Investigation and Preliminary Analysis on Seismic Damage of Structures Subjected to Yushu Ms7.1 Earthquake

Hongfu Chen, Junwu Dai, Baitao Sun, Sining Huang
Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

SUMMARY:
This paper presents observed damage characteristics, damage causes and seismic vulnerabilities of different building structure types during Yushu earthquake of April 14, 2010 in Qinghai Province. According to the reconnaissance report, in the urban area of Yushu region, most buildings are concrete hollow block structures, accounting for more than 50%, followed by adobe structures, and other structures including brick masonry structures, masonry structures with first story frame, brick structures with wood truss and reinforced concrete frame structures, are the minority; While most buildings are adobe structures and stone structures in the outlying town and country. Moreover, lots of Tibetan Buddhism temple constructions are common among this area. The analysis results indicate that the adobe structures in Yushu region suffered the most damages during the earthquake. In Jiegu town, more than 95 percent of adobe buildings were destroyed.

Keywords: seismic damage; vulnerability; damage probability matrix; concrete hollow block masonry

1. INTRODUCTION

According to the data from China Earthquake Network, Yushu Ms7.1 earthquake struck at 7:49 am Beijing time on April 14th, 2010. Yushu locates in the province of Qinghai, China. With a focal depth of 14 kilometers, Yushu earthquake became another strong earthquake two years after Wenchuan Ms8.1 earthquake. The macroscopic epicenter is near Longhongda of Jiegu town, Yushu County. The extremely high shaking area was exposed to intensity Ⅸ, and the distribution of earthquake intensity (FIT of CEA, 2010) is shown in Fig. 1. It was reported that 2,698 people (Chen, et al, 2011) had been confirmed dead, more than 10,000 was injured, direct economic losses was estimated to be near 10 billion RMB till 18:00pm, March 30th.The disaster area is in the southern alpine region of Bayanhar Mountains which lies in the hinder land of Tibet Plateau, belonging to the Shanglaxiu Indosinian fold belt tectonic system. Residents mainly gathered in the relatively gentle valley terraces, especially in Jiegu, in which the Yushu state government lay.

This paper mainly presents seismic damage characteristics and reasons of different structures based on the site survey data, seismic damage matrixes of different structures and preliminary recommendations.

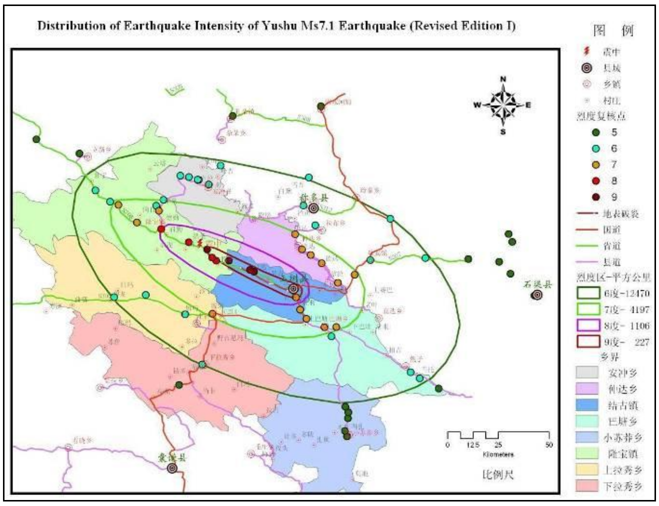

Fig. 1. Intensity Distribution of Yushu Earthquake

2. CAUSES AND CHARACTERISTICS OF BUILDING SEISMIC DAMAGE

2.1. Adobe Structures

The adobe structures in hit area were mainly constructed by adobe and mortar, mostly single layered with wooden truss, which often exist in remote towns and villages. Such structures were built long ago, with lower strength of construction materials, weaker integrity, which led to poor collapse resistant capacity and resulted in a collapse ratio above 95%. For example, the adobe structures of epicenter Jiegu town (intensity Ⅸ) almost all collapsed, see Fig. 2.

Fig. 2. Collapsed Adobe Structure of Jiegu Town

Fig. 3. Seismic Damage of Stone Structure

2.2. Stone Structures

Because the disaster area was located in mountain areas, where materials for sintering clay bricks were difficult to collect, stone structures became the most popular buildings among local Tibetan residents.

The stone structures of the disaster area were mainly constructed with stone and mud mortar, the floor slabs made of large pieces of stone lying on the wooden beam, most with one or two stories, wooden trussed. The stone structures were widely used in remote towns and rural areas, e.g. in Xiewu town, accounted for 95% of all the buildings. This kind of structure had weak bonding strength among stones, and bad integrity, therefore gotten partially collapsed in high intensity areas, which could be shown in Fig. 3. However, there were also some stone structures with high bricklaying quality, adopting ring beams and constructional columns, remained slight damage without collapsed.

2.3. Masonry Structures

The masonry structures of Yushu region were mainly composed of concrete hollow block structures, brick masonry structures and masonry-timber structures. (1) Due to the natural limited conditions, clay bricks were hard to sinter and transportation expenses from other spaces were too high. Therefore, concrete hollow blocks were widely used. Concrete hollow block structures, mostly 2~4 stories took a proportion above 50% in local buildings. Most self-built masonry constructions of the disaster area were built of concrete hollow blocks mixed with mud. Because the mortar joints were relatively less than those of brick structures, and bonding between block and mortar were weaker, therefore buildings were damaged with step-cracks along mortar joint between block, even collapsed. Multi-storey masonry structures with seismic design were damaged with inclined or cross cracks on walls between windows or spandrel walls, and most of them did not collapse even in intensity Ⅸ area , which basically realized the requirements of ‘no collapse in rare earthquakes’ of the seismic design code (GB50011, 2001). (2) Brick masonry structures appeared to be relatively less used in residential buildings, but mainly be applied to schools, hospitals, hotels, office buildings for armed police and government, etc. Most of these buildings were seismic designed, with relatively better seismic measures and construction qualities, which led to better seismic performances (Sun and Chen, 2011; Chen and Sun, 2011). (3) Masonry-timber structures were mainly constructed by sintered clay bricks with mortar, wooden trussed, usually 1~2 stories. These types of buildings were not very common. Masonry-timber structures had a similar seismic damage performance with stone structures, whose roof truss were easily collapsed roof truss and staggered junctions between longitudinal walls and transverse walls were vulnerable. Therefore, concrete block buildings suffered heavier damage than brick masonry buildings, which is shown in Fig. 4.

Fig. 4. Seismic Damage of Masonry Structure (Intensity Ⅸ)

2.4. Masonry Structures with Bottom Frame

This type of structure was mainly occupied by shops along street, mostly 3~5 stories with reinforced concrete frame in the first floor, and masonry structure with concrete hollow brick in the upper structure. The investigation showed that there were lots of ‘semi-frame semi-masonry mixed structures’ with frame frontage and posterior longitudinal wall of masonry structure, which produced a confused condition of determining structure type and should be put into group of ‘masonry structures’. These buildings had a similar seismic damage with those in Wenchuan earthquake (Sun and Zhang, 2010). For instance, damages often appeared in the stiffness transferring story, with inclined or cross cracks in the wall between windows or spandrel wall. In addition, there were also some partial collapses or fallings due to large room in the bottom storey or middle stories, see Fig. 5.

Fig. 5. Seismic Damage of Masonry Structure with Bottom Frame (Intensity Ⅸ)

2.5. RC Frame Structures

According to seismic design code of buildings (GB 50011, 2001), the local fortification intensity of Yushu is Ⅶ (or 0.15g). RC frame buildings, the infill walls of which were mainly composed of concrete hollow bricks, had a small amount in the disaster area, and mainly appeared in luxury hotels, new hospitals or temples. Frame structures suffered similar damages with those in Wenchuan earthquake, whose main damages were included as inclined cracks or ‘X’ shaped shearing cracks in infill walls, concrete spalling of most construction columns end, reinforcement yielding, plastic hinge formation, damages of ‘strong beam and weak column’, collapse of staircase partition, collapse appearing in about one third away from the bottom of staircase for the ‘three-steps construction’, see Fig. 6. Some rare samples of ‘strong column and weak beam’ in the seismic design code were also found. For instance, formation of plastic hinges occurred in several platforms of staircase of the inpatient department of the people’s hospital (which was under construction) of Yushu. It can be shown in Fig. 6 that the frame structure under construction was basically intact, while the adjacent brick masonry construction got partially collapsed.

Fig. 6. Seismic Damage of Frame Structure (Intensity Ⅸ)

2.6. Religious Buildings

For the reason that most local residents believe in Tibetan Buddhism, a lot of religious buildings had been built, such as Buddhist institutes, shags, pagodas, Main Assembly Halls, etc. Because these temples had been built for a very long time, the constructions were mostly adobe structures, stone structures, or soil-stone wall structures with inner frame. The weak integrities and bad seismic performances of these buildings caused heavy seismic damages, which can be seen in Fig. 7.

Fig. 7. Seismic Damage of Religious Building

2.7. Significant Influences of Site Effect

There were five buildings located in the commercial street perpendicular to the Shengli Road and Baqu River. Specific descriptions of these buildings are in Table 1. Fig. 8 and Table 1 shows that seismic damages of structure 1~4 were gradually reduced from the nearby Baqu River bank, which proved the significant influence of site effect.

Table 1. Seismic Damage of Constructions in Commercial Street

Building number	Structure type	Storey number	Damage grade	Descriptions of damage
1	RC Frame structure	4	severe damage	Most column ends of the first floor suffered lantern-type shear failure, which are typical 'strong beam and weak column' failure mechanism. Shear failure in the wall between windows and spandrel walls appeared above the second floor. In addition, several beam ends were damaged, and some stairs collapsed.
2	Masonry structure with bottom frame	4	Moderate/severe damage	Beam-column joints of the first floor remained intact, and penetrating cracks presented in infill walls. Decorative tiles dropped, crossed shear cracks existed in most spandrel walls of the second to fourth floor, and the infill walls of the staircase cracked.
3	Masonry structure with bottom frame	4	Moderate damage	Decorative tiles dropped, inclined shear cracks appeared in part of the spandrel walls of the second and fourth floor, the right side of the divider joint suffered heavier damage than the left one.
4	Masonry structure with bottom frame	4	Slight damage	Inclined cracks appeared in several spandrel walls.

a) overall view

b) No.1 building

c) No.2 building

d) No.3 building

e) No.4 building

Fig. 8. Seismic Damage Of Constructions in Commercial Street

3. SEISMIC VULNERABILITY ANALYSIS FOR TYPICAL STRUCTURES

Three districts of Jiegu Town of Yushu County were surveyed. Number of buildings surveyed were counted up to 2942, including 1487 concrete hollow block masonry structures, 1366 adobe structures (stone structures), 54 brick masonry structures (masonry-timber structures), 27 masonry structures with bottom frame, 8 frame structures. The damage ratios of these structures are shown in Table 2.

Table 2. Damage Ratios

Structures Type	Investigated buildings	Damage grade				
		Intact	Slight damage	Medium damage	Serious damage	Destroyed
concrete hollow block masonry structure	Number	5	185	396	531	370
	percentage（%）	0.34	12.44	26.63	35.71	24.88
adobe structure	Number	0	12	241	581	532
	percentage（%）	0.00	0.88	17.64	42.53	38.95
Brick Masonry Structure	Number	2	15	14	19	4
	percentage（%）	3.70	27.78	25.93	35.19	7.41
masonry structure with bottom frame	Number	0	5	8	12	2
	percentage（%）	0.00	18.52	29.63	44.44	7.41

Statistical results indicate that the total collapse rate of adobe structures reached to 38.95%, the main reason of which was slighter seismic damages in the third district, while actually the collapse rate of the other two districts had reached to 98.85% and 94.53% respectively. Therefore, it can be concluded that adobe structures in high shaking area of Yushu County owned the highest collapse ratio of 95%. The damage ratio of investigated block structures with severe damages or above was 60.59%, while brick masonry buildings with similar damage level had a damage ratio of 42.59%, which indicated that block structures suffered heavier seismic damages than brick masonry ones based on single factor of damage ratio. Damage ratio of level above severe damage of bottom frame structures was 51.85%. Statistically, according to the investigation data, seismic performance of different types of structures in the disaster area of Yushu earthquake can be ranked from lowest to highest as follow: adobe structures, block structures, bottom frame structures and brick masonry structures. Frame structures were not considered together because of few statistical data, yet most of them were formal seismic designed, and had good seismic performances.

4. CONCLUSIONS

(1) The earthquake took place near urban area, and the epicenter was located nearby Yushu County. Seismic damages appeared zonal distribution along the active fault, and passed through Jiegu town where the state government located in, with intensity Ⅸ, causing large damages to building infrastructure and lifeline engineering system of the town, with interruptions of electricity and communications for a time.

(2)Topographic effects and seismic tectonic effects were significantly obvious in this earthquake. Distribution of residential points and seismic tectonic setting had a similar direction, which caused large damages, especially along the river and valley. Site selection and foundation treatment should be considered more seriously. Therefore, advantageous sites that are helpful to seismic resistance should be chosen, while dangerous or disadvantageous ones should be avoided.

(3) Structures had very weak seismic fortification in the disaster area, especially adobe structures, which suffered severe damages. For the limited local economic conditions, adobe structures and masonry structures with concrete hollow brick were the most common constructions, which had poor seismic capacity and got disappointing damage ratio. It is strongly recommended that adobe structures should not be used in the rehabilitation, while masonry buildings with concrete hollow blocks should be adopted with ring beams, constructional columns, core columns according to the code, or be constructed as reinforced masonry structures.

(4) Bottom frame structures had similar seismic damage characteristics with those in Wenchuan earthquake. In high intensity areas, despite of consideration of seismic fortification, this type of structures were damaged severely both in bottom and masonry superstructure. Therefore, appropriate stiffness ratio of bottom frame and upper masonry should be set.

(5) For the reason that most local people believe in Tibetan Buddhism, religious buildings always had large populations inside. It's recommended that reinforced concrete frame structure and reinforced masonry structure should be adopted on such buildings afterwards.

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