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**Citation:** Cai, G., Su, Q., Tsavdaridis, K. D. & Degée, H. (2020). Simplified Density Indexes of Walls and Tie-Columns for Confined Masonry Buildings in Seismic Zones. *Journal of Earthquake Engineering*, 24(3), pp. 447-469. doi: 10.1080/13632469.2018.1453396

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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;

## 24 **1 Introduction**

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

37

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

51

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

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

70

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

78

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

- 84 (1) simplified methods to quantify the tie-column density in confined masonry buildings;  
85 (2) calibration of the relationship between the damage degree and wall- or tie-column density; and  
86 (3) some recommendations for the current seismic design codes which further promotes the standardisation of  
87 CM buildings in earthquake-prone zones.

## 88 **2 Characteristics and seismic damage classification**

### 89 **2.1 Characteristics of CM structures**

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

## 112 2.2 Characteristics of the survey database

113 There is a large number of CM structures which were damaged with different performance loss levels during the  
114 2008 Wenchuan earthquake, even though they did not collapse. The main damage of the buildings, however,  
115 usually took place at the first storey level due to the large seismic shearing forces, as shown in Fig. 3.  
116 Information gathering of damaged buildings can be extremely important for further studies, and helpful to guide  
117 the future design and construction of masonry structures. One of the co-authors of this paper has investigated  
118 238 masonry buildings located at the seismic intensity zones VIII~X during the 2008 Wenchuan earthquake (Su  
119 et al. 2014; Xu et al. 2013), as shown in Fig. 4. The earthquake affected more than half of China's geographic  
120 area as well as other Asian countries and regions, including Liaoning, Shanghai, Hong Kong, Guangdong and  
121 Macao. The surveyed areas mainly included the counties of Qingchuan, Beichuan, Mianzhu, Pengzhou,  
122 Dujiangyan, Wenchuan and Emeishan, and the field investigation has focused on masonry structures. As shown  
123 in Fig. 4, during the Wenchuan earthquake, the total area of the region with a seismic intensity of higher than VI  
124 is 440,442 square kilometres, and is located within the four main provinces of China: Sichuan, Shaanxi, Ningxia,  
125 and Gansu. All surveyed masonry buildings have been constructed since the 1970s, and the number of storeys  
126 varies from 1 to 7. The used masonry units are solid burnt clay or shale blocks having a standard dimension of  
127 240mm×115mm×53mm (length×width×height) and an average weight of 26N/unit. The average compressive  
128 strength of the used solid bricks is 10N/mm<sup>2</sup> with a standard deviation value of 1.5N/mm<sup>2</sup> and a variation  
129 coefficient of 0.15, which was attained by a series of tests per the Chinese test standard GB/T 2542-2012 (2012).  
130 The compressive strength of the mortar from the inspected buildings was obtained by the standard methods of  
131 mortar rebound and point load (GB/T 50315-2000, 2000). The average compressive strength of the mortar used  
132 in the bottom walls of the first floor of the 3 or more storey buildings in the database is 10N/mm<sup>2</sup> (standard  
133 deviation value of 1.9N/mm<sup>2</sup> and a variation coefficient of 0.19). For the bottom walls of the first floor of the  
134 other types of masonry buildings, the mortar has two levels of compressive strength. One is about 5N/mm<sup>2</sup>  
135 (standard deviation value of 0.85 N/mm<sup>2</sup> and variation coefficient of 0.17), and the other one is about 7.5N/mm<sup>2</sup>  
136 (a standard deviation value of 1.35 N/mm<sup>2</sup>, and a variation coefficient of 0.18). In the inspected CM buildings,  
137 tie-columns usually have been arranged at the joint and corner areas of the walls as well as the margins of  
138 openings in the walls. They were reinforced by 10mm deformed steel rebars (approximately 235MPa yielding  
139 strength) and confined by stirrups (diameter=6mm) with a spacing of 200mm.

140

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

### 147 **3 Wall density and existing codes**

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

$$156 \quad d_w = \frac{A_w}{A_f} \quad (1)$$

157 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  
158 calculated storey. Due to the masonry walls in CM structures are still the main structural load carrying  
159 members/systems, in theory, the damage of masonry structures should be reduced when wall density increases,  
160 i.e., correlating the wall density per unit floor ( $d_w/n$ ) with the damage of the masonry buildings during an  
161 earthquake. The following equation presents the calculation of the index:

$$162 \quad d_{wn} = \frac{d_w}{n} = \frac{A_w}{nA_f} \quad (2)$$

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

164 **3.1 Existing code methods**

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

167 **3.1.1 Colombia code (EEAC 2010)**

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

173 
$$d_{wn} \geq A_a / 20 \tag{3}$$

174 where  $A_a$  is a coefficient relative to the effective peak acceleration depending on the different earthquake zones  
175 in Colombia which vary from 0.1 to 0.5. As a reference model, for the CM buildings in high seismic hazard  
176 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  
177 wall density per unit in the code.

178 **3.1.2 Peruvian code-NTE E.070 (2006)**

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

182 
$$d_w \geq \frac{Z.U.S.n}{56} \tag{4}$$

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

184 
$$d_w / n \geq ZUS / 56 \tag{5}$$

185 According to NTE E.030 (2016) in the Peruvian code, the factor 'Z' represents the maximum horizontal  
186 acceleration of ground with a probability of 10% in the past 50 years and varies at different seismic zones. The  
187 factor is expressed as a function of acceleration of gravity and ranges from 0.1-0.45. Therefore, as a reference

188 model for CM buildings in a high seismic hazard zone, this study takes ‘Z’ factor as 0.22 and 0.45 to calculate  
189 the low and upper bounds of the minimum levels of wall density per unit in the code. ‘U’ is the importance  
190 factor of masonry buildings, which is taken as 1.0 for most of common residential and office buildings and as 1.3  
191 for more significant buildings (i.e., Class 2+ and 3 such as cinemas, gyms, and school buildings). The detailed  
192 information of other buildings is obtained in the NTE E.030 code. The factor ‘S’ is related to the construction  
193 soil condition of masonry buildings. In the location of the surveyed masonry buildings, the soil layer is  
194 dominated by pebbles, whose shear wave velocity is greater than 250m/s. Therefore, the factor ‘S’ is taken as  
195 1.0.

### 196 **3.1.3 Eurocode 8: Allowable number of storeys above ground and minimum area of shear walls**

197 Eurocode 8 (CEN 2004) and section 9.7 defined simple masonry buildings and recommended the allowable  
198 number of storeys over ground and required wall areas in two orthogonal directions with a minimum total cross-  
199 sectional area  $A_{\min}$  in each direction for the buildings. The type of masonry buildings in this code has  
200 unreinforced masonry, confined masonry and reinforced masonry buildings. Based on Eurocode 8, Table 2 lists  
201 the allowable number of storeys (n) and the minimum total cross-sectional area of the horizontal shear walls (as  
202  $p_{A,\min}$ , a percentage of the total floor area per storey) of CM buildings. Referring to the current study, this table  
203 also lists minimum cross-sectional area per storey ( $p_{A,\min}/n$ ) for to enable a further comparative study. During the  
204 2008 Wenchuan earthquake, the acceleration responses of masonry buildings located at the seismic intensity  
205 zones VIII and IX are similar with the acceleration cases of 0.1k.g and 0.2k.g in Eurocode 8, respectively.  
206 Therefore, the allowable numbers of storeys of CM buildings in the seismic intensity zones VIII and IX are 3  
207 and 2, respectively. Their average minimum cross-sectional areas per floor of the CM buildings in the two zones  
208 are 1.0~1.25% and 1.75%, respectively, depending on their allowable number of storeys.

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

214

215

### 216 3.2 Relationship between wall density and damage

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

222

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

239

240 On the other hand, the results plotted in these three figures also show that a higher wall density per unit floor  
241 should be provided for CM buildings which are intended to suffer a lower damage when the buildings are  
242 located at same seismic intensity zones. This is normal because a CM building is stronger to resist the shear  
243 caused by an earthquake when it is built with more masonry walls. For example, if a CM building was expected  
244 to avoid collapsing in the seismic intensity IX zone, it should have at least 1.25% of  $d_{wn}$ , however, if the users of  
245 the CM building prefer to avoid moderate damage, the building should have more than twice  $d_{wn}$ . Besides, there

246 are some buildings which are not able to be classified using the proposed wall density which is attributed to the  
247 fact that more RC tie-columns set in these masonry walls largely enhanced the resistance of the CM buildings. In  
248 a sense, such RC tie-columns play a very important role in controlling the damage development of masonry  
249 walls of CM structures. This indicates a detailed and improved assessment that should be used if more  
250 information can be available for the CM buildings, such as the amount and arrangement of tie-columns.

251

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

#### 268 **4 Requirements of tie-columns in confined masonry structures**

269 Tie-columns are the main confining elements of masonry walls which can confine the deformation of the wall  
270 and prevent effectively the collapse of CM buildings during an earthquake. However, the minimum requirement  
271 of the area of tie-column in CM buildings has not been specified yet in many current national codes. Moreover,  
272 there are no clear and concrete provisions, except for providing suggestions about the minimum cross-sectional  
273 size and the spacing of transversal steel of tie-columns such as the ones used in Chilean, Chinese and Mexican

274 regulations and specifications. Therefore, the procedure to quantify reasonably the minimum requirement of tie-  
275 columns is emergent and significant to CM buildings in earthquake-prone zones. On the other hand, a number of  
276 studies have clearly illustrated the enhancing influence of tie-column on the seismic performance of masonry  
277 buildings, e.g., energy dissipation, structural integrity and resistance capacity of collapse, such as the research  
278 conducted by Zhong et al. (1986), Tomažević and Klemenc (1997) , Jin et al. (2009), Astroza et al. (2012), and  
279 Su et al. (2014).

280

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

$$289 \quad d_c = \frac{A_c}{A_f} \quad (6)$$

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

292

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

299

300 Analogously, referring to the above wall density, the tie-column density per unit floor of confined masonry  
301 structures  $d_{cn}$  is proposed, which is expressed as per Eq. 7. This index indirectly presents the confinement level

302 or enhancement ratio of masonry walls regarding supporting CM structures and assisting masonry walls to resist  
303 load action.

$$304 \quad d_{cn} = \frac{A_c}{nA_f} \quad (7)$$

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

$$311 \quad R'_{com} = \frac{\sum W_w}{(A_w + A_c)} = \frac{G \sum A_f}{(A_w + A_c)} = \frac{GnA_f}{(A_w + A_c)} \quad (8)$$

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

$$315 \quad R_{com} = \frac{\sum A_f}{(A_w + A_c)} \quad (9)$$

316 Figs. 10-12 depict the relationship of the simplified axial compression index and tie-column density per unit  
317 floor of the masonry buildings located at different seismic intensity zones. Results show that an increasing  $d_{cn}$   
318 value has resulted in a decrease of the damage degree of confined masonry buildings. For example, having  
319 higher  $d_{cn}$  values such as more than 1‰, the confined masonry structures can effectively prevent heavy damages  
320 in the seismic intensity zones VIII to X. This does not mean that the use amount of tie-columns does not need to  
321 increase when the confined building is built in a stronger earthquake region, as in that case, the building also  
322 needs to be designed with more masonry walls. Therefore, it should be emphasised that the requirement of both  
323 walls and tie-column densities are important for assessing the seismic resistance and damage of CM structures  
324 located in earthquake-prone regions. The results plotted in Figs. 10-12 indicate the positive effect of tie-column  
325 on the damage development of masonry wall. On the other hand, the results also verify that while increasing the  
326 axial compressive action of a masonry wall, the seismic performance of masonry buildings is reduced, i.e., their  
327 damage degree is increased. For example, in the same seismic intensity zone, when using same tie-column

328 density per unit floor, the potential damage levels of the confined buildings change from moderate damage to  
329 collapse. According to Fig. 10, even though no tie-column was used in the masonry wall (i.e., single storey URM  
330 reference sample), confined buildings with a small axial compressive load of the wall still can effectively resist  
331 the earthquake effect without a collapse in the seismic intensity zone VIII.

332

333 Meanwhile, on the basis of the relationship between tie-column density per unit floor and the proposed  
334 simplified index  $R_{com}$  plotted in the Figs. 10-12, the critical levels of tie-column density per unit floor of the  
335 confined masonry buildings in different seismic prone zones for controlling their potential damage degree are  
336 calibrated. Due to the distribution zone of each level of damage is obviously different, through the simply  
337 partition, the proposed critical segmentation interfacial curves are presented in Figs. 10-12 and listed in Table 3.  
338 In this table, the critical values corresponding to the level of slight/no damage or collapse are presented. These  
339 critical values represent the minimum requirements of  $d_{cn}$  values of the CM buildings to control their potential  
340 damage under the damages of slight/no damage or collapse. It should be noted that due to the total area of tie-  
341 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  
342 approximatively  $1/d_{wn}$ . The buildings with the first type of damages can be easily repaired after an earthquake,  
343 and are called as easily-repaired CM buildings. Thus, when a CM building is designed with the minimum  
344 requirement of  $d_{cn}$  value, the building is assessed as safe and can be repaired easily. On the other hand, another  
345 kind of requirement is used for checking the whole structural safety of masonry structures – the collapse  
346 resistance capacity. For CM structures located at seismic intensity VIII zone, no CM building with collapse was  
347 reported during the 2008 Wenchuan earthquake. The minimum requirement of  $d_{cn}$  value for confined masonry  
348 structures corresponding to heavy damage is listed.

## 349 **5 Discussion of wall and tie-column density**

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

## 354 **5.1 Proposed wall density for confined masonry building in seismic intensity zones VIII to X**

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

## 362 **5.2 Requirement of tie columns in CM buildings**

### 363 **5.2.1 A simplified approach**

364 The results plotted in Figs. 10-12 show that all proposed minimum requirements of tie-column per unit floor  $d_{cn}$   
365 for CM buildings are near to an approximate level of 1.0‰, to control the potential damages of the buildings  
366 under slight damage at the earthquake intensity zones VIII to IV. Additionally, the figures show that most of the  
367 inspected CM buildings can avoid effectively collapse and heavy damage when their  $d_{cn}$  values are greater than  
368 1‰. Therefore, the relationship between the tie-column density  $d_c$  and the storey number of CM buildings can be  
369 simplified for controlling the post-earthquake damage, by assuming a linear relation. For typical residential CM  
370 buildings being up to six storeys, the relationship between the density of tie-columns and the proposed storey  
371 number in seismic prone zones is presented in Fig. 14. In this figure, a relative design safety zone for the CM  
372 buildings in earthquake-prone zones was suggested, in which confined masonry buildings should have a higher  
373 tie-column density and a lower allowable storey number when the structures have sufficient shear masonry walls  
374 (e.g., Table 4).

### 375 **5.2.2 Detailed approach**

376 As previously described, the tie-column density per unit floor is one of the important indexes which can be used  
377 to predict the potential damage levels of confined masonry buildings. During practice design and construction  
378 works, however, the spacing of tie-columns is usually re-considered and is determined mainly by designers' or  
379 engineers' experiences and intuition. Therefore, the detailed requirement of the spacing of tie-columns in CM  
380 structures needs to be investigated and discussed further. In order to design a reasonable and reliable spacing of

381 tie-columns in the masonry walls of CM buildings, a simplified coefficient  $\gamma$  is defined which represents the ratio  
 382 of cross-sectional area of tie-columns to the confined masonry walls, and is given by:

$$383 \quad \gamma = \frac{d_c/n}{d_w/n} = \frac{d_c}{d_w} \quad (10)$$

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

$$388 \quad \gamma = \frac{b_c h_c}{L_c t} \quad (11)$$

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

$$390 \quad L_c = \frac{b_c h_c}{\gamma t} \quad (12)$$

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

$$394 \quad L_c = \frac{d_w}{d_c t} b_c h_c = \frac{d_w}{f(R_{com}, n) t} b_c h_c \quad (13)$$

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

$$397 \quad L_c = \frac{d_w}{d_c} b_c = \frac{d_w}{f(R_{com}, n)} b_c \quad (14)$$

398

### 399 **5.3 Maximum allowable spacing of tie-columns in CM buildings**

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

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

409

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

419

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

## 431 **6. Concluding remarks and limitations**

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

440

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

447

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

453 (2). According to the current study, the minimum requirements of wall density per unit floor of confined  
454 masonry buildings to avoid large scale post-earthquake repair works in seismic intensity zones VIII~X are  
455 proposed from 1.7% to 4.0%, while the proposed levels to resist the collapse of CM structures are 1.25% to  
456 2.0%.

457 (3). Some URM structures are discussed as comparative masonry structures, an important finding can be  
458 acquired that the critical values of  $d_{wn}$  of the URM buildings are greater than the ones in the CM buildings  
459 in order to control same damage degree. This means that URM structures need to be designed with more

460 walls to resist seismic effects in the seismic intensity zones VIII to X, compared with the ones in CM  
461 buildings.

462

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

467

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

474

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

480

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

485

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

490

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

497

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

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580

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599

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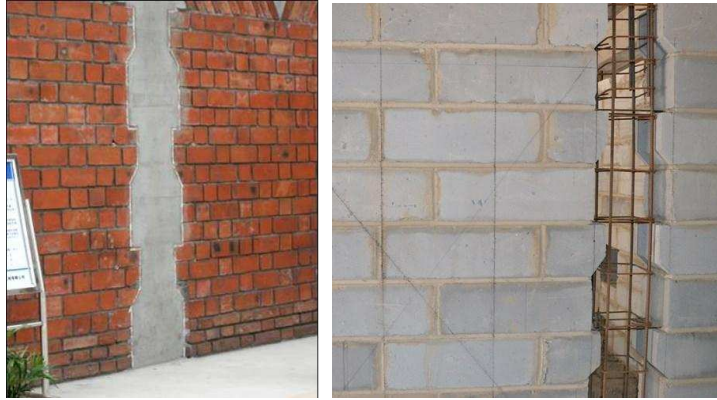
603 Table.3 Minimum requirement of tie columns in confined masonry buildings

604 Table.4 Minimum requirement of  $d_w/n$  to prevent damage of CM buildings

605

606

607 **Fig.1 Tie columns in masonry buildings**



608

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



(a) Global view of CM building



(b) Crack patter in the masonry building

610

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



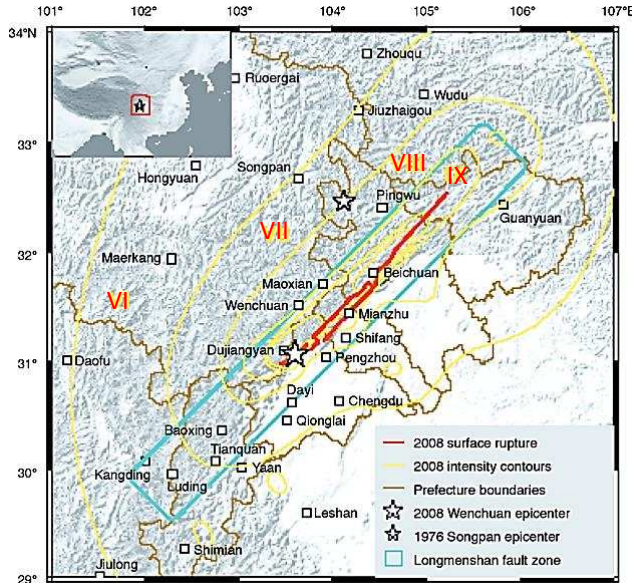
(a) CM structures-1



(b) CM structures-2

612

613 **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)

614

615

616 **Fig.5 Damage states of wall pieces**



(a) Fine crack on wall piece



(b) Large crack on wall piece

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

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

Areas of the different intensity zones (in km<sup>2</sup>)

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



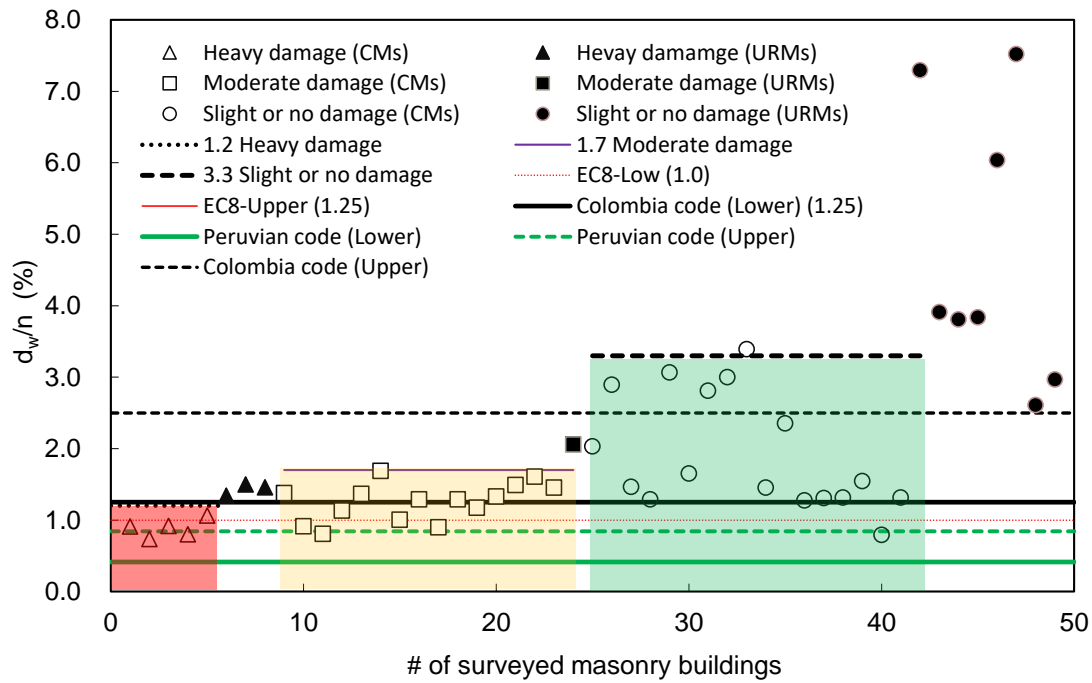
(c) Severe cracks on wall piece



(d) Wall piece broken and extroversion

617

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

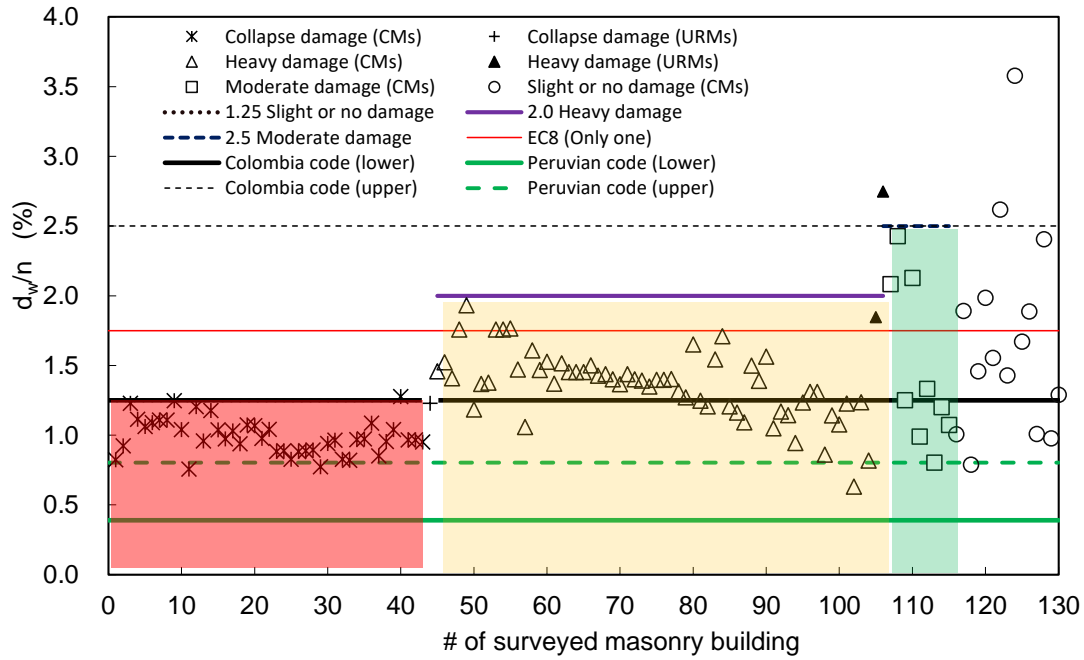


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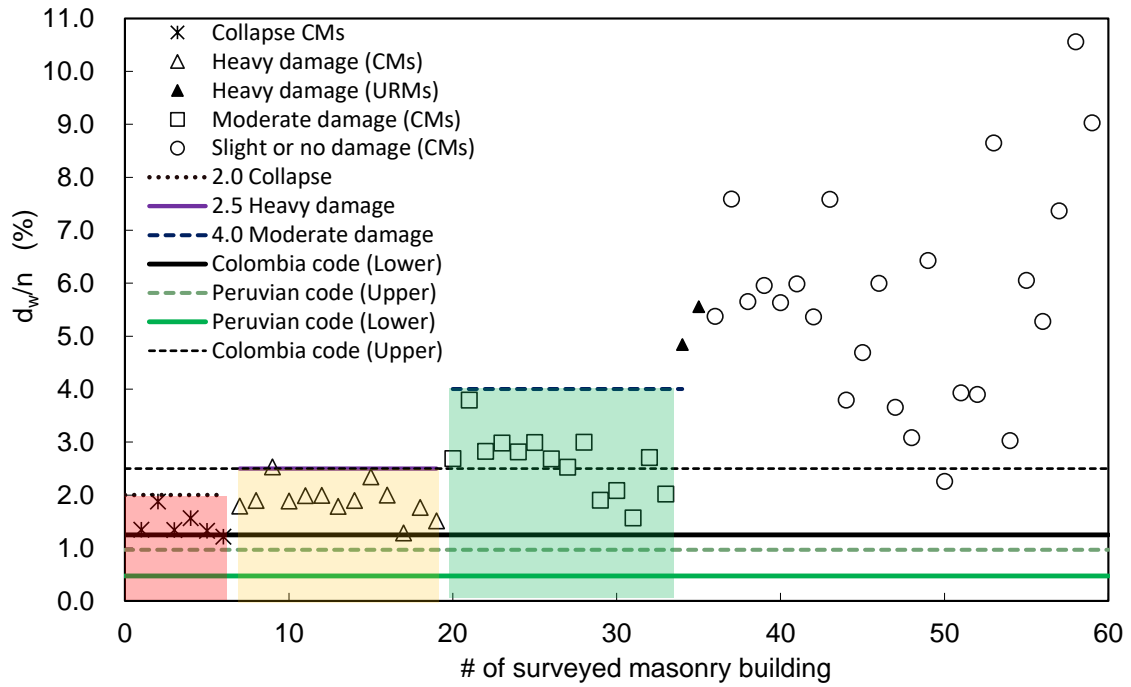
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622 **Fig.7 Relationship of wall density per unit floor value between damage at seismic intensity IX**



623  
624  
625

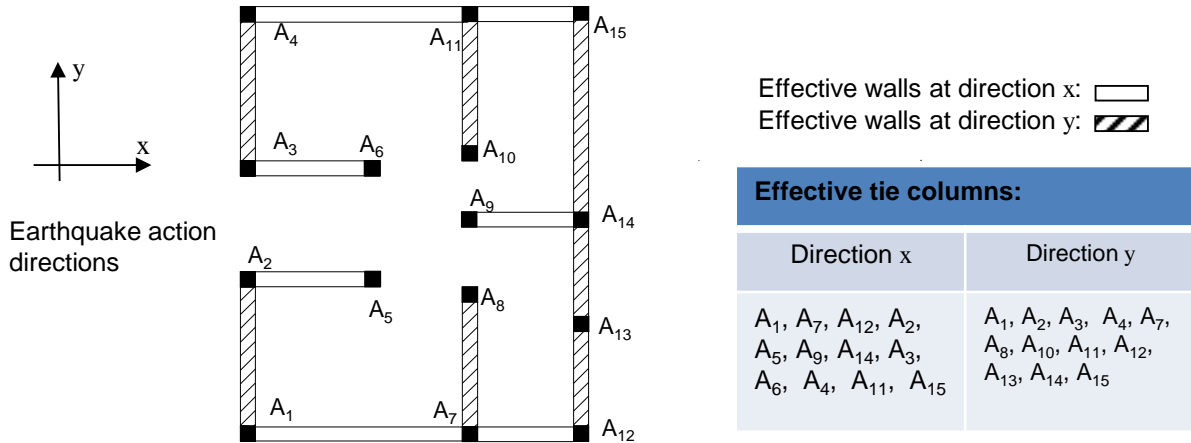
626 **Fig.8 Relationship of wall density per unit floor between damage at seismic intensity X**



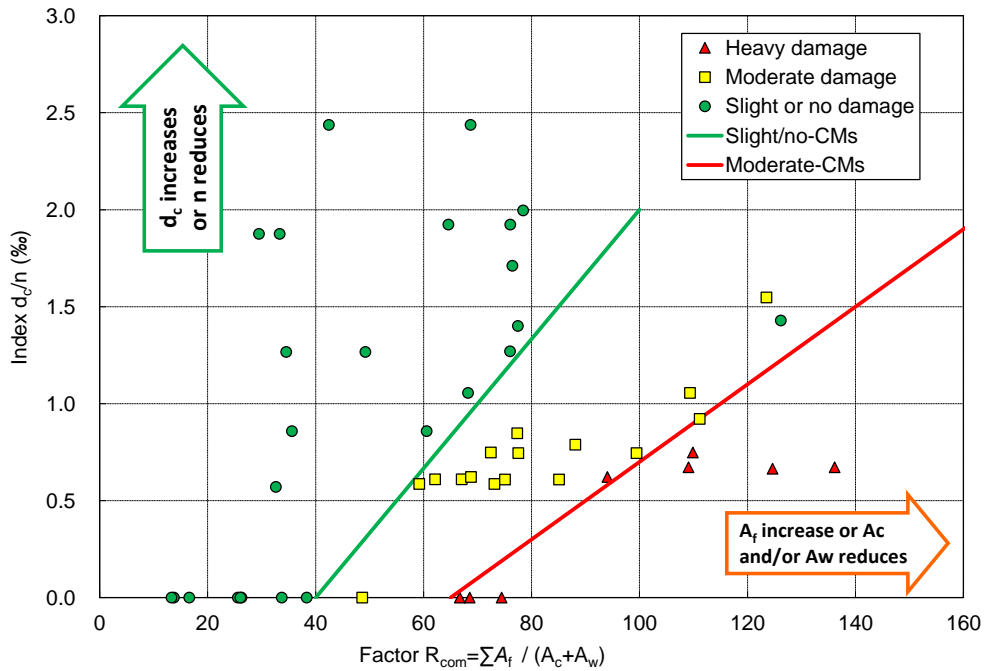
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629  
 630 **Fig.9 Calculation areas of tie columns for the tie-column density**  
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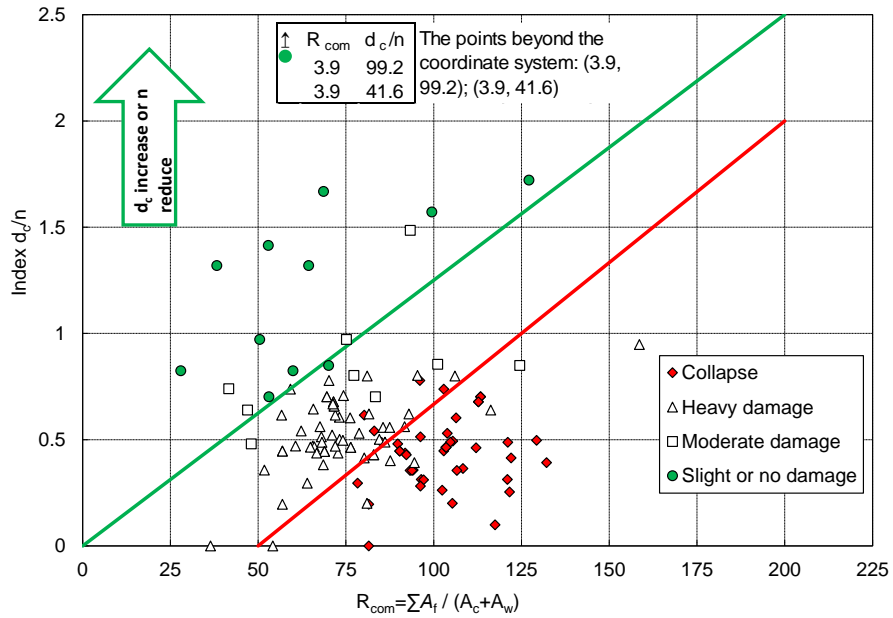


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 634 **Fig.10 Relationship between tie column density per unit floor and damage categories at seismic intensity VIII**



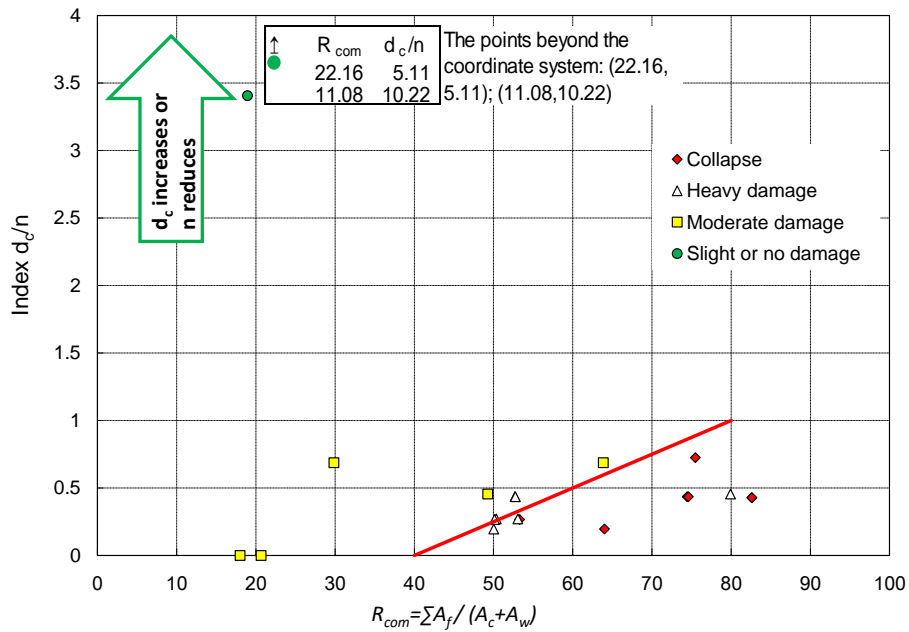
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636 Fig.11 Relationship between tie column density per unit floor and damage categories at seismic intensity IX



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

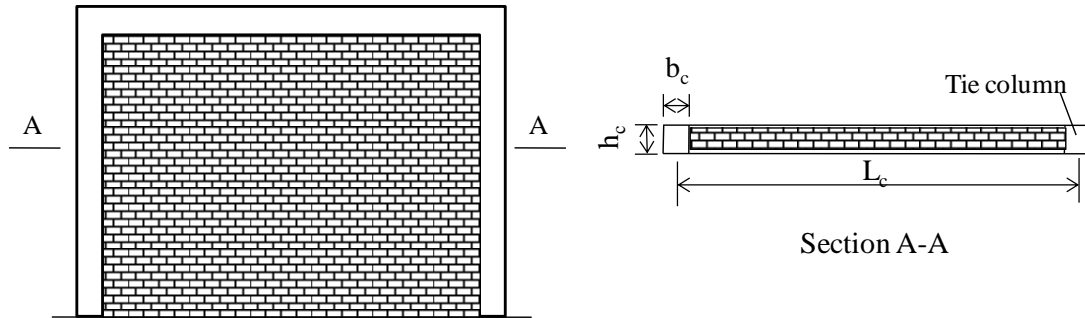


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641 **Fig.13 Definition of confined ratio of masonry wall**

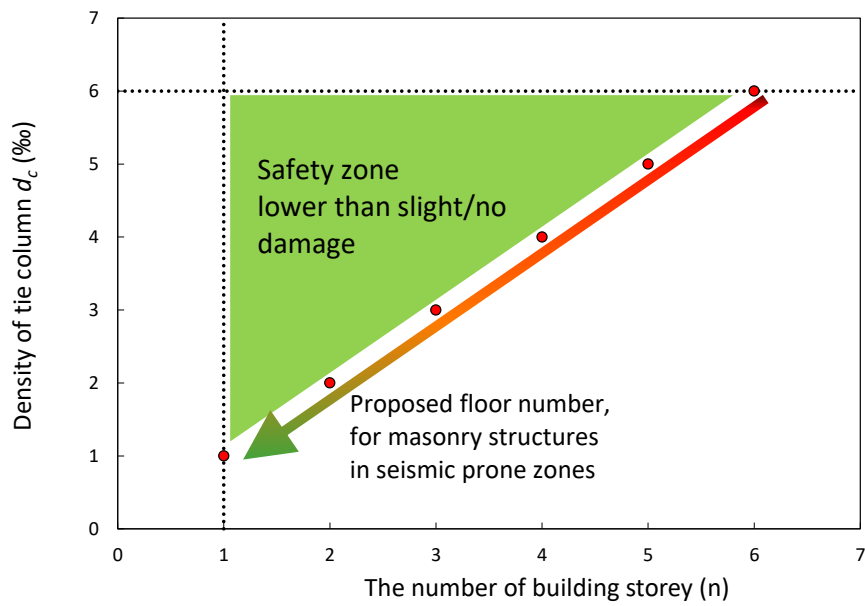
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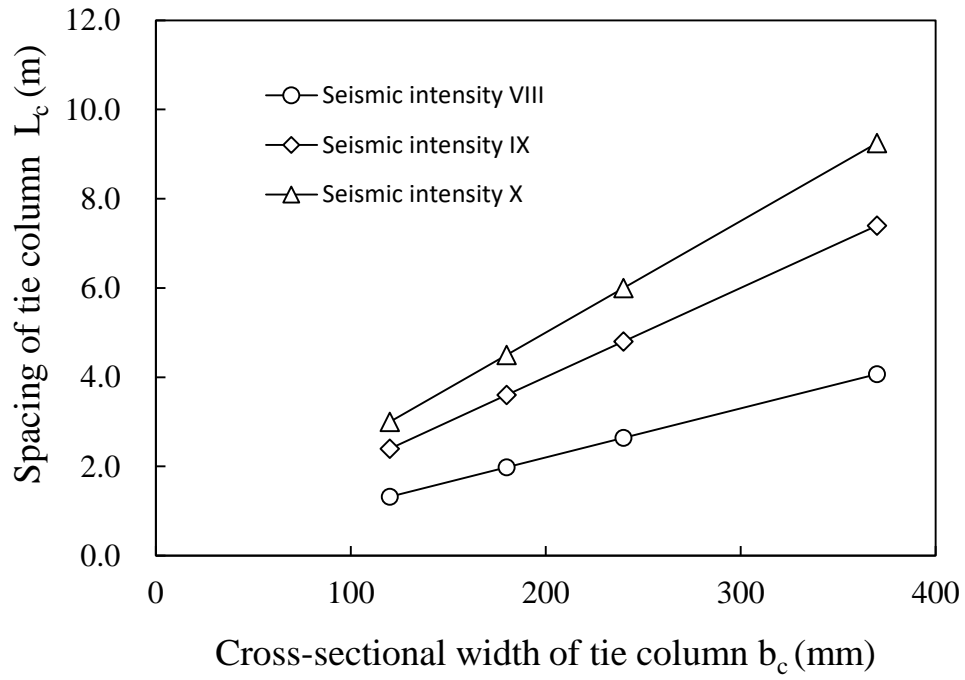
645 **Fig.14A simplified approach for the minimum requirements for tie columns in CM buildings**



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



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

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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

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

Acceleration levels **Storey #	≤0.07k.g (%)		≤0.1k.g (%)		≤0.15k.g (%)		≤0.2k.g (%)	
	$\rho_{A,min}$	$\rho_{A,min}/n$	$\rho_{A,min}$	$\rho_{A,min}/n$	$\rho_{A,min}$	$\rho_{A,min}/n$	$\rho_{A,min}$	$\rho_{A,min}/n$
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;

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

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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	$(R_{com}-40)/40$	

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

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