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Lessons learned from the "5.12" Wenchuan Earthquake: evaluation of earthquake performance objectives and the importance of seismic conceptual design principles

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Abstract: Many different types of buildings were severely damaged or collapsed during the May 12, 2008 Great Wenchuan Earthquake. Based on survey data collected in regions that were subjected to moderate to severe earthquake intensities, a comparison between the observed building damage, and the three earthquake performance objectives and seismic conceptual design principles specified by the national "Code for Seismic Design of Buildings GB50011-2001," was carried out. Actual damage and predicted damage for a given earthquake level for different types of structures is compared. Discussions on seismic conceptual design principles, with respect to multiple defense lines, strong column-weak beam, link beam of shear walls, ductility detailing of masonry structures, exits and staircases, and nonstructural elements, etc. are carried out. Suggestions for improving the seismic design of structures are also proposed. It is concluded that the seismic performance objectives for 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 if seismic design principles are carried out by strictly following the code requirements and ensuring construction quality.

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

1 Introduction

Many different types of buildings and facilities that were designed and constructed during different time periods were impacted by the great "5.12" Wenchuan Earthquake. The field survey shows that the buildings that were designed and constructed with attention to seismic considerations; particularly those built in the late 1990's after the updated seismic code GBJ11-89 was issued in China, performed very well. Most of these buildings were subjected to seismic intensities estimated to be three to four times higher than the intensity specified on zoning maps, and the peak acceleration of the ground motion (PGA), A_{PG}, was 10 times higher than anticipated. They suffered only moderate or severe damage, instead of collapse. Note that in this paper, the term "estimated intensity" is used to describe intensity based on field observations, while "specified intensity" refers to the intensity used in zoning maps.

The three seismic performance objectives given in the code were realized with very few exceptions. However, buildings built before Code GBJ11-89 took effect were either severely damaged or collapsed. It has been recognized in past earthquakes that severe damage or collapse of buildings is often related to factors such as exposure to much higher seismic intensity than expected, distinctive site-dependent attenuation of strong motions, wave propagation laws, site topographic effects, etc. When explaining and understanding earthquake failures, it is necessary to question the quality of the seismic design and the construction, and to perform objective and scientific analyses according to the features of buildings. It was observed from the field survey that some buildings at the same location were seriously damaged or even collapsed, but others suffered only slight damage. Furthermore, in severely impacted regions, some RC structures that were expected to have sufficient earthquake resistance collapsed, while more vulnerable masonry structures survived with a lot of cracks. Many column hinges were observed in the RC structures, but rarely in beams. Some failure modes such as the coupling beam of shear wall structures and collision between seismic partitions, were also observed. In this paper, in addition to a description of the building damage, attention is given to the role of conceptual seismic design principles, such as multiple seismic defense lines, structural integration, "strong column-weak beam" and nonstructural members, etc. in the post-earthquake performance of buildings. The seismic damage to masonry structures, RC structures with large open areas, and foundations are considered, and observed damage is compared with regulations in the current Code GB50011-2001.

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2 Earthquake damage and seismic conceptual design

2.1 Multiple seismic defense lines

Multiple seismic defense lines are required by the Chinese "Code for Seismic Design of Buildings GB50011-2001"(2001) for buildings where safety against collapse due to a major earthquake corresponding to a return period of over 2000 years is required. In a major earthquake, some structural members, for example for RC structures, braces, attached wind walls of column and link beams of shear walls that act as the first defense line (or protective system), are allowed to be damaged first. In such cases, the earthquake energy is dissipated, the dynamic features of the structure change and the earthquake action is reduced. The main structural members such as frame columns and shear walls, which remain as the second defense line, protect the entire structure from collapse. For masonry structures, tie-columns and tie-beams, which act as restraint members to enhance the ductility of the masonry wall, are considered to be the second defense line. Under a major earthquake, masonry walls are allowed to be severely damaged, but collapse is prevented by the tie-columns and tie-beams. Figures 1 and 2 show the collapse of a 3-story RC frame school building with a typical large classroom of 7 m × 9 m, but without any braces or attached wind walls to columns. This school is located in Yingxiu Town, the epicenter area where the specified seismic intensity was VII (corresponding to $A_{PG} = 0.2g$, according to the Chinese code), but the estimated intensity was as high as XI (the corresponding $A_{PG}>1.0g$). Under the vertical earthquake component, which may be larger than the horizontal components, the frame columns were broken first, resulting in the collapse of the entire building. In contrast, a nearby 4-story office building and a 5-story residential building, both masonry structures, suffered severe damage with many cracks within the walls, but did not collapse due to the presence of a combination of RC tie-columns and tie-beams (see Fig. 3).

Bracing systems are widely used in industrial buildings. The bucking of braces may absorb and dissipate earthquake energy to prevent the frame columns from collapse. Figure 4 shows a failure mode of the brace in an industrial buildings in An Xian County, located in a region with an estimated intensity of VIII according to the Chinese code. Figure 5 shows two 4-story buildings in Pingwu County, one RC frame structure and the other a masonry structure, that were under construction when the earthquake occurred. The span of the RC frame structure (on the left) was severely damaged, but the masonry structure (on the right) had less damage because the brick walls were confined by tie-columns and tie-beams, leading to a significant increase in the integral rigidity of the building under

Fig. 1 Collapsed school building (left) in Yingxiu Town (VII/XI) (Note: VII/XI means the specified intensity /estimated intensity and same below)

Fig. 2 Collapsed school building (right) in Yingxiu Town (VII/XI)

Fig. 3 Damaged official building in Yingxiu Town (VII/XI)

large deformation (see Fig. 6). The estimated intensity at this location was IX.

2.2 Strong-column and weak-beam

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

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

Where $M_{\mathrm{by}}^{\mathrm{a}}$ and $M_{\mathrm{cy}}^{\mathrm{a}}$ are the actual moment resistance of the beam and column, respectively, at the joint. Accurate estimation is difficult because of the complexity of the earthquake itself in terms of its three components of ground motion, the contribution of the in-situ RC floor slabs, and the over-yielding strength of steel reinforcing bars. An increase factor of $\eta_{\mathrm{c}} \geq 1$ is usually introduced to increase the design moment resistance of the beams. Therefore,

$$\sum M_{\mathrm{c}} = \eta_{\mathrm{c}} \sum M_{\mathrm{b}} \tag{2}$$

Fig. 4 Buckling brace between columns of an industrial building in Yingxiu Town (VII/XI) of Anxian County (VII/VIII)

To consider the contribution of the floor slabs to the frame beam and other possible influences, the factor η_{c} is generally assumed to be 1.5-2.0. The column is subjected to very complicated dual loading conditions due to multiple horizontal strong ground motions. In general, the requirements for the section design of RC columns can be easily satisfied with the least amount of steel bars, particularly for low rise buildings, as was the case in the impacted areas. In practice, this design often results in a “strong beam-weak column” mechanism as often observed in damaged RC frame structures, which reveals that the beam resistance or the assumed value of the factor η_{c} was significantly underestimated if Eq. (2) was applied in the design. In addition, there are many factors related to the construction of the frames that could result in the occurrence of a “strong beam-weak column,” including the location of a construction joint of the column at the bottom level of the beam, a dense arrangement of reinforcing steel bars in the beam-column joints, which influences the quality of casting of the column concrete, etc. Figure 7 shows the plastic hinges of columns of a two-story cast-in-situ RC frame building, its second floor remains intact as shown in Fig 8. Figure 9 shows a plastic hinge at the top of a column of a residential building with a RC frame structure ground story and the five upper stories constructed of masonry.

2.3 Coupling beam between shear walls

As the first line of seismic defense for shear wall structures in tall buildings, the coupling beam behaves like a “fuse;” it experiences cracking first then yields

Fig. 5 Two buildings side by side in Pingwu County (VII/IX)

Fig. 6 Confined masonry building at the rear of that in Fig. 5

when the level of seismic action is beyond the minor earthquake level. This prevents damage to the adjacent shear walls because the earthquake energy has been dissipated and absorbed by the slightly damaged coupling beams. Code GB50011-2001 regulates that "Besides the normally required reinforcement hoop, details of cross steel should be provided for the coupling beam with a span-to-depth ratio less than 2 and the thickness of the wall less than 200mm." The reason for this is to improve the shear resistance of the coupling beam and satisfy the requirement of the "strong shear-weak moment." Such ductile detailing of the reinforcement has been illustrated in laboratory tests, but the observed damage did not show the desirable results. The coupling beam in a shear wall building in Pengzhou City was seriously damaged in a typical shear failure mode as shown in Fig. 10. However, the twin coupling beams of two frame-shear wall structures in Chengdu City and Xi'an City performed very well. The brick masonry was broken to prevent the coupling beam and the wall itself from failure (see Figs. 11 and 12).

Fig. 7 Plastic hinges at column tops of a dining hall at the ground floor of the Xuankou Middle School in Yingxiu Town (VII/XI)

Fig. 8 The dining hall at the second floor of the building shown in Fig. 7 remains intact

Fig. 9 Plastic hinge at the top of a column (VII/XI)

Fig. 10 Damaged high coupling beam of a shear wall structure in Pengzhou City (VII/VII)

Fig. 11 Twin coupling beam of a frame-shear wall structure in Chengdu City (VII/(VI-VII))

2.4 Ductile detailing and integration of confined masonry structures

The precast RC multi-hole floor slab has been commonly used for schools and residential buildings in China. The integrity of the connections between precast RC structural members is very important to ensure the proper integration of the structure as required by Clause 3.5.5 of Chinese Code (GB50011-2001). Masonry structures are often constructed of brittle materials. Confined masonry structures have been designed and extensively studied 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 enhances the ductility and integration of the structure under large deformations. This specific type of confined structure has been widely used in earthquake-prone regions throughout China. It is seen from past earthquakes that the three earthquake performance objectives can be achieved for buildings that were designed and constructed by strictly following the detailing for tie-column and tie-beam as required in the current seismic code. Figure 13 shows a confined masonry school building that sustained many inclined cracks on the brick walls that were restrained by tie-columns and tie-beams, and survived collapse when subjected to a very high earthquake intensity level.

Unfortunately, some of masonry structures collapsed partly or entirely in the Wenchuan Earthquake due to the poor connection between the precast RC floor slabs and tie-beams, or due to breaking or overturning of the brick walls from the lack of restraints to the tie-columns and tie-beams. Figure 14 shows that there are no connection details for the floor slabs that fell.

2.5 Stair shaft in masonry structures

The stair shaft is at the entrances and exits of buildings, and provides the only way for people to evacuate. The failure and collapse of stair shafts may result in death and/or injury to building occupants, or block the exit way. The stair shafts in masonry structures may easily be damaged due to their relatively large mass, higher walls, steps between floor and stair platform, rigidity of step beams, etc. Clause 7.3.1 of Code GB50011-2001 regulates that tie-columns be

Fig. 12 Twin coupling beam of a frame-shear wall structure in Xi'an City (VII/(VI-VII))

Fig. 13 Damaged masonry school building in Bailu (VII/VIII)

(a) (b) (c)

Fig. 14 Poor connections between precast RC floor slabs and tie-beam provided at the corners of stair shafts, lift tubes, and at the joints of transverse and longitudinal walls on the step level. Clause 7.3.8 requires that a valid connection be detailed between beams for steps and platforms; and the tie-column must be extended up to the top and be connected to the tie-beams of the stair shaft that protrude beyond the roof. Figure 12 shows a collapsed stair shaft of a 3-story school building caused by the breaking of the wall. Figure 15 shows a collapsed stair case of a three-story school building. Fig. 16 shows the failure of steps caused by the structural partition moving to the lower 1/3 length of the stair segment. The damaged step beam and the stair segments that fell are seen in Figs. 17 and 18, respectively.

2.6 Seismic partition details

Code GB50011-2001 requires that a seismic partition be provided for buildings to have adequate spacing depending on the specified intensity, type of structure, structural materials, and building height. The upper buildings should be completely separated along the partition to avoid knocking. Figure 19 shows a masonry structure that partly collapsed due to the knocking of

Fig. 15 Collapsed stair shaft of a three-story school building in Mianzhu County (VII/(VIII~IX))

Fig. 16 Damaged stair shaft of school building in Dujiangyan (VII/(VIII-IX))

Fig. 17 Fractured stair beam at its lower 1/3 position (VII/(VIII-IX))

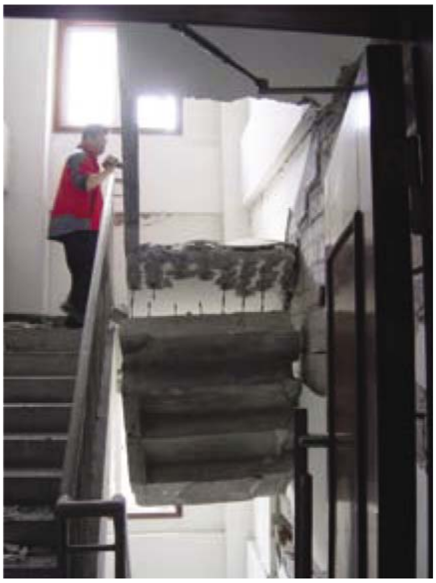

Fig. 18 Falling stair segment

Fig. 19 Partial collapse of building due to knocking along the partition (VII/VIII)

buildings along the partition. Figure 20 shows knocking of two multi-story masonry buildings. It is not always necessary to have a partition if the building has a regular configuration in plan or elevation.

2.7 Loading and force transfer paths

The earthquake actions in two horizontal directions may cause rotation of buildings as seen in Fig. 21, where the corner walls on the top of the masonry building rotated slightly. This means that the building sustained two-horizontal seismic actions at the corner. When the earthquake forces are transferred along the X and Y axes in the building plan, the walls at the corner should remain connected tightly. If an opening exists near the corner, structural failures will certainly occur (see Fig. 22).

2.8 Performance of nonstructural members

Nonstructural members include architecture elements, mechanical facilities, pipelines, as well supports and connections fixed to the main structure, etc. Code GB50011-2001 regulates that “the seismic design should take into account the effects of infilling walls on the structure, an improper installation of infilling walls may cause failures of structural systems and should be avoided” and “a valid connection between the architecture cladding and curtain is required to prevent injuring induced by falling.” Many failures and collapses of brick infilled walls and light ceilings were observed in the event (see Figs. 23 and 24). A large amount of property loss resulted from damage to nonstructural members whether or not the main structure remained safe. One exception is glass claddings, which behaved very well during the earthquake. Even where failures and damage occurred to the main structure and infilled walls and ceilings, the glass cladding system remained safe or was only slightly damaged (see Figs. 25 and 26). Clause 4.2.6 of “Technical Code for Glass Claddings JGJ102-2003”[2] requires the glass cladding system to have a drift resistance of three times the elastic drift limit allowed for the main structure. It is said that the

Fig. 20 Knocking of partition (VII/VIII)

Fig. 22 Failure of walls at the corner of two buildings (VII/VIII)

Fig. 21 Rotation at upper corner of a masonry building (VII/VIII)

Fig. 23 Damaged infilled wall of perforated brick of a school building in Dujiangyan (VII/(VIII~IX))

Fig. 24 Damaged ceiling of a school building in Deyang City (VI/VII)

Fig. 25 Glass cladding of a school building remains intact in Dujiangyan (VII/(VIII-IX))

Fig. 26 Two slices of glass fell down from the cladding in Anxian County (VII/IX)

performance objective for a moderate level earthquake (with a return period 475 years) for glass cladding systems could be achieved if this requirement is satisfied.

3 Conclusions

The author has performed field studies in the disaster region several times following the “5.12” Wenchuan Earthquake. The study regarding damage to different types of buildings constructed during different time periods proves that most of the buildings that were seismically designed and constructed since the 1990 s survived and were 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 withstood moderate to severe damage without collapse even when the estimated seismic intensity was three to four degrees higher than the specified intensity (i.e., the corresponding peak acceleration was about 10 times larger). This survey and study also showed that the basic requirements for seismic design, i.e., seismic conceptual design principles, are especially significant in ensuring the seismic resistance of structures. The strong column-weak beam concept is the basic requirement for RC structures to guarantee the objective of no collapse for major earthquake. Unfortunately, strong beam-weak column damage occurred in some impacted areas due to a lack of a comprehensive understanding of seismic conceptual design principles. Seismic design should avoid irregular planning and asymmetrical loading systems.

A seismically resistant structure should be fully integrated and have the largest possible number of internal and external redundancies. Redundancy is necessary to prevent collapse of the entire building due to the failure of its individual members. The confined masonry structure with tie-columns and tie-beams was created and widely applied in China following the 1976 Tangshan Earthquake. It is noticed that this type of structure may, in some cases, behave better than RC frame structures in seismic areas. Attention should be given to the seismic design of stair shafts in masonry buildings, particularly in schools, hospitals, and residential and office buildings. Some deaths and/or injuries were caused by the collapse of stair shafts that occurred prior to the collapse of the main building. Failures of nonstructural members, such as diaphragms, infilled walls, ceilings, claddings, etc., might result in a large economic losses and interruption of normal building operations.

References

Code for Seismic Design of Buildings GB 50011-2001 (2001,), Beijing: China Architecture & Building Press.

Technical Code for Cladding Engineering JGJ102-2003 (2003), Beijing: China Architecture & Building Press.