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STUDY ON BUILDING DAMAGES IN THE 512 WENCHUAN EARTHQUAKE IN CORRESPONDENCE WITH THE PROVISIONS OF THE SEISMIC DESIGN CODE GB50011 OF CHINA

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ABSTRACT :
Different kinds of buildings were severely damaged or collapsed during the May 12, 2008 Great Wenchuan Earthquake. Based on the field survey data in regions of moderate to severe intensity, studies on building damages in respect to three earthquake performance objectives and essential requirements for seismic conceptual design issued by the national "Code for Seismic Design of Buildings GB50011-2001" are carried out [1]. The real damage and the predicted damage on a given earthquake level for different structures are compared. Discussions on the seismic conceptual design with respect to multiple defense lines, strong column-weak beam, ductility detailing of masonry structures, stair shaft of buildings, loading and force transfer paths, etc. are taken. It is concluded that the seismic performance objectives on three earthquake levels, i.e. "no failure under minor earthquake level", "repairable damage under moderate earthquake level" and "no collapse under major earthquake level" can be achieved while the seismic design is carried out by strictly following the code requirements and the construction quality is guaranteed.

KEYWORDS:
Wenchuan Earthquake, building damage, seismic conceptual design, multiple defense lines

1. INTRODUCTION

Different types of buildings and facilities which were designed and constructed in different periods in disaster regions of China suffered from the Great 512 Whenchuan Earthquake, 2008[2]. The field survey has shown that buildings designed and constructed seismically, particularly those built in late 1990's while the updated seismic design code GBJ11-89 was executed in China[3], have performed very well. Even though they were suffered from a seismic intensity estimated at the surveyed region (or named simply hereafter as estimated intensity) of 3～4 degree higher than the specified intensity specified on the zoning map (or named simply hereafter as specified intensity) that means the estimated peak acceleration of the ground motion (PGA) is 10 times of the specified one, most of them suffered only moderate or severe damage, instead of collapse. The protection goal of three seismic performance objectives are realized excepting for a very few cases. For buildings built before the Code GBJ11-89 mostly suffered severe damage or collapse. It has been recognized that severe damage or collapse of buildings may be related to the much higher seismic intensity, the distinctive site-dependent attenuation of strong motions, the wave propagation law, and the site topographic effect, etc. It is necessary for explaining and understanding earthquake failures to question the qualities of the seismic design and the construction and have objective and scientific analyses according to the features of buildings. It was observed that at a same site, some buildings were seriously damaged or even collapsed, but some only suffered slight damage. In highly affected regions, some RC structures which were suggested to have sufficient high earthquake resistance collapsed, but the vulnerable masonry structures survived with a lot of cracks. For RC frame structures hinges were observed often in columns, but rarely in beams. The stair shaft and lift tube of masonry buildings suffered severe damages or collapse. The disaster has resulted in tremendous losses of life and property, on the other hand, the earthquake damage in this disastrous event would serve as useful lessons and guidelines for handling future disasters. In this paper, attention is paid not only to the description of the building damage, but also to the discussions of the seismic conceptual design principles, such as the seismic multiple defense lines, the structural integration, the mechanism of “strong column-weak beam” etc. The mechanism of seismic damages to masonry structures and RC structures are taken into consideration and are compared with regulations of the current Code GB50011-2001.

2. EARTHQUAKE DAMAGE AND SEISMIC CONCEPTUAL DESIGN

2.1 Multiple seismic defense lines

The multiple seismic defense lines are required for building structures by Chinese “Code for Seismic Design of Buildings GB50011-2001”(2001) that are significant for building safety against collapse on the major earthquake level corresponding to a return period of over 2000 year. On the major earthquake level, some structural members, for example for RC structures, braces, attached wind walls to columns of frame structures and coupling beams of shear walls, acting as the first defense line (or protective system) are allowed to be first damaged. In such case the earthquake energy is dissipated, the dynamic feature of the structure is changed and the earthquake action has been reduced therefore. The main structural members such as frame columns and shear walls which remain as the second defense line after the first defense line yielding, and therefore they protect the whole structure from collapse. For masonry structures, tie-columns and tie-beams which acting as restraint members to enhance the ductility of the masonry wall can be seen as the second defense line. Under major earthquake, masonry walls are allowed to be severely damaged but the structure can be escaped from collapse owing to the existing of the tie-columns and tie-beams. Figures 1 shows the collapse of a 3-story school building of RC frame structure with a typically spacious classroom of 7m×9m, but without any braces or attached wind walls to columns. This school is located in Yingxiu Town, the epicenter area where the seismic specified intensity is 7 (the corresponding PGA = 0.1g, according to the Chinese code), but the estimated intensity is as high as 11 (the corresponding PGA>1.0g). Under the action of the vertical earthquake component which may be larger than the horizontal ones, the frame columns were broken first and result in collapse of the whole building. In contrast, near by the above school building there is a 4-story office building of masonry structure, though they were severely damaged with a lot of cracks within walls, but did not collapse owing to the combination of RC tie-columns and tie-beams provided (see Fig. 2).

Fig. 1 Collapsed school building in Yingxiu Town (7/11)*

Fig. 2 Damaged office building in Yingxiu Town (7/11)

* note：7/11 means the specified intensity / the estimated intensity（the same holds hereafter）

Figure 3 shows two 4-story buildings side by side of one RC frame structure and one masonry structure whose construction did not completed yet before the event, in Pingwu County with an estimated intensity 9, where the left building built of one span RC frame structure was severely damaged, but the right one of masonry structure remains safely because the brick walls are confined by tie-columns and tie-beams, leading to a significant increase in the integral rigidity and ductility of the building under large deformation. (see Fig. 4).

Fig. 3 Two buildings side by side in Pingwu County (7/9)

Fig. 4 Confined masonry building in the rear (7/9)

2.2 Strong Column-Weak Beam

The design strategy of strong column-weak beam issued in Chinese Code GB50011-2001 can be expressed by following equations:

$$\sum M_{cy}^{a} > \sum M_{by}^{a} \tag{1}$$

Where M_{by}^{a} and M_{cy}^{a} are the actual moment resistance of the beam and column, respectively, at the joint. Their accurate estimation are rather difficult because of factors related to the complexity of the earthquake action of the three components and the contribution of the in-situ RC floor slabs, so that a factor of $\eta_c \geq 1$ is usually introduced to increase the design moment resistance of columns. Therefore,

$$\sum M_c = \eta_c \sum M_b \tag{2}$$

To consider the contribution of the floor slabs to the frame beam and other possible influence the factor η_c is generally assumed to be 1.5～2.0, as column is under a very complicated dual loading condition due to the couple of horizontal strong motions. In general, the section design of RC columns can be easily satisfied with the least amount of steel bars, particularly for low rise buildings as in the earthquake affected areas of this event. It can be obviously known that the practical design often results in a mechanism of “strong beam-weak column” as often observed in the damage of RC frame structures, and it reveals that the beam resistance or the assumed value of the factor η_c was significantly underestimated, if the Eq. (2) had been applied in the design. Figure 5 shows the plastic hinges of the frame columns of the west wind of the school. Figure 6 shows a plastic hinge at the top of a column of a residential building with 5-story upper masonry structures and a ground story of RC frame structure.

Fig. 5 Plastic hinges of the frame columns of Yingxiu School (7/11)

Fig. 6 Plastic hinges at top of columns of a residential building (7/9)

2.3 Ductile detailing and integration of confined masonry structures

The precast RC multi-hole floor slab has been commonly used for school and residence buildings in China. The connection validity of precast RC structural members is very important to ensure the integration of the structure as required by Clause 3.5.5 of Chinese Code GB50011-2001. Unfortunately, some of masonry structures collapsed partly or entirely in the event due to the poor connection between the precast RC floor slabs and beam as shown in Figure 7. As masonry structures are often constructed of brittle material, the confined measures have been created and studied extensively after the 1976 Great Tangshan Earthquake in China. The combination of RC tie-column and tie-beam forms a restraining frame for masonry walls that significantly enhance the ductility and integration of the structure under large deformation. This specific type of confined structure has been widely used in earthquake-prone regions nation-wide. It is learned from past earthquakes that the three earthquake performance objectives can be reached for buildings which were designed and constructed strictly by following the requirement of detailing for tie-column and tie-beam issued in the current seismic code. Figure 8 shows a school building of confined masonry structures sustained a lot of inclined cracks in brick walls restrained within the boundary of tie-column and tie-beam, but survived The precast RC multi-hole floor slab has been commonly used for school and residence buildings in China. The connection validity of precast RC structural members is very important to ensure the integration of the structure as required by Clause 3.5.5 of Chinese Code GB50011-2001. Unfortunately, some of masonry structures collapsed partly or entirely in the event due to the poor connection between the precast RC floor slabs and beam as shown in Figure 7. As masonry structures are often constructed of brittle material, the confined measures have been created and studied extensively after the 1976 Great Tangshan Earthquake in China. The combination of RC tie-column and tie-beam forms a restraining frame for masonry walls that significantly enhance the ductility and integration of the structure under large deformation. This specific type of confined structure has been widely used in earthquake-prone regions nation-wide. It is learned from past earthquakes that the three earthquake performance objectives can be reached for buildings which were designed and constructed strictly by following the requirement of detailing for tie-column and tie-beam issued in the current seismic code. Figure 8 shows a school building of confined masonry structures sustained a lot of inclined cracks in brick walls restrained within the boundary of tie-column and tie-beam, but survived from collapse on major earthquake intensity level.

Fig. 7 Fallen RC beam and precast floor slabs in Pingwu (7/9)

Fig. 8 Damaged school building of brick structure in Bailu (7/8)

2.4 Stair shaft in masonry structures

The stair shaft is the entrance and exit of buildings, and provides people the way to evacuate from incidents. The failure or collapse of stair shafts may kill or injure escapers, or stack the exit way. The stair shaft of masonry structure may easily be damaged due to their relatively large mass, higher walls, steps between floor and stair plateform, and rigidity of step beams etc. The Clause 7.3.1 of Code GB50011-2001 regulates that tie-columns be provided at corners of stair shaft and lift tube and at the joints of transverse and longitudinal walls on the step level. The Clause 7.3.8 requires that a valid connection be detailed between beams for steps and plateform and so on; the tie-column be extended up to the top and be connected with the tie-beams of the stair shaft which protrudes beyond the roof. Figure 9 shows a collapsed stair shaft of a 3-story school building due to the wall breaking. Figure 10 shows a RC stair shaft remained with masonry structures besides collapsed. The Clause 7.1.7 Item 4 regulated that the stair shaft not be set in the end span or at the corner of building because the structural torsion may cause damages at these portions as shown in Figs. 11 and 12. The failure of steps was occurred because the structural partition was taken place at a position of the lower 1/3 length of the stair segment. Again, we can see the damaged step beam and the broken stair segment falling down in Figs. 13 and 14, respectively.

Fig. 9 Collapsed stair shaft of masonry school building in Mianzhu County (7/8~9)

Fig. 10 Remained RC stair shaft of masonry school building in Dujiangyan County (7/8~9)

Fig. 11 Collapse of the stair shaft in the end of building plan (7/8)

Fig. 12 The closely view of collapsed stair shaft (7/8)

Fig. 13 Fractured stair beam at its lower 1/3 position (7/8~9）

Fig. 14 Stair segment falling

2.5 Loading and force transfer paths

The earthquake actions in two horizontal directions may cause rotation of buildings as seen in Fig. 15, where the corner walls on the top of the masonry building rotated slightly. It means that the building sustained two-horizontal seismic actions at the corner. The earthquake forces transferred along the X and Y axes in the building plan so that its walls at the corner should keep connected straightly and tightly. In case of an opening or curve wall existing near or around the corner, structural failures shall certainly appear (see Figure 16).

Fig. 15 Rotation at upper corner of a masonry building

Fig. 16 Failure of walls at the corner of buildings (7/8)

3. CONCLUSIONS

The author has been several times in the disaster region taking field survey after the 512 Wenchuan Earthquake. The study on damage to different kinds of buildings constructed in different periods tells the truth that most of buildings which were seismically designed and constructed since 1990's have been survived and be able to achieve the three seismic performance objectives, i.e., "no failure under minor earthquake, reparable under moderate earthquake and no collapse under major earthquake". Many buildings might suffer moderate to severe damage but without collapse even the seismic estimated intensity is higher than the specified intensity by 3 or 4 degrees (the corresponding peak acceleration is about 10 times larger). The survey and study also show that the basic requirement for seismic design, i.e. the seismic conceptual design, has special significance for ensuring the seismic resistance of structures. Besides the structure response analysis, the seismic conceptual design is some how more important for earthquake resistance of buildings. To be an engineer, handle of conceptual design is particularly required other than only using the software. The idea of "strong column-weak beam" is the basic requirement for RC structures to guarantee the objective of "no collapse for major earthquake. " Unfortunately, a contrast and harmful condition, i.e., "strong beam-weak column" damage happened in some affected areas because lack of a deep understanding of the conceptual design. The seismic design should avoid from irregular planning and asymmetric loading system. A seismic structure should have the integration and the largest possible number of internal and external redundancies. Redundancy is necessary for structures to prevent collapse as whole due to the failure of individual members. The confined masonry structure with tie-column and tie-beam was created and widely applied in China since 1976 Tangshan Earthquake. It is noticed that the confined masonry structure could in some cases behave better than RC frame structures in seismic area. Attention should be paid to the seismic design for stair shaft of masonry buildings, particularly for schools, hospitals, residential and office buildings. Some injures and deaths were caused by the collapse and stack of stair shaft that occurred prior to the collapse of the main building. Failures of non-structural members, such as diaphragm, infilling wall, ceiling, cladding, etc. might result in a big economic lose and interruption of the normal operation of buildings.

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