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ORIGINAL PAPER

Seismic intensity map and typical structural damage of 2010 Ms 7.1 Yushu earthquake in China

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Abstract On April 14, 2010, a devastating Ms 7.1 earthquake occurred in Yushu, China. In the most severely struck area of Jiegu Town, approximately 94 % of the structures were damaged. A seismic intensity map was obtained based on field investigation data of structural damage in 63 residential areas, and the differences in structural damage in four intensity regions were quantitatively compared using a seismic capacity index and a damage index. The typical damage for five types of structures in the epicentral area of Jiegu Town was described and summarized in detail. Some recommendations for improving seismic capacity of buildings are provided; they include avoiding mountainous topography, non-uniform materials, and irregular layouts, as well as considering an appropriate arrangement of structural columns and belt courses for hollow concrete block and brick masonry structures. This paper provides valuable information for structural seismic design, post-earthquake reconstruction, and related work.

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1 Introduction

On April 14, 2010, at 7:49 a.m. (Beijing Time), an Ms 7.1 earthquake, with its epicenter located in the village of Rima, struck Yushu County, Qinghai Province, in the western part of China. Through strike-slip faulting in the tectonically complex region of the eastern Qinghai–Tibetan Plateau, the earthquake was one of the most devastating earthquakes in the history of the region, with damage extending over a distance of several hundred kilometers from its epicenter, according to the Catalogue of Chinese Historical Strong Earthquakes (The Earthquake Disaster Prevention Department of China Earthquake Administration 1995). Figure 1 shows the epicenter of the main shock as well as distributions of the aftershocks (M $\geq$ 3.0) and surface ruptures (CENC 2010). The earthquake affected 27 cities in seven counties: Yushu, Chengduo, Zhiduo, Zaduo, Nangqian, Qumalai, and Shiqu (MLR 2010), and caused a significant number of casualties, including 2,698 dead, 270 missing, and 12,135 injured (Xinhua News Agency 2010). The most severely damaged area was in Jiegu Town, Yushu County, that experienced a seismic intensity level of IX on the Chinese Seismic Intensity Scale (GB/T 17742-2008). In Jiegu, more than 94 % of the buildings were damaged to various degrees because of the low seismic resistance of buildings and locations near the fault rupture.

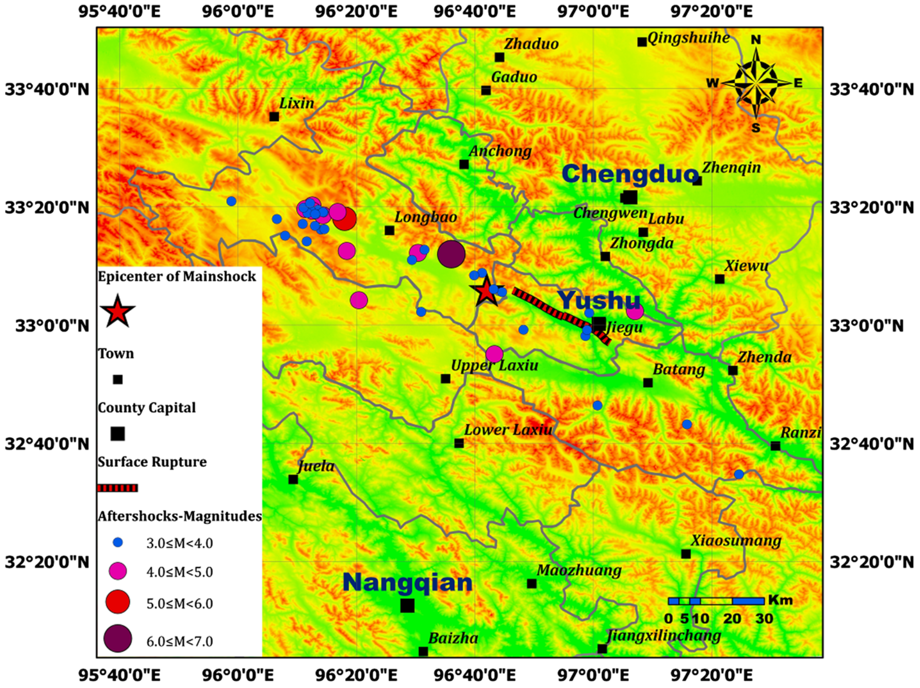


Fig. 1 The epicentral area of the 2010 Yushu earthquake

Immediately after the earthquake, the Institute of Engineering Mechanics (IEM) of the China Earthquake Administration (CEA) sent a team of experts and graduate students to the affected area to study its effects. Over a period of 20 days, the team investigated the earthquake disaster with respect to seismic intensity distribution, structural damage, casualty numbers, and infrastructure damage and developed a seismic intensity map of the Yushu earthquake based on data collected from 1,539 buildings in 63 residential areas. Moreover, after the investigation of 5,394 buildings in Jiegu Town, the typical damage mechanisms of various types of structures were identified and categorized in detail. The lessons learned from this exercise and the advices with respect to improving the seismic capacity of buildings are summarized herein.

2 Seismic intensity survey

The latest version of the Chinese Seismic Intensity Scale (GB/T 17742-2008) was issued in 2008 after the Wenchuan earthquake. Compared with earlier versions of the Chinese Seismic Intensity Scale (Liu 1980; GB/T 17742-1999), the 2008 version had two significant changes: (1) The evaluation of seismic density now refers to damage to three types of buildings: Type A: adobe, stone, or brick houses with wooden trusses; Type B: single- or multi-story brick masonry buildings not reflecting earthquake-resistant design; and Type C: single- or multi-story brick masonry buildings reflecting earthquake-resistant design of Seismic Fortification Intensity VII under the Code for Seismic Design of Buildings (GB50011-2010); and (2) the evaluation criteria for intensity grades VI, VII, and VIII are now slightly higher. The 2008 version of the Chinese Seismic Intensity Scale resembles the Modified Mercalli Intensity (MMI) Scale (Wood and Neumann 1931) in terms of its evaluation criteria, while the evaluation criteria for intensity grades VI, VII, VIII, and IX are slightly lower than those of the European Macroseismic Scale (Grünthal et al. 1998; Li 2010).

A total of 1,539 buildings in 63 residential areas were investigated to determine the earthquake disaster distribution in terms of the damage ratio within each sample area. Table 1 lists five grades of structural damage (none, slight, moderate, extensive, and

Table 1 Damage grades and descriptions for structural damage survey (GB/T 17742-2008 2008)

Code	Damage Grade	Reparability	Description
ND(1)	None	No need	No damage to structural and non-structural elements, or very slight damage to few non-structural elements, reusable without repair
SD(2)	Slight	Yes	Few fine cracks in a few structural elements, or visible cracks in non-structural elements, reusable either without repair or after simple repair
MD(3)	Moderate	Yes	Minor cracks on the majority of structural elements, or heavy damage to non-structural elements, reusable after general repair
ED(4)	Extensive	Difficult	Heavy damage to the majority of structural elements, extensive large cracks in structural elements, or partial collapse in non-structural elements, very difficult to repair
CD(5)	Complete	No	Very heavy damage to the majority of structural elements, partial or total collapse of the building, incapable of repair

complete damage) and gives a description of each one. Most of the surveyed buildings are one- and two-story adobe and stone structures constructed without considering the effects of possible earthquakes. Referring to the 2008 version of the Chinese Seismic Intensity Scale (GB/T 17742-2008), the survey results yield the seismic intensity map shown by the solid lines in Fig. 2.

The earthquake area is located on the Qinghai–Tibetan Plateau at an average altitude of about 4,200 meters. This is a low population density region occupied mainly by nomadic people who have settled there in recent decades. Most of the sampled villages (except for the larger towns) are very small. The number of buildings differs significantly from village to village, with some villages having only a few households while others have dozens of households. Facing these difficult challenges, the survey team made a great effort to strengthen the quality of the survey by enlarging the sample size and improving survey precision in terms of achieving better agreement between the survey results and the actual earthquake disaster.

By integrating the structural damage and local residents' perceptions and responses in 63 residential areas, a surveyed seismic intensity map (SSIM) was developed and is indicated by solid lines in Fig. 2. Moreover, the contours of SSIM were interpolated from the sample points by following an elliptical shape, the general shape of the intensity contours in earthquakes. Figure 2 shows that the areas of intensity regions VI, VII, VIII, and IX are 12,470, 4,197, 1,106, and 227 km^2, respectively. For comparison, the temporary seismic intensity map (TSIM) (IEM 2011) for emergency and disaster rescue management is also shown by dashed lines in Fig. 2. Based on high-intensity investigation as well as specialists' experiences after the earthquake, the TSIM for determining the distribution of relief supplies and rescue teams was immediately produced. A comparison of the SSIM

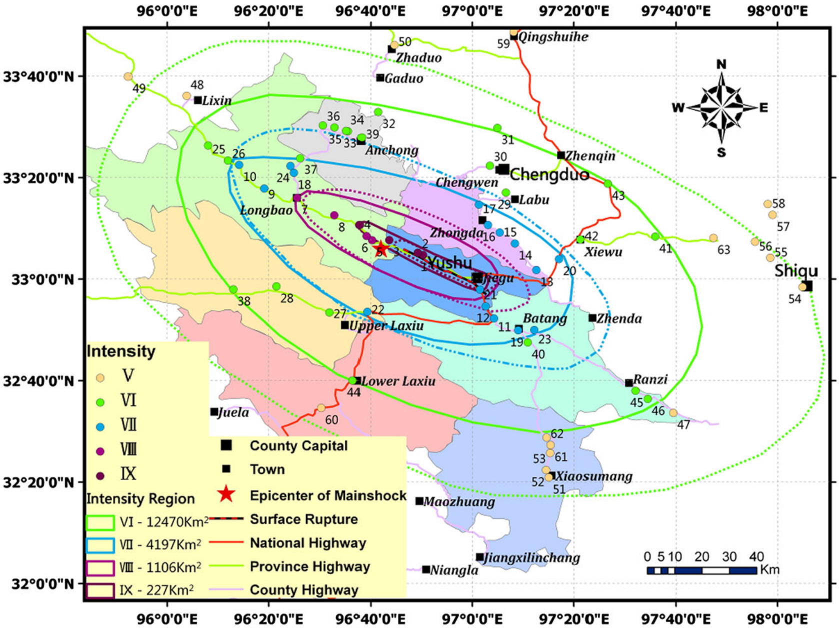


Fig. 2 The surveyed (*solid lines*) and temporary (*dashed lines*) seismic intensity maps of the Yushu earthquake

and the TSIM indicates that: (1) the VI region in the SSIM is significantly smaller than the corresponding region in the TSIM, especially along its long axis; (2) the VII region in the SSIM is narrower in both the southeast and northeast directions than the corresponding region in the TSIM; (3) the VIII region in the SSIM is shorter in the southeastern direction; and (4) the IX region in the SSIM is longer along its long axis in the northwest direction. The SSIM should be more accurate than the TSIM because more time was allotted for the survey and for detailed analysis of structural damage.

To compare the damage differences between the four intensity regions, Fig. 3a presents the average damage ratios of their most common non-engineered adobe and stone buildings. Figure 3b shows seismic capacity indices (SCI) and damage indices (DI) for the four regions; these are expected values in terms of the ratio distribution of damage grades and the corresponding SCIs and DIs calculated using Eq. (1a, 1b) (Lin et al. 2010, 2011):

$$\mathrm{SCI} = \sum_{i=1}^{5} \mathrm{SCI}_{\mathrm{ds}i} \times P_{\mathrm{ds}i} \tag{1a}$$

$$\mathrm{DI} = \sum_{i=1}^{5} \mathrm{DI}_{\mathrm{ds}i} \times P_{\mathrm{ds}i} \quad or \quad \mathrm{DI} = 1 - \mathrm{SCI} \tag{1b}$$

where i denotes the particular damage state code for a given building as: none (1), slight (2), moderate (3), extensive (4), and complete (5) and $\mathrm{SCI}_{\mathrm{ds}i}$ denotes the seismic capacity index ($\mathrm{SCI}_{\mathrm{ds}1} = 0.925$, $\mathrm{SCI}_{\mathrm{ds}2} = 0.75$, $\mathrm{SCI}_{\mathrm{ds}3} = 0.525$, $\mathrm{SCI}_{\mathrm{ds}4} = 0.275$, $\mathrm{SCI}_{\mathrm{ds}5} = 0.075$) given as the average value of the four commonly used criteria. The SCI can quantitatively measure the capacity of a building to resist seismic damage (e.g., Otani 2000; Xie 2008). The higher the SCI of a building, the lesser the damage there will be. $\mathrm{DI}_{\mathrm{ds}i}$ is the damage index ($\mathrm{DI}_{\mathrm{ds}i} = 1 - \mathrm{SCI}_{\mathrm{ds}i}$) that measures the damage extent of a building (e.g., Park and Ang 1985; Angeletti et al. 1988). The higher the DI of a building, the greater the damage. $P_{\mathrm{ds}i}$ is the ratio of the ith damage grade.

Figure 3 shows that (1) the VI region had the least damage in terms of the highest percentage of buildings with slight or none damage grades (89.78 %) and the highest seismic capacity (SCI = 0.80); (2) the VII region had a uniform distribution of damage and similar values of DI and SCI; and (3) the VIII and IX regions had few buildings at slight and none damage grades, the lowest SCIs (0.29 and 0.10), and the most buildings with extensive and complete damage grades and with the highest DIs (0.71 and 0.90).

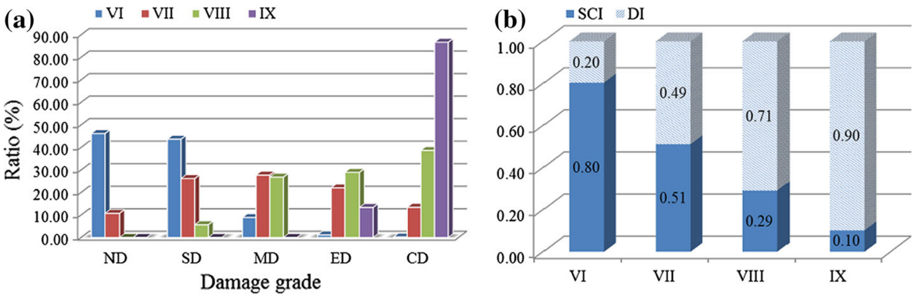


Fig. 3 **a** The damage ratios of non-engineered adobe and stone buildings in four intensity regions, **b** seismic damage and capacity indices in four intensity regions

3 Performance of five types of structures in Jiegu Town

Jiegu Town is located at the area of intersection of the Zhaqu and Baqu Rivers. Along the narrow valleys of these two rivers, Jiegu Town exhibits a T-shaped urban plan, as shown in Fig. 4a. Because of the high population and the considerable number of non-engineered buildings, the damage in this town was more severe than that in other locations. The damage to the southwestern and southern parts of this town was more severe than in the eastern and central parts, as can be seen in Fig. 4; this is due to the proximity of surface ruptures marked by red dashed dotted lines in Fig. 4a.

The Chinese Seismic Design Code (GB50011-2010) was revised after the 2008 Wenchuan earthquake, but most of the engineered structures were constructed before 2010 and thus only in conformance with the older version codes (e.g., GBJ 11-1989, GB50011-2001). According to the GB 50011-2001 code, the seismic fortification intensity of Jiegu Town was VII; the actual seismic intensity of Jiegu Town, however, reached IX in the earthquake. In addition, Jiegu Town is an undeveloped area, and most of its buildings are non-engineered and therefore have high vulnerability.

In Jiegu Town, the survey team mainly investigated five types of structures: adobe (or stone) houses, concrete block structures, reinforced concrete (RC) frame structures, brick masonry structures, and bottom RC frame structures. A total of 5,394 of about 15,000

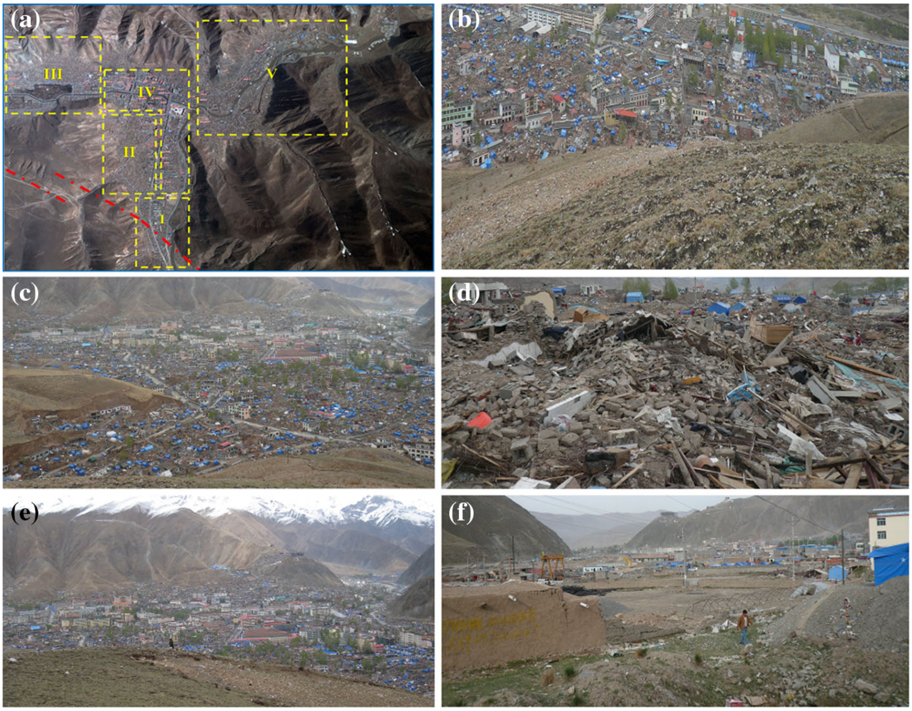


Fig. 4 Overview of Yushu Town after the earthquake: **a** remote-sensing image after the earthquake (National Administration of Surveying, Mapping and Geoinformation, 2010), **b** damage to southern part I, **c** damage to southwestern part II, **d** damage to western part III, **e** damage to central part IV, **f** damage to eastern part V

Table 2 Number of five types of structures at five damage grades

Structural type	Damage grade					Total
	ND	SD	MD	ED	CD	
Adobe and stone	6	29	262	660	1,465	2,422
Concrete block	261	279	611	804	627	2,582
RC frame	15	12	12	9	3	51
Brick masonry	27	22	65	120	35	269
Bottom RC frame	3	9	18	31	9	70
Total	312	351	968	1,624	2,139	5,394

buildings in Jiegu Town were sampled and investigated. Table 2 shows the damage distribution (number of buildings in each damage grade) for each structural type.

The typical damage to the five types of structures in Jiegu Town will be introduced in detail in later sections, and the damage ratios of five damage grades among the five parts of Jiegu Town will be analyzed and compared. Some guidelines for improving structural seismic design and construction based on the survey results and statistical data will also be given.

3.1 Adobe and stone structures

The survey results shown in Table 2 indicate a high percentage of adobe and stone buildings in Jiegu Town. Although Chinese seismic design codes (e.g., GBJ 11-1989, GB50011-2001) stipulated detailed construction regulations for both adobe and stone houses, most of the residential houses were self-constructed without inclusion of seismic design measures. Most of these non-engineered buildings were single-story houses, while a few were two-story houses. Their four main features can be summarized as follows: (1) The adobe or stone material was combined with mud of very low strength and viscosity; (2) most houses had rubble mud foundations that were fragile under earthquake conditions; (3) most of the self-constructed buildings had arbitrary configurations that could lead to torsional damage; (4) the bearing walls of some houses were built with mixed materials (e.g., a mix of adobe with stone, concrete block, and brick) that can undergo non-uniform deformation during earthquakes.

Because of these adverse features, adobe and stone structures are vulnerable to earthquakes. The survey shows that more than 60 % of the adobe and stone structures in Parts I through V of Jiegu Town were completely destroyed in the earthquake, and an additional 30 % sustained severe damage in the form of cracks, partial collapse, and out-of-plane failure of bearing walls, as shown in Fig. 5.

Figure 6 shows the damage percentages of adobe and stone structures expressed in five grades: none (0.25 %), slight (1.20 %), moderate (10.82 %), extensive (27.25 %), and complete (60.49 %).

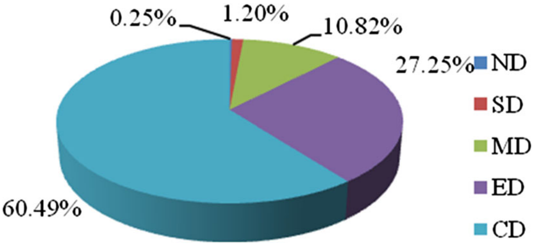
3.2 Concrete block structures

To protect the natural environment in Jiegu Town, use of clay brick was prohibited, and concrete block construction was readily and widely used because of plentiful raw materials and mature manufacturing techniques. Many of the concrete block buildings, especially the self-constructed low-rise buildings, were built without considering seismic design

Fig. 5 **a** Complete destruction of 16 single-story adobe houses with timber roofs near Shengli Road (Part IV), **b** 12 collapsed adobe houses with timber roofs near Hongwei Road (Part V), **c** complete destruction of more than 60 adobe houses with timber roofs in Saiyigou Village (Part II), **d** more than 70 collapsed adobe houses with timber roofs in Shuangyong Lane (Part I), **e** complete destruction of adobe buildings versus standing of other buildings around North Xihang Road (Part II), **f** partially collapsed gables and cracked interior walls in a single-story stone house near Qionglong Road (Part V)

principles, although the Chinese seismic design codes (e.g., GBJ 11-1989, GB50011-2001) stipulated detailed design and construction regulations for concrete block structures. The survey results indicate that non-engineered concrete block buildings had more severe damage than engineered concrete block buildings. There were five main problems for both non-engineered and engineered buildings: (1) Structures had poor integrity and low seismic capacity due to a lack of sufficient structural columns and belt courses; (2) the quality of some concrete blocks was poor and they were easily crushed under strong earthquake

Fig. 6 Percentages of adobe and stone structures at five damage grades



excitation because they were made from low-strength concrete without considering proper mix proportions; (3) the connection between adjacent blocks was poor as a result of using low-strength mortar, lack of sufficient mortar, and sometimes because of use of mud as an adhesive material for connecting blocks; (4) corner walls were easily separated because of a lack of connection measures between walls or between walls and columns; and (5) inappropriate foundations caused failure of some buildings; for example, some belt courses were cast on a macadam foundation that became loose in the earthquake. Figures 7 and 8 show typical failure patterns and damage characteristics of the concrete block structures.

Figure 9 shows the percentage of concrete block structures for five damage grades. The percentage of complete damage of concrete block structures was 24.28 %, less than half the percentage values for adobe and stone structures at the same grade. Compared to adobe and stone structures, the percentages of damaged concrete block structures at the other four damage grades were all higher, especially for those at the none and slight damage grades that increased to 10.11 and 10.81 % from 0.25 to 1.20 %, respectively. It can thus be stated that the seismic capacity of concrete block structures was superior to that of adobe and stone structures.

3.3 RC frame structures

Jiegu Town had a relatively small number of RC frame structures because of the high cost of long-distance transportation of materials. Most of the RC frame structures were designed and constructed according to Chinese seismic design codes (e.g., GBJ 11-1989, GB50011-2001). The four damage features of such structures can be summarized as follows: (1) the most common damage is that the ends of columns yielded and crushed like plastic hinges while the ends of beams remained intact. This damage pattern is known as a "strong-beam weak-column" mechanism; it deviates from the expectations of seismic design code and could result in collapse of a whole building; (2) low deformation capacity and weak connection between walls and columns caused many non-bearing walls to crack or partially collapse out-of-plane; (3) inappropriate construction and layout of infill walls led to shear damage of columns; this is known as a "short-column" effect; and (4) the first floors of some buildings had more severe damage than the upper floors because they had larger openings and fewer infill walls to allow space for parking, shopping, reception, and lobby, while the upper stories were divided into small rooms by a greater number of infill walls. Since the first floor was subjected to earthquake loading, it had a much larger inter-story drift than that of the upper floors. Figures 10, 11, 12 and 13 show the most typical types of damage.

Figure 14 shows the percentages of RC frame structures lying in the five damage grades. Compared to concrete block structures, the percentages of RC frame structures at complete and extensive damage grades significantly decreased to 5.88 and 17.65 %, while the percentages of none and slight damage grades increased considerably to 29.41 and 23.53 %.

Fig. 7 **a** A completely collapsed concrete block building near South Xihang Road (Part II), **b** an extensively damaged teaching building in a college (Part III), **c** an extensively damaged male-student dormitory building at a college (Part III), **d** partially destroyed bearing wall on the first floor of an elementary school building (Part III), **e** partially collapsed and cracked bearing walls of a concrete block building near North Xihang Road (Part II), **f** cracked bearing walls at the first story of a concrete block building near West Xihang Road (Part II)

3.4 Brick masonry structures

Although brick masonry structure is traditional in China, the number of masonry buildings in Jiegu Town is small due to a limited local production of masonry blocks and the inconvenience of transportation of construction materials. While most of the brick masonry structures were designed and constructed in conformance with Chinese seismic design codes (e.g., GBJ 11-1989, GB50011-2001), for some structures appropriate structural

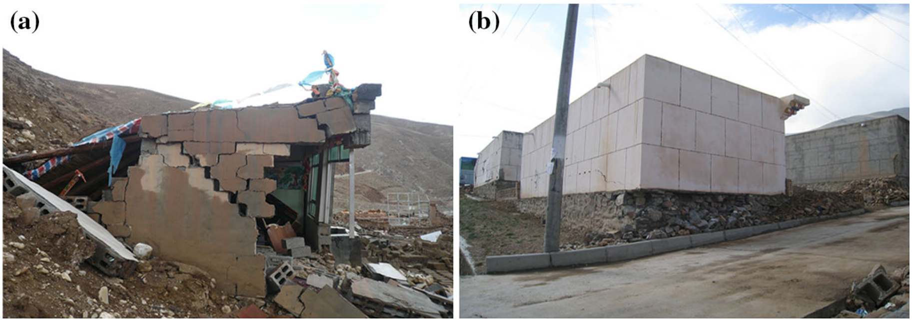


Fig. 8 **a** A partially collapsed single-story concrete block building caused by failure of a mountain slope (Part II), **b** the crushed foundation of a single-story partially damaged concrete block building (Part II)

Fig. 9 Percentages of concrete block structures at the five damage grades

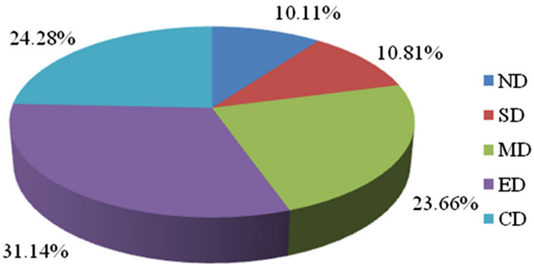


Fig. 10 A tilting RC frame building of a police station with yielded column ends on the soft first floor and cracked, partially destroyed infill walls (Part I)

measures (e.g., the number of belt courses and the location of structural columns) were not sufficiently taken into account. Masonry buildings exhibited four damage patterns: (1) Some exterior longitudinal walls cracked with large fractures associated with large openings in the wall (i.e., windows and doors). Walls between windows had diagonal X-shaped cracks caused by shearing forces; (2) some interior bearing walls had severe damage at the corners of doors and windows that were extremely fragile under the earthquake's influence; (3) some walls had out-of-plane failure patterns caused by failure of connections between walls or between walls and columns; and (4) a few masonry buildings collapsed completely or partially due to a lack of structural columns and belt

Fig. 11 A tilting three-story RC frame building at Xinjian Road with a destroyed soft first floor and cracked and broken columns on the second floor (Part III)

Fig. 12 A four-story RC frame building near Shangye Road and Baqu River with yielded column ends in the soft first story and cracked infill walls around some upper floor windows (Part IV)

courses. Figures 15, 16, and 17 show the most typical types of damage to masonry buildings.

Figure 18 shows the percentages of masonry structures for the five damage grades. The percentage of complete and extensive damage grades accounted for 57.62 %, very close to the 55.42 % for the concrete block structure, but much higher than the 23.53 % for the RC frame structure. The percentages of none, slight, and moderate damage grades are close to those for concrete block structures.

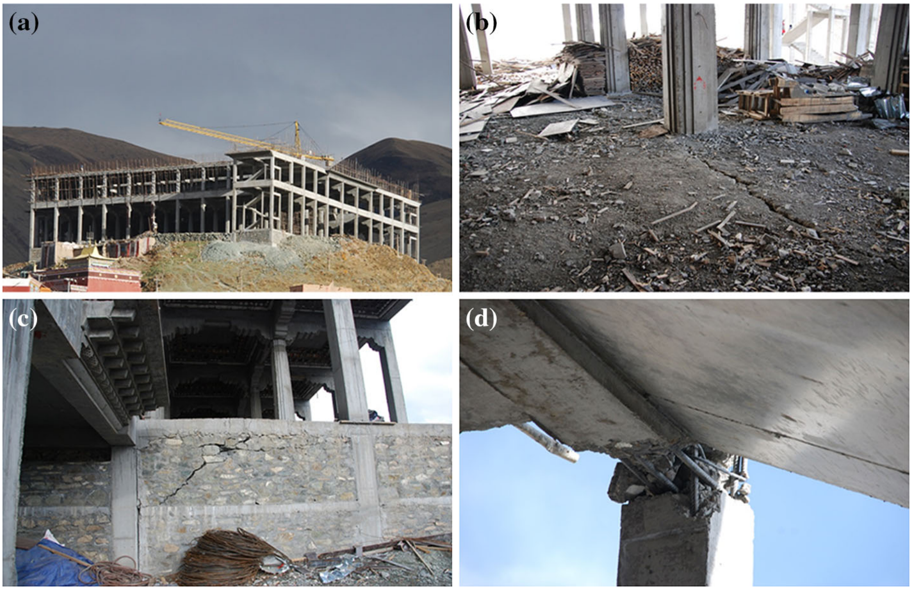


Fig. 13 An RC frame building under construction at the top of a mountain; it exhibits cracked ground, a partially damaged foundation, and yielded column ends due to the mountain topography and the failure of the slope (Part V)

Fig. 14 Percentages of RC frame structures at five damage grades

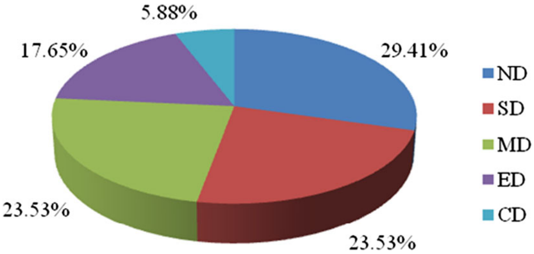
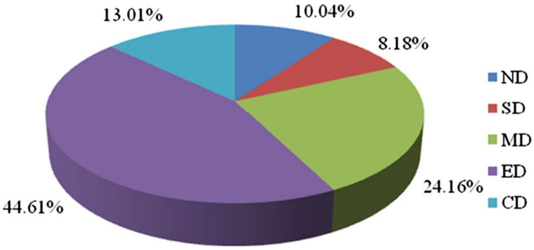


Fig. 15 A building in a college with X-shaped cracks in bearing walls and severe damage to interior walls (Part III)

Fig. 16 X-shaped cracks in bearing walls and cracked and partially destroyed interior longitudinal walls in an office building of a police station constructed without columns and belt courses (Part I)

Fig. 17 X-shaped cracks in most bearing walls, and broken columns on the first floor of a four-story masonry building of Yushu First National Middle School that was constructed using cast slabs, columns, and belt courses (Part IV)

Fig. 18 Percentage of brick masonry structures at five damage grades



3.5 Bottom frame structure

A bottom frame structure is a special structure type with a reinforced concrete frame for the first floor and a masonry or concrete block structure at upper floors. Chinese seismic design codes (e.g., GBJ 11-1989, GB50011-2001) stipulated detailed design and construction regulations for bottom frame structures, particularly with respect to controlling lateral stiffness variation in the vertical direction, limiting the number of stories, limiting story height, and arrangement of first-story earthquake-resistant walls. The investigation showed, however, that such seismic design measures were insufficiently considered. In this earthquake, the most common damage pattern for this type of structure was that upper

Fig. 19 Collapsed second floor that was used as a large restaurant in the Gesaer Hotel building (Part I)

floors, especially the second floors, had much more severe damage than the first floors, as shown in Figs. 19 and 20a. A few buildings had completely collapsed first floors and slightly damaged upper floors as shown in Fig. 20b; this was also the most common damage pattern for this type of structure in the 2008 Wenchuan earthquake (Civil and Structural Groups of Tsinghua University, Xinan Jiaotong University, and Beijing Jiaotong University 2008; He et al. 2011a, b).

Figure 21 shows the percentages of bottom frame structures corresponding to the five damage grades. The percentage of complete and extensive damage grades accounted for 57.15 %, very close to those of concrete block and brick masonry structures. The percentage for the none damage grade was only 4.29 %, significantly less than those of concrete block, RC frame, and masonry structures.

4 Summary of structural damage

All percentages of structural damage described in the preceding section are shown in Fig. 22a. The seismic damage and capacity indices for each structure type were calculated using a method originally proposed by the authors in earlier studies (Lin et al. 2010, 2011) and are shown in Fig. 22b. Adobe and stone structures had the most severe damage as reflected by their highest percentage of complete damage (60.49 %) and their lowest seismic capacity index (0.19). More than 64 % of the death toll was caused by the collapse of adobe and stone buildings. In the future, such structures should not be built in high-seismic-risk zones due to risks caused by low-strength materials, weak clay–straw covered by tiles, and loose connections among walls, beams, and purlins. Brick masonry and concrete block structures have similar damage intensities with approximate damage indices of 0.59 and 0.60, respectively. These two structural types should exhibit less damage if designed and constructed strictly following the design codes, including providing a sufficient number of belt courses and structural columns as well as by using stronger mortar. Unfortunately, because most buildings representing these two structural types in Jiegu Town did not satisfy these requirements, they had severe damage resulting in many casualties. More than 30 % of the death toll was caused by the collapse of concrete block buildings, while about 2 % were caused by the collapse of brick masonry buildings. The bottom frame structure had the second lowest percentage of no damage (4.29 %). The damage to bottom frame buildings was caused mainly by stiffness discontinuities in the vertical direction. It is thus suggested that this kind of structure should no longer be

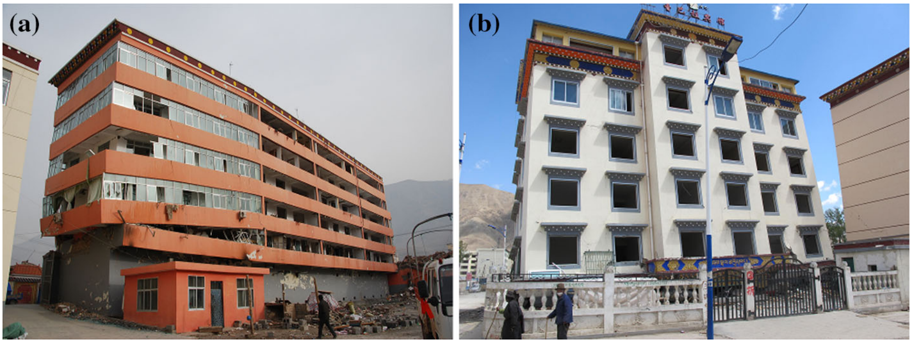


Fig. 20 **a** Partially destroyed second floor in a building of Yushu Construction Company that has an RC frame for the first floor and masonry structure at upper floors (Part IV), **b** the six-story Xiangbala Hotel at Mengtong Road with a completely destroyed soft first floor and slightly damaged upper stories (Part IV)

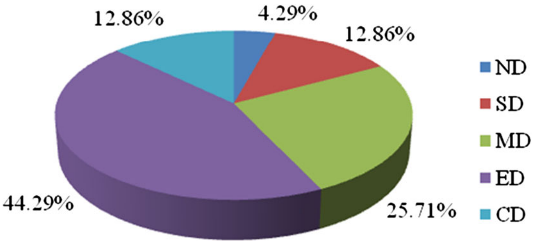


Fig. 21 Percentages of bottom frame structures at five damage grades

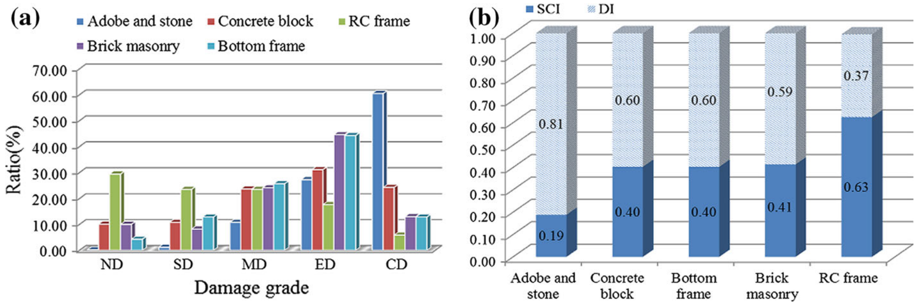


Fig. 22 **a** Damage ratios of the five types of structures, **b** damage indices and seismic capacity indices of the five types of structures

constructed in high-seismic-risk zones or should at least include specific measures to ensure an appropriate distribution of vertical stiffness. The RC frame structure had the best seismic performance in terms of the lowest percentage of complete damage (5.88 %) and the highest seismic capacity damage index (0.63). The main problem was that the "strong-column weak-beam" fortification target of the seismic code had not been achieved in the RC buildings of Jiegu Town. Use of this type of structure should be encouraged in high-seismic-risk zones, especially when superior construction quality can be achieved. The “strong-column weak-beam” mechanism should be encouraged and the “soft story” effect avoided.

5 Recommendations for structural design and construction

After comprehensive analysis of structural damage characteristics and the reasons for failure, the following procedures are recommended for seismic-resistant design and construction of structures in similar areas.

(1) Since site conditions and mountainous topography typically have a significant impact on structural damage, loose soil sites and unstable slopes must be avoided or sufficiently improved. If needed, appropriate measures, such as ground improvement and slope reinforcement, should be taken to deal with unfavorable soil types. Buildings erected on steep slopes with uneven underlying stiffness may suffer structural collapse or severe damage during earthquake shaking, so either the ground should be reconfigured to form a horizontal plane or a special reinforcement should be applied to the first layer. Because a foundation with mud masonry rubble can easily break and cause instability, this type of foundation should also be avoided and replaced by concrete masonry or other affordable solid foundations.

(2) In undeveloped areas where most dwellings are arbitrarily self-built, the material is usually non-uniform and the layout is not regular. Such building types mainly include adobe wooden structures, low-rise block structures, stone structures, and stone–adobe mixed masonry structures. Such buildings were severely damaged in the earthquake; therefore, it is necessary to teach local residents to build earthquake-resistant buildings and the local government and/or related departments could organize engineers and specialists to compile handbooks and/or brochures featuring simple wording and detailed photographs. Moreover, the government could encourage the local media to broadcast information related to seismic-resistant design materials. If trained civil engineers are available, residents contemplating construction should first consult them and use recommended materials to avoid seismic damage resulting from uncoordinated carrying and deformation capacity due to mixed use of different materials (e.g., mixed use of adobe, stone, and block), and select a seismic-resistant structural approach (e.g., avoiding irregular building shapes that lead to structural damage).

(3) Hollow concrete block structures without core columns suffered extremely severe damage in the earthquake; therefore, during the design and construction of this type of structure, the structural or core column should be laid out in such a way as to improve the seismic capacity of this structure and make use of the advantages of a hollow concrete block (e.g., low density and high strength).

(4) In the Chinese seismic design code, the RC frame structure is expected to achieve a “strong-column weak-beam” yielding mechanism. However, during previous earthquakes in China, including the two recent great earthquakes (2008 Wenchuan and 2010 Yushu), few structures had achieved a desired seismic fortification objective. Especially in the Yushu earthquake, most of the structures incurred column-end damage. Further research is required to determine a yielding mechanism for an RC frame structure that would experience beam damage prior to column damage. A related research topic should focus on the contribution of

infill walls to structural stiffness, the strengthening effect of a floor slab on the beams, and damage mechanisms of beam–column joints. The seismic design code must be amended after these problems have become well understood.

(5) In the earthquake, the infill walls of RC frame buildings were partially destroyed and exhibited severe cracks and out-of-plane falling. Following corrective analysis and design, when performing seismic-resistant design, the infill walls should be inserted into a simulation model as non-bearing elements appropriately linked to load-bearing elements. A connection between infill walls and main frames to prevent out-of-plane destruction and collapse of the infill walls might also be required.

(6) For brick masonry structures, cracking or even collapse of load-bearing walls is a common failure pattern. The survey found, however, that a more thoughtful arrangement of structural columns and belt courses can significantly improve building integrity and reduce collapse probability. The design and construction of the structure should therefore strictly follow the specification. In addition, outer vertical walls, including the walls below and between windows, should together form a lateral force-resisting system. The dimensions of vertical walls can also have a significant impact with respect to damage to them. It is also necessary to take into account the impact of window and door openings on the seismic performance of the whole structure.

(7) For bottom frame structures, several buildings had severe damage on floors with low stiffness, and some even experienced entire floor collapse. The damage in several earthquakes indicates that this kind of structure is inappropriate for high-seismic-intensity areas.

(8) Some adjacent buildings were too close together, resulting in pounding damage. Maintaining an appropriate distance between buildings should be considered in their design and construction to avoid damage caused by pounding and crushing from adjacent collapsed buildings.

(9) Some buildings conforming to formal design and construction methods demonstrated good performance when subjected to the earthquake. Such buildings were often not even damaged, in contrast to many surrounding severely damaged self-built houses. The use of formal design and construction methods to ensure the quality of structures should be maximized in the construction of future buildings, especially in rural areas. However, some buildings, designed and constructed strictly following the seismic design code, suffered severe damage, with some even collapsing. According to the damage investigation, the current Chinese seismic design code should be amended with respect to several aspects, including seismic fortification grades for different areas, seismic design of foundations, and seismic design of adobe or stone buildings. More detailed code stipulations should also be provided to ensure overall seismic performance through the use of multiple seismic defenses (structural redundancy) to avoid instabilities resulting from failure of a small number of structural components.

(10) The 2010 Yushu earthquake provided basic data for amending the seismic design code and also raised the following questions for future research: (1) How can RC frame structures achieve a “strong-column weak-beam” mechanism? (2) Would increasing the moment coefficient of column ends in the seismic code represent a reasonable approach? (3) What is an appropriate layout of structural columns, core columns, and beams for brick masonry structures and concrete block structures? (4) How can one ensure that the seismic performance of buildings conforms to the

three key earthquake-resistant design objectives (i.e., no damage in a minor earthquake, repairable damage in a moderate earthquake, no collapse in a great earthquake)?

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References

Angeletti P, Bellina A, Grandori EG, Moretti A, Petrini V (1988) Comparison between vulnerability assessment and damage index, some results. Proceedings of 9th World Conference on Earthquake Engineering, Tokyo-Kyoto, Japan, Vol. 7. pp. 181–186

CENC (The China Earthquake Networks Center) (2010) Data of the Yushu Earthquake. http://www.csndmc.ac.cn/newweb/ (in Chinese). Accessed 16 Sept 2012

Civil and structural groups of Tsinghua University, Xinan Jiaotong University and Beijing Jiaotong University (2008) Analysis on seismic damage of buildings in the Wenchuan earthquake. J Build Struct 29:1–9 (in Chinese)

Earthquake disaster prevention department of china earthquake administration (1995) Catalogue of Chinese historical strong earthquake (23rd Century B.C.–1911 A.D.). Seismological Press, Beijing in Chinese

GB/T 17742-1999 (1999) Chinese seismic intensity scale. Standards Press of China, Beijing in Chinese

GB/T 17742-2008 (2008) Chinese seismic intensity scale. Standards Press of China, Beijing in Chinese

GB50011-2001 (2001) Code for seismic design of buildings. China Architecture and Building Press, Beijing in Chinese

GB50011-2010 (2010) Code for seismic design of buildings. China Architecture and Building Press, Beijing in Chinese

GBJ 11-89 (1989) Code for seismic design of buildings. China Architecture and Building Press, Beijing in Chinese

Grünthal G, Musson RMW, Schwarz J, Stucchi M (1998) European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie, vol 15, Luxembourg

He CR, Chen Q, Han SL, Zhang R (2011a) Earthquake characteristics and building damage in high-intensity areas of Wenchuan earthquake II: Dujiangyan and Pengzhou City. Nat Hazards 57:279–292

He CR, Zhang R, Chen Q, Han SL (2011b) Earthquake characteristics and building damage in high-intensity areas of Wenchuan earthquake I: Yingxiu town. Nat Hazards 57:435–451

IEM (Institute of Engineering Mechanics) (2011) Report on building structure and infrastructure damage survey of Yushu Earthquake. (in Chinese)

Li SQ (2010) Study on the comparison of seismic intensity scales. Dissertation, Institute of Engineering Mechanics, China Earthquake Administration. (in Chinese)

Lin S, Xie L, Gong M, Li M (2010) Performance-based methodology for assessing seismic vulnerability and capacity of buildings. Earthq Eng Eng Vib 9(2):157–165

Lin S, Xie L, Gong M, Li M (2011) Methodology for estimating seismic capacity of city building. J Nat Disasters 20(4):31–37 (in Chinese)

Liu H (1980) On the Chinese seismic intensity scale. Proceedings of the 7th world conference on earthquake engineering, Istanbul, Turkey, Vol. 2, pp. 569–567

MLR (2010) Overall Planning of recovery and reconstruction after the Yushu earthquake. http://www.mlr.gov.cn/zwgk/ghjh/201006/t20100613_722000.htm (in Chinese). Accessed 20 Oct 2012

National administration of surveying, mapping and geoinformation (2010) The high definition images of Yushu town before and after earthquake. http://www.sbsm.gov.cn/article/chyw/201004/201004000646 94.shtml (In Chinese). Accessed 23 Sept 2012

Otani S (2000) Seismic vulnerability assessment methods for buildings in Japan. Earthq Eng Eng Vib 2(2):47–56

Park YJ, Ang AHS (1985) Mechanistic seismic damage model for reinforced concrete. J Struct Eng 111:722–739

Wood HO, Neumann F (1931) Modified Mercalli intensity scale of 1931. Bull Seismol Soc Am 21:277–283

Xie LL (2008) Assessment of a city's capacity for earthquake disaster prevention. The 14th world conference on earthquake engineering, Beijing, China, Paper No. K011

Xinhua news agency (2010) China to Mourn Quake Dead, public entertainment to be suspended. http://news.xinhuanet.com/society/2010-05/31/c_12163647.htm (in Chinese). Accessed 20 Oct 2012