie-column density is also presented herein.

The results of this field investigation are beneficial to understand the seismic performance of confined masonry structures in earthquake prone zones, as they represent a series of full-scale tests subjected to a real earthquake. This paper also helps to understand the potential damage levels of new and existing CM buildings and realise if some effective remediation could be attained. In summary, this work contributes to the current design and assessment of CM buildings by providing:

(1) simplified methods to quantify the tie-column density in confined masonry buildings;

(2) calibration of the relationship between the damage degree and wall- or tie-column density; and

(3) some recommendations for the current seismic design codes which further promotes the standardisation of CM buildings in earthquake-prone zones.

2 Characteristics and seismic damage classification

2.1 Characteristics of CM structures

Unreinforced masonry (URM) buildings are the oldest structural types for human habitation because of the materials used which are easily available and their low construction cost. On the other hand, the URM structures present congenital deficiencies when they are used in seismic prone regions, which propelled the development of its improved versions, i.e. confined masonry (CM) and reinforced masonry (RM) buildings. CM structures have been applied commonly in many earthquake-prone countries such as Slovenia, India, Chile, and China. In CM structures, horizontal and vertical confining elements are built around masonry walls which are made of masonry units (e.g., bricks and concrete blocks) and mortars. The main vertical confining members, the so-called tie-columns, are usually made of reinforced concrete and connected with the masonry wall through connection reinforcements such as steel bars. These connections are usually implemented using two 500mm length steel rebars (diameter=6mm) spaning between 500mm and 600mm (such as in China). The confining elements are assumed to be integrated into the structural wall. Thus, unlike RC frame beams and columns, these confining members are not explicitly designed via structural design calculations using specific codes of practices. Based on previous experiences and field investigations, the confining elements are still effective in the following aspects: 1) improve the structural integrity and stability of masonry walls in the matters of in-plane and out-of-plane behaviours; 2) confine the deformation of masonry walls and enhance the structural shear resistance; and 3) prevent the brittle damage of masonry walls. Fig. 2 shows a CM structure which has successfully resisted a seismic attack with IX seismic intensity during the 2008 Wenchuan earthquake and survived with some moderated damages at its first storey. Fig. 2 (b) also verifies the positive effect of confining elements on the secondary damage of masonry walls, although shear cracks are still concentrated on the base walls at the first storey of the building. These results present the positive effects of confining elements on the collapse resistance of masonry buildings during an earthquake. This can provide valuable rescue/escape time and space for the users of the buildings.

2.2 Characteristics of the survey database

There is a large number of CM structures which were damaged with different performance loss levels during the 2008 Wenchuan earthquake, even though they did not collapse. The main damage of the buildings, however, usually took place at the first storey level due to the large seismic shearing forces, as shown in Fig. 3. Information gathering of damaged buildings can be extremely important for further studies, and helpful to guide the future design and construction of masonry structures. One of the co-authors of this paper has investigated 238 masonry buildings located at the seismic intensity zones VIII~X during the 2008 Wenchuan earthquake (Su et al. 2014; Xu et al. 2013), as shown in Fig. 4. The earthquake affected more than half of China's geographic area as well as other Asian countries and regions, including Liaoning, Shanghai, Hong Kong, Guangdong and Macao. The surveyed areas mainly included the counties of Qingchuan, Beichuan, Mianzhu, Pengzhou, Dujiangyan, Wenchuan and Emeishan, and the field investigation has focused on masonry structures. As shown in Fig. 4, during the Wenchuan earthquake, the total area of the region with a seismic intensity of higher than VI is 440,442 square kilometres, and is located within the four main provinces of China: Sichuan, Shaanxi, Ningxia, and Gansu. All surveyed masonry buildings have been constructed since the 1970s, and the number of storeys varies from 1 to 7. The used masonry units are solid burnt clay or shale blocks having a standard dimension of 240mm×115mmm×53mm (length×width×height) and an average weight of 26N/unit. The average compressive strength of the used solid bricks is 10N/mm^2 with a standard deviation value of 1.5N/mm^2 and a variation coefficient of 0.15, which was attained by a series of tests per the Chinese test standard GB/T 2542-2012 (2012). The compressive strength of the mortar from the inspected buildings was obtained by the standard methods of mortar rebound and point load (GB/T 50315-2000, 2000). The average compressive strength of the mortar used in the bottom walls of the first floor of the 3 or more storey buildings in the database is 10N/mm^2 (standard deviation value of 1.9N/mm^2 and a variation coefficient of 0.19). For the bottom walls of the first floor of the other types of masonry buildings, the mortar has two levels of compressive strength. One is about 5N/mm^2 (standard deviation value of 0.85 N/mm^2 and variation coefficient of 0.17), and the other one is about 7.5N/mm^2 (a standard deviation value of 1.35 N/mm^2, and a variation coefficient of 0.18). In the inspected CM buildings, tie-columns usually have been arranged at the joint and corner areas of the walls as well as the margins of openings in the walls. They were reinforced by 10mm deformed steel rebars (approximately 235MPa yielding strength) and confined by stirrups (diameter=6mm) with a spacing of 200mm.

As it was reported in previous research (GB/T 24335 2009, 2009), the damage levels of masonry structures depend significantly on the degree of damage of their base walls positioned in the earthquake direction. The damage degree of masonry structures is divided into four levels, i.e., collapse, heavy damage, moderate damage, and slight/no damage, which is defined and listed in Table 1. The amassment of these damages is mainly in accordance with the cracks and damage condition of the base wall pieces – i.e., fine cracks, large cracks, and the collapse of the walls. Fig. 5 depicts several examples of the damage pattern of cracks and collapses.

3 Wall density and existing codes

Wall density is often considered as one of the most significant factors to evaluate the seismic safety of masonry buildings, which was usually used to characterize masonry structures (e.g., Kuroiwa 2002). It represents the area percentage of masonry walls in the whole floor plan area, which can also be interpreted as the effective support area ratio of walls at each floor. This is because masonry walls are still the main load-carrying members in CM structures. The previous earthquake investigations showed that masonry buildings with adequate wall density were able to resist an earthquake without collapse. Referring to the previous studies (Lourenço and Roque 2006; Franch et al. 2008; Lourenço et al. 2013; Meli et al. 2011; Brzev 2007), the wall density in a given direction is calculated as the wall area in the direction divided by the floor area and is expressed as:

$$d_w = \frac{A_w}{A_f} \tag{1}$$

where A_w is the total cross-section areas of the walls in the calculated direction, A_f is the total floor area of the calculated storey. Due to the masonry walls in CM structures are still the main structural load carrying members/systems, in theory, the damage of masonry structures should be reduced when wall density increases, i.e., correlating the wall density per unit floor (d_w/n) with the damage of the masonry buildings during an earthquake. The following equation presents the calculation of the index:

$$d_{wn} = \frac{d_w}{n} = \frac{A_w}{nA_f} \tag{2}$$

where n is the number of storeys of the masonry building.

3.1 Existing code methods

The following sections introduce several national codes which provide specified and quantified recommendations for the wall density index.

3.1.1 Colombia code (EEAC 2010)

Colombian code (EEAC 2010) states that a confined wall to be considered as a structural wall it must be continuous from the foundation to its upper level and cannot have any openings. The minimum strength of units for confined masonry walls must meet specified levels depending on the materials of the units; for instance at least 3MPa for clay hollow block. The minimum requirement of wall density per unit floor in the code is related to the seismic acceleration response and is given by:

$$d_{wn} \geq A_a / 20 \tag{3}$$

where A_a is a coefficient relative to the effective peak acceleration depending on the different earthquake zones in Colombia which vary from 0.1 to 0.5. As a reference model, for the CM buildings in high seismic hazard zones, this study will take A_a as 0.25 to 0.5 as the low and upper bound of the minimum requirement levels of the wall density per unit in the code.

3.1.2 Peruvian code-NTE E.070 (2006)

Peruvian current code states that the requirements of walls in masonry buildings depend significantly on their seismic acceleration response characteristic, the importance of the building and the construction soil condition where the building is. Therefore, the code suggested the minimum wall density of masonry buildings as:

$$d_w \geq \frac{Z.U.S.n}{56} \tag{4}$$

Based on this, the minimum requirement for the wall density per unit floor in masonry buildings is given by:

$$d_w / n \geq ZUS / 56 \tag{5}$$

According to NTE E.030 (2016) in the Peruvian code, the factor ‘Z’ represents the maximum horizontal acceleration of ground with a probability of 10% in the past 50 years and varies at different seismic zones. The factor is expressed as a function of acceleration of gravity and ranges from 0.1-0.45. Therefore, as a reference model for CM buildings in a high seismic hazard zone, this study takes 'Z' factor as 0.22 and 0.45 to calculate the low and upper bounds of the minimum levels of wall density per unit in the code. 'U' is the importance factor of masonry buildings, which is taken as 1.0 for most of common residential and office buildings and as 1.3 for more significant buildings (i.e., Class 2+ and 3 such as cinemas, gyms, and school buildings). The detailed information of other buildings is obtained in the NTE E.030 code. The factor 'S' is related to the construction soil condition of masonry buildings. In the location of the surveyed masonry buildings, the soil layer is dominated by pebbles, whose shear wave velocity is greater than 250m/s. Therefore, the factor '*S*' is taken as 1.0.

3.1.3 Eurocode 8: Allowable number of storeys above ground and minimum area of shear walls

Eurocode 8 (CEN 2004) and section 9.7 defined simple masonry buildings and recommended the allowable number of storeys over ground and required wall areas in two orthogonal directions with a minimum total cross-sectional area A_{min} in each direction for the buildings. The type of masonry buildings in this code has unreinforced masonry, confined masonry and reinforced masonry buildings. Based on Eurocode 8, Table 2 lists the allowable number of storeys (n) and the minimum total cross-sectional area of the horizontal shear walls (as $p_{A,min}$, a percentage of the total floor area per storey) of CM buildings. Referring to the current study, this table also lists minimum cross-sectional area per storey ($p_{A,min}$/n) for to enable a further comparative study. During the 2008 Wenchuan earthquake, the acceleration responses of masonry buildings located at the seismic intensity zones VIII and IX are similar with the acceleration cases of 0.1k.g and 0.2k.g in Eurocode 8, respectively. Therefore, the allowable numbers of storeys of CM buildings in the seismic intensity zones VIII and IX are 3 and 2, respectively. Their average minimum cross-sectional areas per floor of the CM buildings in the two zones are 1.0~1.25% and 1.75%, respectively, depending on their allowable number of storeys.

It should be noted that the summary reported does not consider other important criteria such as geometric requirements, reinforcement and detailing requirements, which must also be taken into account in the practical design of masonry buildings. As shown in Table 2, according to the different allowable number of storeys, the minimum requirement of wall area is obtained. The comparative studies of the present paper consider the difference and discuss the code in terms of the lower-upper bound of the calculated requirement of wall area.

3.2 Relationship between wall density and damage

Using the surveyed buildings in the seismic intensity zones VIII~X of the 2008 Wenchuan earthquake, the relationships between all kinds of damage to the confined masonry buildings and their wall density values are studied and compared respectively, as presented in Figs. 6-8. An obvious distinguishment is presented between these buildings with different damage degree which indicates it is highly feasible to use the wall density index to predict the potential damage of CM structures.

When masonry buildings are located at an earthquake intensity VIII zone, the critical levels of wall density per unit floor of a CM building with heavy damage are less than 1.2%, while the ones of a CM building with moderate damage are less than 1.7%, as shown in Fig. 6. However, the results indicated that the structural damage level to buildings increases with ground motion levels during an earthquake for all CM buildings. This verifies that masonry walls are yet the main seismic-resistant members in CM buildings. For example, for buildings experiencing heavy damage in the seismic intensity IX and X zones, their corresponding critical d_{wn} values increased and reached 2.0% and 2.5% (yellow zones in Fig. 7 and 8), respectively. In summary, the critical d_{wn} values of the CM buildings having moderate damage level are 2.5% and 4.0% in the seismic intensity IX and X zones, respectively (green zones in Fig. 7 and 8). These critical values can be applied for assessing the level of damage that CM buildings can escape during an earthquake. For instance, when a CM building is located at a seismic intensity zone IX but also is arranged more than 2.0% of wall density per unit floor, the potential damage level of the building can be considered as less than the heavy damage listed in Table 1. Meanwhile, as some comparative objects, the results of several URM structures are plotted in the figures as well. Results show that the critical values of d_{wn} of the URM buildings are generally greater than the ones in the CM buildings with same damage degree in the three seismic intensity zones. This means that URM structures need to have a higher number of masonry walls than the ones of CM buildings to resist the same seismic actions.

On the other hand, the results plotted in these three figures also show that a higher wall density per unit floor should be provided for CM buildings which are intended to suffer a lower damage when the buildings are located at same seismic intensity zones. This is normal because a CM building is stronger to resist the shear caused by an earthquake when it is built with more masonry walls. For example, if a CM building was expected to avoid collapsing in the seismic intensity IX zone, it should have at least 1.25% of d_{wn}, however, if the users of the CM building prefer to avoid moderate damage, the building should have more than twice d_{wn}. Besides, there are some buildings which are not able to be classified using the proposed wall density which is attributed to the fact that more RC tie-columns set in these masonry walls largely enhanced the resistance of the CM buildings. In a sense, such RC tie-columns play a very important role in controlling the damage development of masonry walls of CM structures. This indicates a detailed and improved assessment that should be used if more information can be available for the CM buildings, such as the amount and arrangement of tie-columns.

Figs. 6-8 show the minimum requirement zones of each existing code in different seismic zones. According to the plotted results, CM buildings can effectively escape collapse in the seismic intensity zones VIII and IX when the buildings use the minimum wall density values recommended by EC8. But the CM buildings still need to be checked by local provisions and relevant codes. The differences caused by the different allowable storey number above ground are not large in the three seismic zones examined. However, only five CM buildings have been inspected in seismic intensity X zone, thus more filed data and studies are required in the future. According to the Colombian code of practice, the CM buildings can survive in seismic intensity zones VIII and IX when their wall area meet the minimum requirement obtained per the design provision of a small-high seismic hazard (A_a=0.25) as it is given in the code (i.e., the lower limit in Figs. 6 and 7). However, for the confined masonry structures located at the seismic intensity zone X shown in Fig. 8, the higher values are suggested by the codes in an effort to avoid the buildings' collapse. Comparing with other codes, the critical wall area suggested by the Peruvian code is not fit to the design of the CM in China, in particular, in seismic intensity zone IX and X. It is worth to mention that due to the fact that most of the inspected CM buildings reported in this study are geometrically regular and mainly subjected to shear effects without torsion actions, the above calibrations and discussions are mostly applicable to geometrically regular CM buildings such as the ones commonly found countries in China and Chile.

4 Requirements of tie-columns in confined masonry structures

Tie-columns are the main confining elements of masonry walls which can confine the deformation of the wall and prevent effectively the collapse of CM buildings during an earthquake. However, the minimum requirement of the area of tie-column in CM buildings has not been specified yet in many current national codes. Moreover, there are no clear and concrete provisions, except for providing suggestions about the minimum cross-sectional size and the spacing of transversal steel of tie-columns such as the ones used in Chilian, Chinese and Mexican regulations and specifications. Therefore, the procedure to quantify reasonably the minimum requirement of tie-columns is emergent and significant to CM buildings in earthquake-prone zones. On the other hand, a number of studies have clearly illustrated the enhancing influence of tie-column on the seismic performance of masonry buildings, e.g., energy dissipation, structural integrity and resistance capacity of collapse, such as the research conducted by Zhong et al. (1986), Tomaževič and Klemenc (1997) , Jin et al. (2009), Astroza et al. (2012), and Su et al. (2014).

Referring to the wall density defined in Section 3, to clearly specify the required amount of tie-columns in masonry walls, a tie-column density per unit floor index is proposed in the study. The index is suggested as the survey report suggested that the CM buildings with large tie-column density per unit floor presented lower damage. It is worth trying to explore whether the tie-column density per unit floor can be used to assess the seismic behaviour of confined masonry buildings and to quantify the minimum design requirements of tie-columns for structural designers. In case that is feasible, it can be regarded as a beneficial supplement of the wall density index, and provide a complete assessment method for CM structures. Therefore, the tie-column density index is defined in the form of:

$$d_c = \frac{A_c}{A_f} \tag{6}$$

where A_c is the total effective cross-section areas of tie-columns in the seismic direction, as shown in Fig. 9 and A_f is the total plane area of each floor.

The effective calculation area of tie-columns is the total cross-section area of the columns which can provide effective confinement to the masonry walls in the calculation direction. In general, the tie-columns are located at the junctions of two or more walls. Besides, it should be noted that some tie-columns are not included in the calculation of the density index when they cannot confine the wall in the seismic direction. For example, the column A_8 and A_{16} cannot be calculated to the effective area of the tie-columns in the direction x, as shown in Fig. 9.

Analogously, referring to the above wall density, the tie-column density per unit floor of confined masonry structures d_{cn} is proposed, which is expressed as per Eq. 7. This index indirectly presents the confinement level or enhancement ratio of masonry walls regarding supporting CM structures and assisting masonry walls to resist load action.

$$d_{cn} = \frac{A_c}{nA_f} \tag{7}$$

Using the same surveyed confined buildings, the relationships between damage levels and tie-column density per unit floor are calibrated at the seismic intensity zones VIII~X of the same earthquake, respectively. On the other hand, as the number of storeys is one of the most important factors of masonry structures which significantly affects the axial compressive action of a masonry wall, in particular, for base walls. Therefore, the axial compressive load of masonry walls has a significant influence on the seismic performance of masonry structures. A simplified index of axial compression R'_{com} of these masonry walls is introduced herein and defined as:

$$R'_{com} = \frac{\sum W_w}{\left(A_w + A_c\right)} = \frac{G\sum A_f}{\left(A_w + A_c\right)} = \frac{GnA_f}{\left(A_w + A_c\right)} \tag{8}$$

where, G is the self-weight unit area of all masonry walls per floor and is taken as constant (12kN/m^2) according to the Chinese code (GB 50011, 2010). Therefore, the simplified index of axial compression can be modified as R_{com} and is calculated as follows:

$$R_{com} = \frac{\sum A_f}{\left(A_w + A_c\right)} \tag{9}$$

Figs. 10-12 depict the relationship of the simplified axial compression index and tie-column density per unit floor of the masonry buildings located at different seismic intensity zones. Results show that an increasing d_{cn} value has resulted in a decrease of the damage degree of confined masonry buildings. For example, having higher d_{cn} values such as more than 1‰, the confined masonry structures can effectively prevent heavy damages in the seismic intensity zones VIII to X. This does not mean that the use amount of tie-columns does not need to increase when the confined building is built in a stronger earthquake region, as in that case, the building also needs to be designed with more masonry walls. Therefore, it should be emphasised that the requirement of both walls and tie-column densities are important for assessing the seismic resistance and damage of CM structures located in earthquake-prone regions. The results plotted in Figs. 10-12 indicate the positive effect of tie-column on the damage development of masonry wall. On the other hand, the results also verify that while increasing the axial compressive action of a masonry wall, the seismic performance of masonry buildings is reduced, i.e., their damage degree is increased. For example, in the same seismic intensity zone, when using same tie-column density per unit floor, the potential damage levels of the confined buildings change from moderate damage to collapse. According to Fig. 10, even though no tie-column was used in the masonry wall (i.e., single storey URM reference sample), confined buildings with a small axial compressive load of the wall still can effectively resist the earthquake effect without a collapse in the seismic intensity zone VIII.

Meanwhile, on the basis of the relationship between tie-column density per unit floor and the proposed simplified index R_{com} plotted in the Figs. 10-12, the critical levels of tie-column density per unit floor of the confined masonry buildings in different seismic prone zones for controlling their potential damage degree are calibrated. Due to the distribution zone of each level of damage is obviously different, through the simply partition, the proposed critical segmentation interfacial curves are presented in Figs. 10-12 and listed in Table 3. In this table, the critical values corresponding to the level of slight/no damage or collapse are presented. These critical values represent the minimum requirements of d_{cn} values of the CM buildings to control their potential damage under the damages of slight/no damage or collapse. It should be noted that due to the total area of tie-columns which is a lot smaller than the area of the walls, the values of the R_{com} in this table can be attained as approximatively $1/d_{wn}$. The buildings with the first type of damages can be easily repaired after an earthquake, and are called as easily-repaired CM buildings. Thus, when a CM building is designed with the minimum requirement of d_{cn} value, the building is assessed as safe and can be repaired easily. On the other hand, another kind of requirement is used for checking the whole structural safety of masonry structures – the collapse resistance capacity. For CM structures located at seismic intensity VIII zone, no CM building with collapse was reported during the 2008 Wenchuan earthquake. The minimum requirement of d_{cn} value for confined masonry structures corresponding to heavy damage is listed.

5 Discussion of wall and tie-column density

Generally, the relevant provisions for wall density of confined masonry walls have been specified in current codes. This section discusses and analyzes them in depth using the inspected masonry structures. Meanwhile, considering that tie-columns pay a very important role in confined masonry system, this section also includes discussions of tie-column density.

5.1 Proposed wall density for confined masonry building in seismic intensity zones VIII to X

As described previously, the minimum requirement of wall density can be obtained through analysing and calibrating the relationship between the wall density per unit floor d_{wn} and the actual damage degree of the inspected CM buildings during the 2008 Wenchuan earthquake. The detailed minimum requirements of d_{wn} to prevent moderate and larger damage of CM structures located at seismic intensity VIII to X zones are presented in Table 4. It can be seen that the proposed minimum requirements of d_{wn} of confined masonry buildings to avoid large scale post-earthquake repairing work at the seismic intensity VIII~X zones are 1.7% to 4.0%, while the levels are 1.25% to 2.0% to resist the collapse of CM structures, respectively.

5.2 Requirement of tie columns in CM buildings

5.2.1 A simplified approach

The results plotted in Figs. 10-12 show that all proposed minimum requirements of tie-column per unit floor d_{cn} for CM buildings are near to an approximate level of 1.0‰, to control the potential damages of the buildings under slight damage at the earthquake intensity zones VIII to IV. Additionally, the figures show that most of the inspected CM buildings can avoid effectively collapse and heavy damage when their d_{cn} values are greater than 1‰. Therefore, the relationship between the tie-column density d_c and the storey number of CM buildings can be simplified for controlling the post-earthquake damage, by assuming a linear relation. For typical residential CM buildings being up to six storeys, the relationship between the density of tie-columns and the proposed storey number in seismic prone zones is presented in Fig. 14. In this figure, a relative design safety zone for the CM buildings in earthquake-prone zones was suggested, in which confined masonry buildings should have a higher tie-column density and a lower allowable storey number when the structures have sufficient shear masonry walls (e.g., Table 4).

5.2.2 Detailed approach

As previously described, the tie-column density per unit floor is one of the important indexes which can be used to predict the potential damage levels of confined masonry buildings. During practice design and construction works, however, the spacing of tie-columns is usually re-considered and is determined mainly by designers' or engineers' experiences and intuition. Therefore, the detailed requirement of the spacing of tie-columns in CM structures needs to be investigated and discussed further. In order to design a reasonable and reliable spacing of tie-columns in the masonry walls of CM buildings, a simplified coefficient γ is defined which represents the ratio of cross-sectional area of tie-columns to the confined masonry walls, and is given by:

$$\gamma = \frac{d_c/n}{d_w/n} = \frac{d_c}{d_w} \tag{10}$$

As illustrated in Fig. 13, in a confined masonry wall, b_c and h_c are the cross-sectional width and height of tie-column, respectively. L_c is the central spacing between two tie-columns. Therefore, in a confined masonry wall shown in Fig. 13, the coefficient γ of the calculation masonry wall can be established according to Eq. 10 and is shown as:

$$\gamma = \frac{b_c h_c}{L_c t} \tag{11}$$

The spacing of tie-columns in CM buildings herein is shown as:

$$L_c = \frac{b_c h_c}{\gamma t} \tag{12}$$

As tie-column density d_c in masonry buildings is a function of proposed axial compression simplified index, it is calculated according to the recommended minimum requirement of tie-columns corresponding to different damage levels listed in Table 3. The spacing of tie-columns in a masonry wall is expressed as:

$$L_c = \frac{d_w}{d_c t} b_c h_c = \frac{d_w}{f\left(R_{com},\ n\right) t} b_c h_c \tag{13}$$

When the sectional height h_c of tie-column equals to the thickness t of masonry units, the spacing of tie-columns can be simplified as:

$$L_c = \frac{d_w}{d_c} b_c = \frac{d_w}{f\left(R_{com},\ n\right)} b_c \tag{14}$$

5.3 Maximum allowable spacing of tie-columns in CM buildings

From the above analyses, it is found that the spacing of tie-columns is significantly determined by the width of tie-columns and the ratio of the cross-sectional areas of tie-columns to masonry walls. Generally, the pervious experiences indicate that the width, b_c, of tie-columns is equal to the height, h_c, of tie-column. Besides, in many national provisions such as the Chinese design code of masonry structures (GB 50003-2011, 2011), the height of tie-column is usually suggested as the same level as the thickness of masonry wall as shown in Fig 13.

Therefore, the coefficient γ at seismic intensity zones (VIII-X) can be attained from Table 3, for controlling the potential damage of CM buildings. Using this coefficient, the maximum allowable spacing of tie-column in CM buildings can then be calculated when the width of tie-column is specified, such as the commonly used width levels in China are 120, 180, 240 and 370mm.

To simply illustrate the processes and demonstrate a representative application, Fig. 15 presents the detailed calculation results of the spacing of tie-columns through the proposed simple approach. It should be noted that the requirement levels of the spacing of tie-columns mean the maximum allowable spacing of the tie-columns in the confined masonry buildings which can effectively control their post-earthquake damage under easily repairable levels. It should be noticed that the spacing of the structural columns in the paper is only the theoretical minimum requirement for the tie-column. The arrangement of tie-columns in CM structures should also take into account other factors such as the out-of-plane failure and the ratio of the height of masonry wall to a thickness of masonry units. In general, the maximum spacing of tie-columns is set at the spacing between 4m and 5m.

Fig. 15 depicts that the spacing of tie-columns is affected largely by their width and seismic density in the earthquake direction. When the CM building is located at a higher intensity earthquake zone, the maximum allowable spacing levels of tie-columns in the masonry walls increase as the seismic intensity levels. This is attributed the fact that when CM building is at a higher seismic intensity zone, the minimum requirement of wall density also increases as the seismic intensity which might result in the spacing of tie-columns needs to increase. This indicates again that both the wall and proposed tie-column densities are important to assess the structural safety of confined masonry structures during an earthquake. Additionally, there is an obvious increase in the spacing of tie-columns as the cross-sectional width of the columns increases. According to the construction experience in China, since the thickness of bearing masonry walls (GB 50011-2010, 2010) was usually recommended as 240mm, the allowable spacing of tie-columns in masonry walls when CM buildings are built at seismic intensity zones VIII to X results to be 2.6m, 4.8m, and 6.0m, respectively.

6. Concluding remarks and limitations

Masonry structures are commonly used for the multi-storey residential buildings in many developing countries such China and Chile. Though confining elements have a significant influence on the seismic performance of masonry structures, their detailed requirements are not widely provided by the current design codes. Through analyses reported in this study, some conclusions are drawn. It should be noted that due to the characteristics of the inspected CM building samples reported in the study, the conclusions and results presented in the current paper are more applicable for China. However, they can also be utilised as a useful reference to several countries where multi-storey CM buildings with regular geometrical features exist such as in Chile, Peru, Slovenia and India.

In the present study, the relationships between wall density per unit floor d_{wn} and the damage levels of CM buildings are discussed for structures located at the earthquake intensity zones VIII~X during an actual earthquake, the 2008 Wenchuan earthquake. The reported CM buildings include more than 200 single to multi-story masonry buildings with/without tie-columns built from the 1970s to 1990s. Based on the analysis and comparison, the detailed requirements of wall density per unit floor in CM structures located in different seismic zones are provided.

(1). The study shows that to control the same level damage at higher seismic intensity earthquake zones or to better control damages at the same earthquake zone, a higher wall density per unit floor should be provided for CM buildings. However, when more RC tie-columns are used in CM buildings, the potential damage of CM buildings cannot be assessed using the proposed wall density for the confining elements largely enhanced the resistance of the masonry walls.

(2). According to the current study, the minimum requirements of wall density per unit floor of confined masonry buildings to avoid large scale post-earthquake repair works in seismic intensity zones VIII~X are proposed from 1.7% to 4.0%, while the proposed levels to resist the collapse of CM structures are 1.25% to 2.0%.

(3). Some URM structures are discussed as comparative masonry structures, an important finding can be acquired that the critical values of d_{wn} of the URM buildings are greater than the ones in the CM buildings in order to control same damage degree. This means that URM structures need to be designed with more walls to resist seismic effects in the seismic intensity zones VIII to X, compared with the ones in CM buildings.

This paper also proposes a tie-column density per unit floor d_{cn} to discuss the seismic safety of CM building and provides critical values to control different post-earthquake damage levels in the structures. According to the tie-column density, the maximum allowable spacing of these tie-columns in masonry walls positioned in the earthquake direction can be attained as follows.

(1) By introducing a simplified index related to axial compressive of masonry walls, R_{com}, the relationship between the index and the tie-column density per unit floor d_{cn} of the CM buildings located at different seismic intensity zones has been quantized. Results show that an increasing d_{cn} has resulted in a decrease in the damage degree of confined masonry buildings. This does not mean that the use amount of tie-columns does not need to increase when the confined building is constructed in a stronger earthquake region, as in that case, the building also needs to be designed having more masonry walls.

(2) The axial compression action of masonry wall has a significant influence on the seismic performance of the masonry structures. A higher axial compression will result in a heavier damage in masonry structures. Similarly, even though no tie-columns were set in a masonry wall (i.e., single storey URM reference samples), the confined buildings with a small axial compression of the wall can still effectively resist earthquake effects without a collapse in the seismic intensity zone VIII.

(3) Based on the relationship between the index R_{com} and the tie-column density per unit floor d_{cn}, the study proposed the critical levels of d_{cn} of the confined masonry buildings in different seismic prone zones for controlling their potential damage degree. The proposal is helpful to estimate the capacity of CM buildings to resist slight/no damage or collapse in the three aforementioned seismic intensity zones.

(4) This study proposes a simplified approach to quantify the critical levels of d_{cn} of the CM buildings with up to six storeys. In general, when the density, d_{cn}, is greater than 0.001, the confining members can effectively reduce the damage of CM buildings and control the damages under an easily repairable level when they are built at the seismic intensity zones VIII to X and meet the proposed minimum wall density requirement.

(5) To provide a simplified design procedure of tie-columns in CM building, a simplified confinement ratio of tie columns γ is proposed and is defined as the ratio of cross-sectional area of the tie-column to the confined masonry walls. Employing this ratio, the maximum allowable spacing of the tie-column in CM buildings can be provided when the width of the tie-column is specified. For example, the maximum allowable spacing levels of tie-columns are 2.64m, 4.8m, and 6.0m for CM buildings at seismic intensity zones VIII, IX and X when 240mm masonry walls are used in the structures, respectively.

Since most of the inspected CM buildings reported in the study are geometrically regular such as the ones in China and Chile and mainly subjected to shear effects without torsion actions, the above analyses and discussions are mostly applicable to geometrically regular CM buildings. Meanwhile, based on the discussion reported here, it should be emphasised that the requirement of wall and tie-column densities is of paramount importance for the seismic resistant design of CM structures located in earthquake-prone regions.

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Lists of figures and tables

Fig.1 Tie columns in masonry buildings

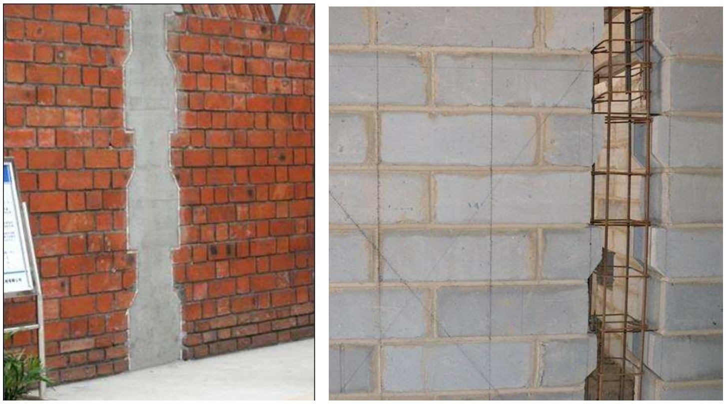


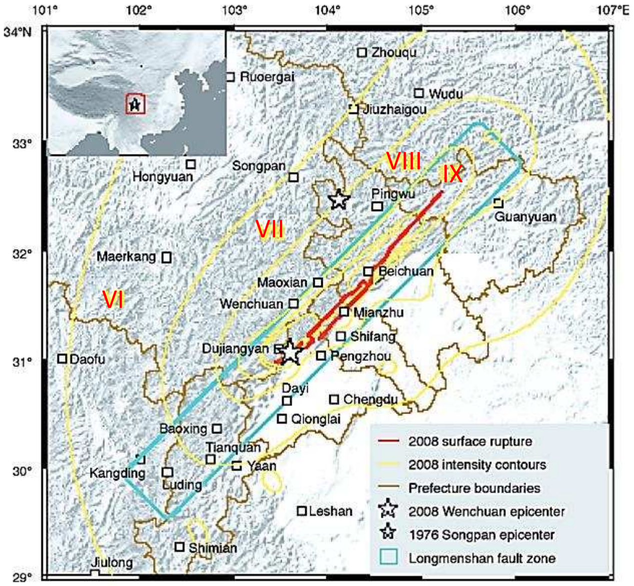
Fig.2 Wall damage of CM structures (Dujianyan, seismic intensity IX)

(a) Global view of CM building (b) Crack patter in the masonry building

Fig.3 Collapse resistance of CM structures (Beichuan, seismic intensity IV+)

(a) CM structures-1 (b) CM structures-2

Fig.4 Earthquake intensity and damage distribution of the 12 May 2008 Wenchuan earthquake



Map of the region affected by the 2008 Wenchuan earthquake.
Issued by China Earthquake Administration (CEA) in 2008 and modified by Xu et al. (2008) and Chen et al. (2010). (the figure is from Cheng and Booth 2011)

Earthquake intensity levels vs. PGA in Chinese code GB50011-2010 (2010)

Earthquake Intensity	Horizontal Peak Ground Acceleration (PGA) (cm/s^2)
VI	50
VII	100-150
VIII	200-300
IX	>400

Areas of the different intensity zones (in km^2)

XI: 2419; X: 3144;
IX: 7738; VIII: 27786;
VII: 84449; VI: 314906;

Fig.5 Damage states of wall pieces

(a) Fine crack on wall piece (b) Large crack on wall piece

(c) Severe cracks on wall piece (d) Wall piece broken and extroversion

Fig.6 Relationship of wall density per unit floor between damage at seismic intensity VIII

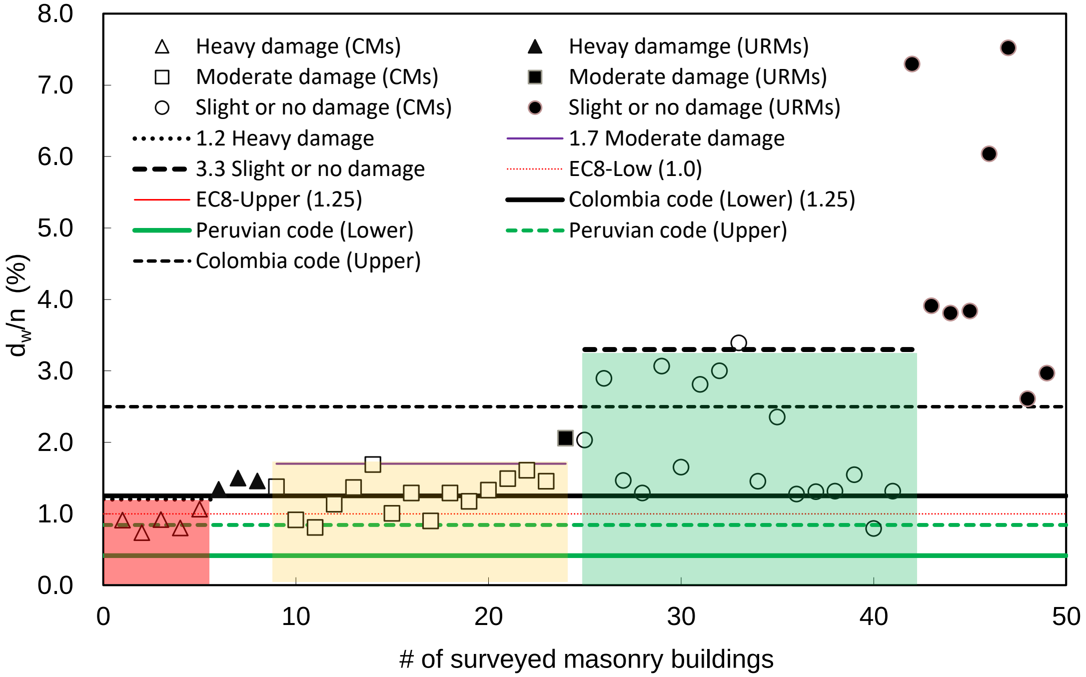
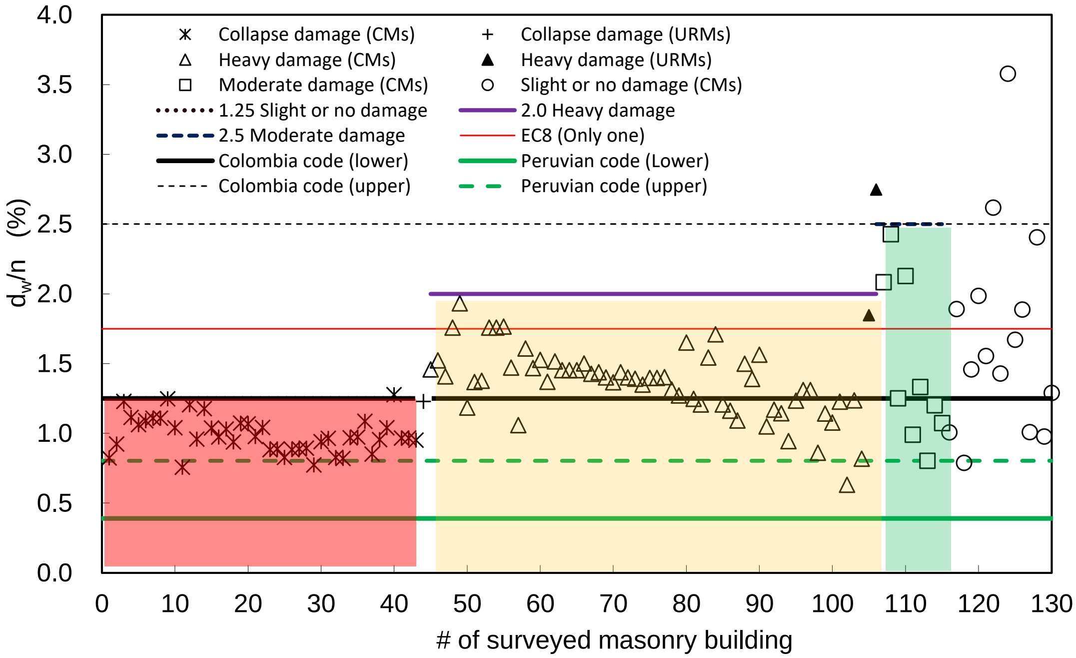


Fig.7 Relationship of wall density per unit floor value between damage at seismic intensity IX



626 **Fig.8 Relationship of wall density per unit floor between damage at seismic intensity X**

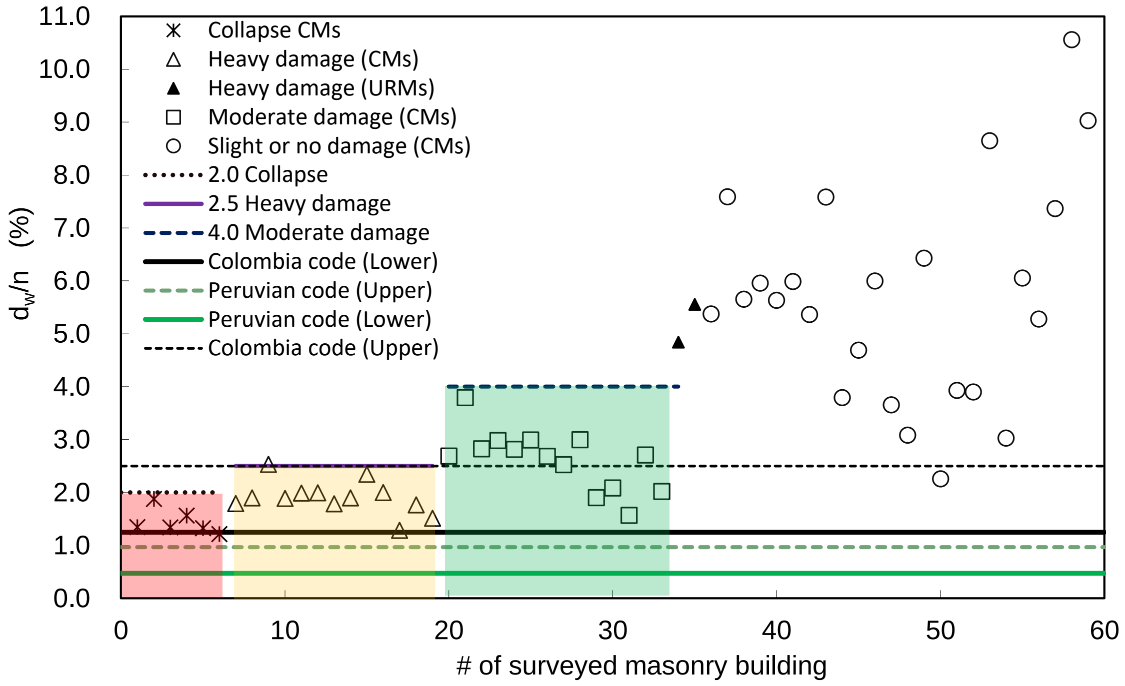


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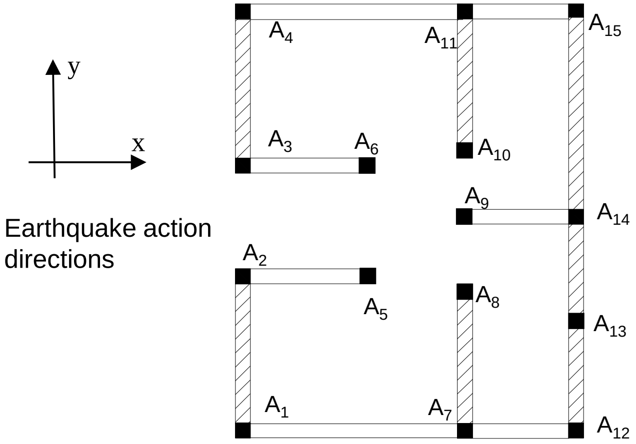
Fig.9 Calculation areas of tie columns for the tie-column density



Effective walls at direction x: ▭
Effective walls at direction y: ▨

Effective tie columns:

Direction x	Direction y
A_1, A_7, A_{12}, A_2, A_5, A_9, A_{14}, A_3, A_6, A_4, A_{11}, A_{15}	A_1, A_2, A_3, A_4, A_7, A_8, A_{10}, A_{11}, A_{12}, A_{13}, A_{14}, A_{15}

Fig.10 Relationship between tie column density per unit floor and damage categories at seismic intensity VIII

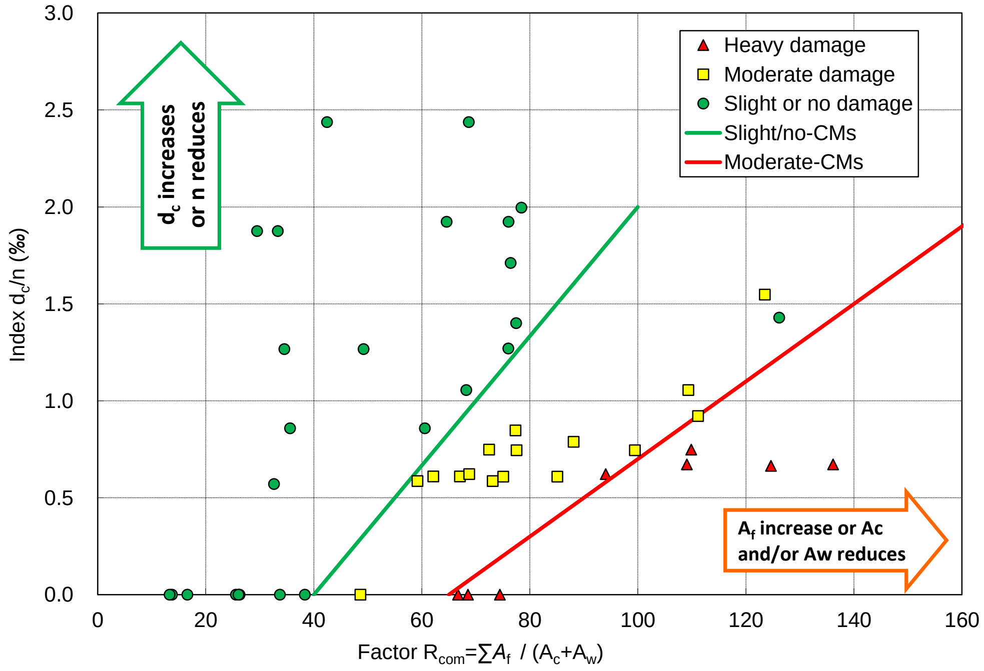


Fig.11 Relationship between tie column density per unit floor and damage categories at seismic intensity IX

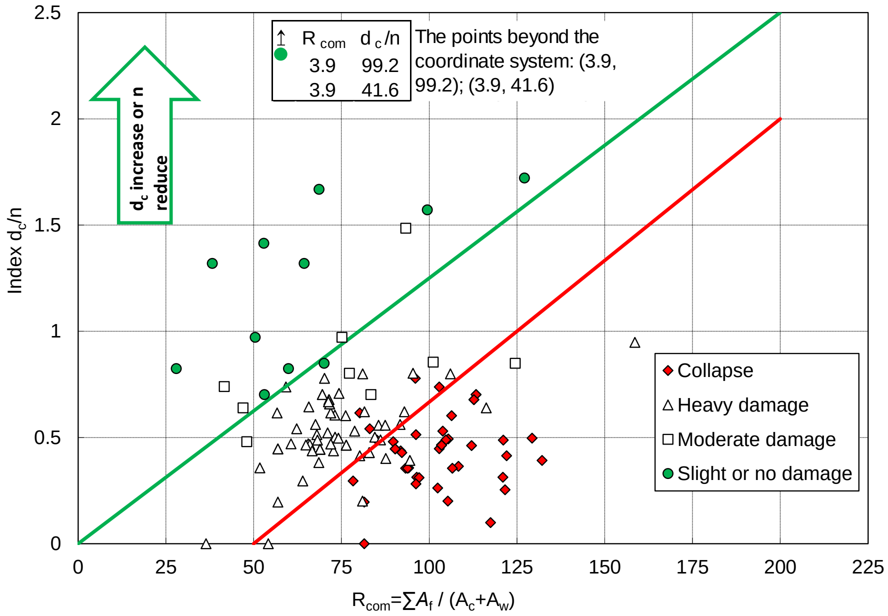


Fig.12 Relationship between tie column density per unit floor and damage categories at seismic intensity X

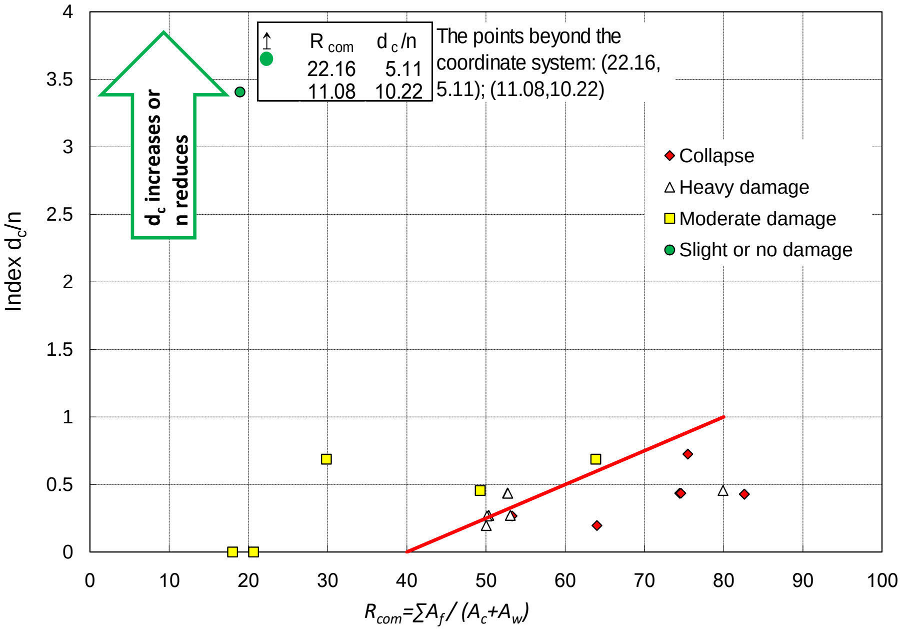


Fig.13 Definition of confined ratio of masonry wall

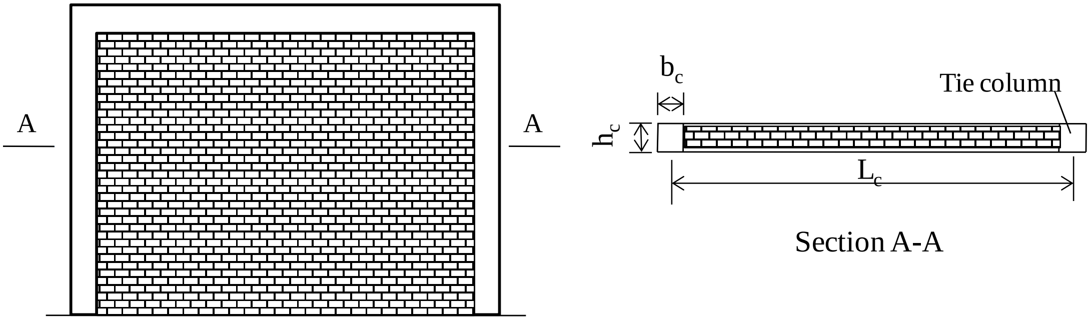


Fig.14A simplified approach for the minimum requirements for tie columns in CM buildings

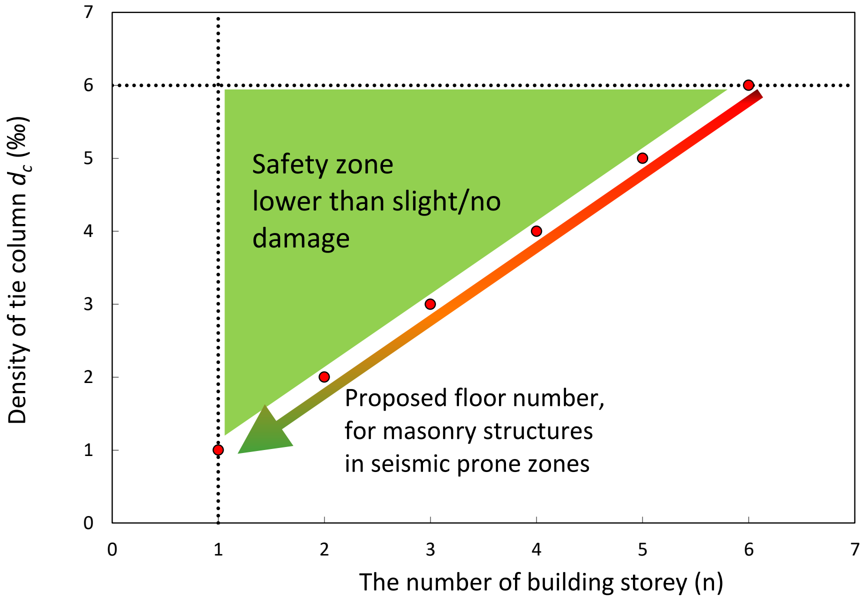


Fig.15 Maximum allowable spacing of tie column in CM building at seismic intensity zones VIII~X

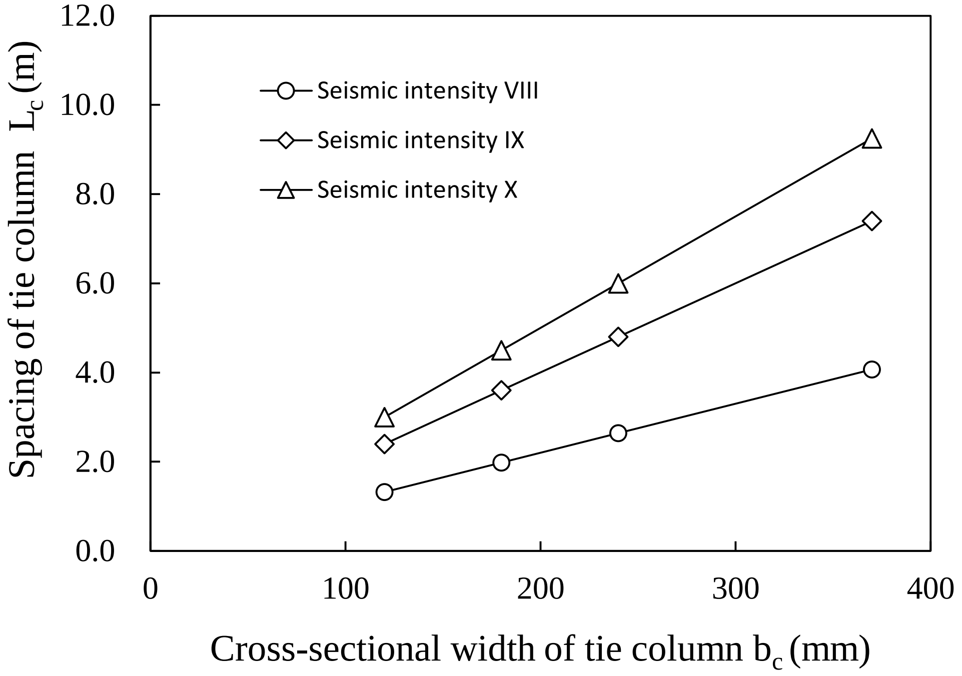


Table.1 Damage categories and treatment suggestions post-earthquake of masonry structure

Damage categories	Damage description: Cracking and collapse	Treatments and measures
Slight or no damage	No obvious damage occurs in any wall pieces; or the number of the wall pieces with small cracks is less than 50% of all wall pieces in the seismic direction;	Small-scale repair such as surface repair
Moderate damage	The number of the wall pieces with small cracks is more than 50% of the total walls in the seismic direction; or the number of the wall pieces with large cracks is less than 50% of the total wall; or the number of wall pieces with severe cracks under 10% of the total one;	Large-scale repair including partial reconstruction;
Heavy damage	The number of wall pieces with large cracks is more than 50% of all wall pieces in the seismic direction; or the number of wall pieces having either severe cracks range from 10% to 50% of the total walls in the seismic direction;	Total/partial reconstruction;
Collapse	The number of wall pieces having the severe cracks, broken or collapse is more than 50% of the total walls in the seismic direction; or total collapse of building structure;	Total demolition and reconstruction

Table.2 Eurocode 8 allowable number of storeys and minimum average cross-sectional area for confined masonry buildings

Acceleration levels	≤0.07k.g (%)		≤0.1k.g (%)		≤0.15k.g (%)		≤0.2k.g (%)	
**Storey #	$p_{A,min}$	$p_{A,min}/n$	$p_{A,min}$	$p_{A,min}/n$	$p_{A,min}$	$p_{A,min}/n$	$p_{A,min}$	$p_{A,min}/n$
2	2.00	1.00	2.50	1.25	3.00	1.50	3.50	1.75
3	2.00	0.67	3.00	1.00	4.00	1.33	N/A	N/A
4	4.00	1.00	5.00	1.25	N/A	N/A	N/A	N/A
5	6.00	1.20	N/A*	N/A	N/A	N/A	N/A	N/A
Intensity in Wenchuan Earthq.	VII		VIII		-		IX	

*N/A: Not acceptable;

**Roof space above full storeys is not included in the number of storeys;

Table.3 Minimum requirement of tie columns in confined masonry buildings

Seismic intensity zones	Damage levels	Minimum requirement of tie columns (d_{cn}) (‰)	Remarks
VIII	Slight or no damage	(R_{com}-40)/30	In CM structures, due to $A_c \ll A_w$, so $R_{com} \approx 1/d_{wn}$; In case d_{wn} has been specified, d_{cn} can be attained easily.
	Heavy damage	(R_{com}-65)/50	
IX	Slight or no damage	(R_{com})/80	
	Collapse	(R_{com}-50)/75	
X	Slight or no damage	—	
	Collapse	(R_{com}-40)/40	

Table.4 Minimum requirement of wall density per unit floor d_{wn} to prevent damage of CM buildings

No.	Seismic intensity	Proposed critical values of wall density per unit floor		
		Collapse	Heavy damage	Moderate damage
1	VIII	N/G*	1.10%	1.70%
2	IV	1.25%	2.00%	2.50%
3	X	2.00%	2.50%	4.00%

*N/G means the value is not gained, for no collapsed CM building was reported in the seismic intensity VIII zone of the Wenchuan earthquake.