Earthq Eng & Eng Vib (2010) 9: 147-155 **DOI**: 10.1007/s11803-010-0001-9

Revision of seismic design codes corresponding to building damages in the "5.12" Wenchuan earthquake

Wang Yayong†

Institute of Earthquake Engineering, China Academy of Building Research, Beijing 100013, China

Abstract: A large number of buildings were seriously damaged or collapsed in the "5.12" Wenchuan earthquake. Based on field surveys and studies of damage to different types of buildings, seismic design codes have been updated. This paper briefly summarizes some of the major revisions that have been incorporated into the "Standard for classification of seismic protection of building constructions GB50223-2008" and "Code for Seismic Design of Buildings GB50011-2001." The definition of seismic fortification class for buildings has been revisited, and as a result, the seismic classifications for schools, hospitals and other buildings that hold large populations such as evacuation shelters and information centers have been upgraded in the GB50223-2008 Code. The main aspects of the revised GB50011-2001 code include: (a) modification of the seismic intensity specified for the Provinces of Sichuan, Shanxi and Gansu; (b) basic conceptual design for retaining walls and building foundations in mountainous areas; (c) regularity of building configuration; (d) integration of masonry structures and pre-cast RC floors; (e) requirements for calculating and detailing stair shafts; and (f) limiting the use of single-bay RC frame structures. Some significant examples of damage in the epicenter areas are provided as a reference in the discussion on the consequences of collapse, the importance of duplicate structural systems, and the integration of RC and masonry structures.

Keywords: Wenchuan earthquake; earthquake damage to buildings; revision of seismic design codes

1 Introduction

Many buildings and infrastructure were seriously damaged or collapsed in the "5.12" Wenchuan earthquake of 2008. A much better understanding of the damage mechanism of different types of buildings has been obtained through comprehensive observations in the field. There was a legal requirement to quickly update China's seismic codes following this event, and experts from throughout the country worked to complete this process. The new versions of the "Standard for Classification of Seismic Protection of Building Constructions GB50223-2008" and "Code for Seismic Design of Buildings GB50011-2001 (2008 version) " were completed within three months after the event and were issued on July 30, 2008 by the national administration. The aim of the newly issued codes is to guarantee the seismic safety of construction and to guide the recovery and reconstruction process in the disaster areas.

This paper summarizes the main changes to the codes based on typical damage observed during the event. It is recognized that the buildings that were designed and constructed following the seismic regulations of the 1989 Code or the 2001 Code performed very well. Most of these buildings were severely damaged by the main shock of the event, since an estimated seismic intensity of 3–4 times greater than the specified intensity occurred in the epicenter region, but they still did not collapse. The three seismic performance objectives of "operational at the minor earthquake level," "life safety at the moderate earthquake level" and "collapse prevention at the major earthquake level" were achieved. The main causes of severe damage were a lack of seismic measures in older buildings and low-cost housing in rural areas, and poor quality of design and construction. In addition, the higher effective seismic intensity beyond the specified intensity, the effects of wave propagation, and topographic and geological conditions contributed to the serious losses in this disaster.

It was observed through the field investigation of damage to buildings that different types of buildings suffered varying degrees of damage even at the same site. For example, some RC structures with a higher seismic capacity collapsed and masonry structures with a lower seismic capacity had severe cracks but did not collapse. In the region of high seismic intensity, sudden collapse of the bottom part of some structures

Correspondence to: Wang Yayong, Institute of Earthquake Engineering, China Academy of Building Research, Beijing 100013, China
Tel: 86-10-84282354
E-mail: yayongwang@sina.com
†Professor

Supported by: National Natural Science Foundation of China Under Grant No. 50439010; NSFC and Korea Science and Engineering Foundation Under Grant No. 50811140341
Received April 15, 2010; **Accepted** May 14, 2010

was caused by a lack of redundancy and/or a duplicate structural system, while serious failures of other structures occurred because of large open spaces and irregular configurations. Other types of damage observed throughout the disaster region included "strong beam and weak column," knocking and sequential collapse due to improper arrangement of partitions, destruction of stair shafts in masonry houses, pre-cast RC floor and room slabs as well as nonstructural members, etc. Therefore, the study of the seismic behavior of buildings had to be carried out both for damaged and collapsed buildings, as well as for those that cracked but stood or even remained in good condition, in order to offer successful experiences together with the failure lessons to be included in future code revisions.

2 Revision of "Standard for Classification of Seismic Protection of Building Constructions GB50223-2008" (cited as the 2008 Standard)

2.1 Lowest requirement for seismic risk reduction

The 2008 Standard regulates that all engineered buildings, including new, rebuilt and expanded structures, shall identify their seismic class which shall not be ranked below the corresponding class regulated in the Standard. The lowest requirement of seismic risk reduction is based on a combination of factors, including the environment of earthquake risk potential, the ability to predict the occurrence of an earthquake, the occupancy and operation of buildings and infrastructures, as well as the sequence of potential disasters. This means that the seismic category for buildings shall handle both safety and economics. It also sometimes allows the seismic class to be enhanced for a specified building in case the owner wants to do so.

2.2 Seismic category of buildings

The seismic category of buildings can be expressed as either Class A (special), Class B (important), Class C (regular) or Class D (proper) in the 2008 Standard.

The previous 1995 Standard focused on seismic requirements for lifeline systems to ensure continuation of industrial and economic activities. Instead, the updated 2008 Standard gives more attention to life safety and the impact to society, and also to emergency response and rescue work. The field survey has shown that the "5.12" earthquake occurred during school hours, at 2:28 pm, and thousands of pupils were killed or injured by collapsed school buildings. This indicated that the seismic capacity of school buildings had to be upgraded. The 2008 Standard has therefore stressed that the seismic category all buildings holding pupils in kindergartens, primary and secondary schools be at least Class B (important), which had already been required for kindergartens and primary schools by the 2004 Standard. In addition, the seismic category of large scale hospital buildings has to be Class A (special) or Class B (important) to accommodate emergency rescue needs. It is also necessary to upgrade the seismic category of local hospitals and clinics with the capability to perform surgical operations from Class C to Class B, to enable first aid to be available immediately after an event. The 2008 Standard has regulated that buildings functioning as a rescue center be of Class A or B, and that infrastructure such as gas and water supply systems and drainage engineering, and facilities for public service such as supermarkets, sports, entertainment, etc., be categorized as Class B.

3 Revision of "Code for Seismic Design of Buildings GB50011-2008" (cited as the 2008 Code)

3.1 Modification to the national standard "The Map of Earthquake Zoning in China GB18306-2001" for Western China

Earthquake zoning parameters such as seismic intensity, basic peak ground acceleration (PGA) and seismic design categories have been modified following the "5.12" Wenchuan earthquake for over 70 cities and counties in Sichuan, Gansu and Shaanxi provinces.

3.2 Geological disaster and seismic design for buildings in mountainous areas

Many buildings were severely damaged in mountainous areas in the earthquake. A strict limit for siting construction has been given in the revised 2008 Code, so that Class A and B buildings are prohibited from being located in areas with a high potential for geological hazards, such as landslides, rock falls, ground subsidence, cracking, debris flow and earthquake rupture slipping, etc. Some buildings with damage induced by geological disasters are shown in Fig. 1 to Fig. 4.

Figure 1 shows totally collapsed buildings in a range of 27 m wide along the rupture line, and an area of about 220 m wide, where moderate to severe damage occurred. This indicates that the location of buildings should meet a requirement of a minimum distance of 200 to 300 m from the earthquake rupture issued by the code. Not long after the event, a heavy rain fell for two days on September 23–24, 2008, which induced a turbulent debris flow from the mountain area, sweeping Beichuan County and burying many streets and buildings. The debris cover was 6 m at shallow sites to over 40 m at its deepest. Figure 4 shows a four-story apartment building buried by the mud flow.

Retaining walls are required by the 2008 Code for construction in mountainous areas. Space between the building foundation from the foot of a hill is also specified in the 2008 Code. It is very dangerous and forbidden to locate a building on a retaining wall.

Fig. 1 Collapses induced by rupture slipping on the ground (Photo from Yuan Yifan)

Fig. 2 Maoba High School buried by a rock slide in Qushan Town, Beichuan County

Fig. 3 Apartment building partially buried by landslide in Wenchuan County

Figure 5 shows a failure of the bottom frame structure of a complex building used for commerce and residential purposes in Beichuan County, where severe damage was caused by pressure from the retaining wall.

Fig. 4 Apartment building mostly buried by debris flow late Sept. in Beichuan County

Fig. 5 Bottom frame structure severely damaged due to failure of slope wall

3.3 Essential requirements for seismic design

3.3.1 Regularity of configuration

The 2008 Code has stressed that both architects and engineers should follow seismic design concepts. Special measures should be taken for irregular configurations of a building. It is prohibited to design an irregular building to be located in seismic regions. Much damage was caused by irregular designs in this event. For example, two complex buildings with a bottom frame of RC and a masonry structure above were severely damaged and even partially collapsed due to their irregular plan and elevation (see Figs. 6 and 7). Figure 8 shows a damaged complex building with a two-story RC bottom frame and an upper masonry structure. It is known that this type of complex structure performs poorly in earthquake regions and should be carefully designed or not used.

3.3.2 Structural integrity and conceptual design

Structural integrity primarily depends on the detailing of the joints among structural members in addition to their own strength. The 2008 Code has regulated that conceptual designs with "strong column and weak beam," "capacity of strong shear and weak

Fig. 6 Damaged RC bottom frame structure (0.1g/0.4g). Note: (0.1g/0.4g) = (specified PGA/estimated PGA)

Fig. 7 Damaged upper walls of masonry building with RC bottom frame structure (0.1g/0.4g)

Fig. 8 Damaged masonry building with two-story RC bottom frame structure (0.1g/1.0g)

Fig. 9 Plastic hinges on top of a column (0.1g/0.3g) (Photo from Yao Qiulia)

moment" and "strong joint and weak element" should be used for RC structures. The RC boundary beam and tie column, and RC core column or reinforced wall should be used for masonry structures. Finally, partial or complete buckling and yielding of elements should be avoided for steel structures. Reliable measures should be taken to guarantee the integrity of the joints among pre-cast RC slabs of the roof and floor system.

3.3.2.1 "Strong column and weak beam" design for RC frame structures

The definition of strong column and weak beam indicates that the moment capacities of the beam and column at the joint should be defined as

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

The 2001 Code simply adopts a factor η_{c} to enlarge the moment capacity of the column by

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

where η_{c} = 1.1, 1.2, 1.4, respectively, for different grades of RC columns. However, in practice, the goal of strong column and weak beam cannot be achieved because the flexural stiffness of the beam is multiplied simply by a factor of 1.5–2.0 to consider the area where the floor slab joins with the beam while calculating the moment at the ends of the beam. In the "5.12" Wenchuan earthquake, the failure of many RC frame structures was due to problems associated with a "strong beam and weak column. Figure 9 shows the failure mechanism of a six-story RC frame structure in Dujiangyan City. Plastic hinges can be seen at the top of the column of the ground floor, but beams and slabs remained undamaged. Figure 10 shows a collapsed RC frame structure in Beichuan County, the epicenter area, where it can be seen that the reinforcement ratio of the beams was much larger than the columns.

3.3.2.2 Cast-in-situ RC floor and roof slabs

The floor and roof systems integrated with cast-in-situ RC slabs performed well in cases of large deflection, which have been commonly used in multi-story and tall buildings. In the 2008 Code, the use of cast-in-situ RC floor slabs was encouraged for large masonry schools and hospitals. Figure 11 shows the collapsed ground floor and internal walls of a five-story student hostel building made of masonry. Note that the cast-in-situ RC floor slab remains with large deflection.

3.3.2.3 Pre-cast RC floor and roof slabs

The field survey revealed that pre-cast floor and roof slabs might collapse if the support wall or beam was broken or large horizontal displacement occurred due to poor detailing of the joints and structural integration. Figure 12 shows a completely collapsed three-story primary school masonry building. There was no connecting detail between either the slab & beam or the slab & slab. Figure 13 shows a partially collapsed five-story masonry school building that lacked the required RC tie- column and boundary-beam.

The goal of collapse prevention can be achieved even for pre-cast RC structures if the connection details between slabs, slab & wall, and slab & support beam are properly designed and constructed. Figures 14–16 show a three-story masonry school building which was subjected to earthquake forces scaled at an estimated seismic intensity of four times the specified intensity. The building was severely damaged but remained standing due to the excellent connection between the RC slabs and tie-beams surrounding each floor and the roof.

Therefore, the 2008 Code has regulated that reliable measures to ensure the integrity of the connection joint among pre-cast RC slabs of the floor and roof system be mandated.

3.3.2.4 Duplicate earthquake resistance system

The concept of a duplicate earthquake resistance system was addressed in the 2001 Code, which was significant in preventing the collapse of some structures. It is known that the secondary members of a structure, such as the bracing of a frame structure or the coupling beam of a shear wall structure, may be damaged before major members such as a column and/or shear wall are

Fig. 10 Less reinforcements to column than beam (0.1g/1.0g)

Fig. 12 Collapsed pre-cast RC floor slabs (0.1g/0.2g)

Fig. 11 Large deflection of floor formed with cast-in-situ RC beams and slabs (0.1g/1.0g)

Fig. 13 Partially collapsed masonry structure due to lack of required tie-column and boundary-beam (0.1g/0.3g)

affected, to reduce the earthquake forces. The RC tie-column and boundary-beam are required to enhance the ductility of masonry walls and could act as secondary members to prevent masonry structures from collapse in major earthquakes.

(1) Features of structural damage in epicenter regions

The ground motion in the epicenter area was so strong that the bottom floor of many structures suddenly collapsed at the moment of the initial arrival of the earthquake wave, and therefore the ground motion could be isolated by the collapsed layer to save the upper stories from severe failures. Figure 17 shows a confined masonry apartment building located in Beichuan County, in the epicenter area. The two bottom-stories were destroyed and suddenly collapsed by the first shock at the initial arrival of earthquake wave, but the five upper stories remained intact.

(2) Structural redundancy

The 2008 Code required structural systems to avoid a loss of loading capacity and seismic capacity due to the failure of a part of the structure or its elements. Adoption of a duplicate system and increasing the structural redundancy by means of a multi-bay frame, additional braces or shear wall is encouraged. The seismic capacity of key parts of a structure and its members should be enforced to prevent the entire structure from sequential collapse.

It was learned from building damage in the 1995 Kobe earthquake, 1999 Chi-Chi earthquake and again in the 2008 Wenchuan earthquake that use of a single-bay RC frame structure for tall buildings should be restricted due to its lack of structural redundancy.

Figure 18 shows the Xuankou High School before the event in Yingxiu Town, Wenchuan County. The five-story teaching building and laboratory were constructed of two-bay RC frame structures with some redundancy. Fortunately, more than 1,200 students escaped from these two buildings, which survived the main shock with an intensity of over 11 degrees (PGA≈1.0 g) in the epicenter area. The teaching building partially collapsed and the laboratory totally collapsed in the aftershock (see Figs. 19–21).

(3) Ductility of masonry structures

For masonry structures, the limits of height, number of stories and floor heights are specified in the 2008 Code. The limits for Class B buildings should be taken based on a seismic intensity of one degree higher than the specified intensity. For Class B school and

Fig. 14 Severely damaged three-story masonry school building (0.05g/0.20g)

Fig. 15 Collapse of transverse wall (0.05g/0.20g)

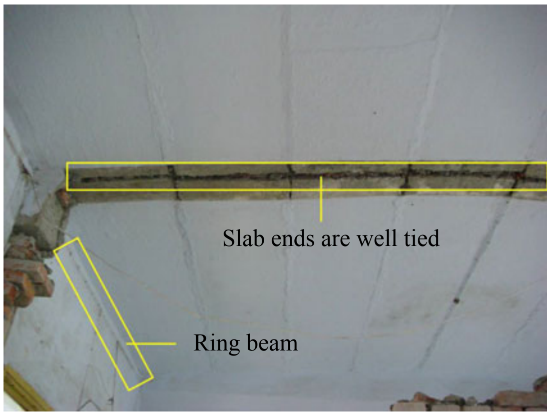

Fig. 16 Stable floor of pre-cast slabs with excellent joints and tie-beams (0.05g/0.20g)

Fig. 17 Two bottom stories collapsed and five upper stories remained standing, Beichuan County (0.1g/1.0g)

hospital buildings, the limits should be defined based on a seismic intensity of two degrees higher than the specified one. Some questions were proposed after the "5.12" Wenchuan earthquake. Could masonry structures be used again in earthquake-prone areas? Should school buildings be made of RC? Should pre-cast RC slabs be prohibited for use as the floor system for masonry structures? The careful study of the performance of masonry structures in regions severely impacted by a disaster indicates that if the special technique of using a confined RC boundary-beam and tie-column has been taken, the seismic performance objectives of "operational at the minor earthquake level," "life safety at the moderate earthquake level" and "collapse prevention at the major earthquake level" can be achieved for masonry structures.

For example, there was a four-story RC single-bay frame hospital structure and a masonry residential structure located side by side at the site of an effective seismic intensity of 9 degrees (PGA = 0.40 g) in Nanba Town, Pingwu County. The seismic design was based on the specified intensity of 7 degrees (PGA = 0.10 g), which was much lower than the estimated actual intensity at the site. The hospital building was severely damaged and nearly collapsed, while the residential building survived due to the excellent confinement of the masonry structure (see Figs. 22–24).

(4) Collision and sequential collapse

A seismic partition for a building with an irregular plan is required by the design code. The position and the width of the separation joint should be set depending upon the specified seismic intensity, type of structure

Fig. 18 Xuankou High School constructed in 2006

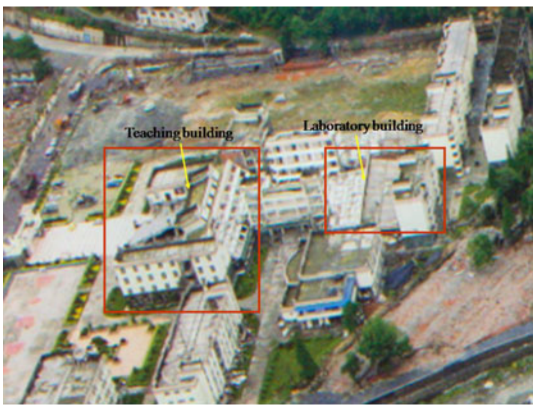

Fig. 19 Damaged Xuankou High School (0.1g/1.0g)

Fig. 20 Partially collapsed teaching building (0.1g/1.0g)

Fig. 21 Totally collapsed laboratory building (0.1g/1.0g)

Fig. 22 Damage to two nearby buildings (0.1g/0.4g)

and building height. The upper structures at both sides of the partition should be completely separated to avoid knocking. However, it is not necessary to set partitions for any irregular building. The 2008 code requires that the width of a partition be large enough to avoid collision of the upper structures during earthquakes that may result in a sequential collapse. Figures 25–26 show an example of a sequential collapse of buildings in Beichuan County, the epicenter area. The commercial buildings on the left side of the street sequentially collapsed due to knocking from the office building on the right side of the street.

(5) Seismic design of stair shaft

The stair shaft, at the entrance and exit of buildings, provides the only way for people to evacuate and should therefore guarantee safety in the case of any disaster, including earthquake. Clause 7.3.1 of the 2008 Code stresses that RC tie-columns should be set up at the corners of stair shaft and exterior walls, ends of step beam, the joints of interior and exterior walls, etc. in masonry structures. Clause 7.3.8 again requires that the pre-cast step beam be appropriately connected with the platform beam, and the RC tie-columns should expand up to the top of the stair shaft above the roof. Figure 27 shows a severely damaged three-story masonry teaching building. The stair shaft collapsed due to a lack of tie-

Fig. 25 Collision between an office building and apartment buildings in Beichuan County (0.1g/1.0g)

Fig. 23 Severely damaged four-story RC single-bay frame single span hospital building (0.1g/0.4g)

Fig. 26 Sequential collapse of commercial buildings in Beichuan County (0.1g/1.0g)

Fig. 24 Good performance of four-story confined masonry apartment building (0.1g/0.4g)

Fig. 27 Collapsed stair shaft of a three-story school building in Mianzhu County (0.1g/0.3g)

Fig. 28 Six-story masonry residence building remained stable with a severely damaged stair shaft (0.1g/0.3g)

columns at its corners. In contrast, Fig. 28 presents an example of a successful design. Although the brick walls and step beams of the six-story masonry residential building were severely damaged, the stair shaft remained stable because the tie-columns were appropriately set at the ends of the platform beam.

4 Conclusions

Some members of the Code Editorial Group have taken part in field investigations in the disaster areas after the "5.12" Wenchuan earthquake. A large amount of damage data from buildings and infrastructure was collected. The study of building damage on structures of different ages in accordance with the corresponding design codes was carried out after the earthquake. A revision of the "Standard for Classification of Seismic Protection of Building Constructions GB50223-2008" and "Code for Seismic Design of Buildings GB50011-2001(2008 version)" was completed within three months and published on 30 July, 2008.

In general, the seismic capacity of many structures has been upgraded. The seismic class for schools, hospitals and buildings with a high occupancy rate, low-cost houses in rural areas, and infrastructure has been raised to a higher level by the 2008 Standard.

A study that compared code regulations with observed damage has shown that the seismic conceptual design, i.e., the essential requirements issued by the code, is sometimes more significant and difficult for engineers to deal with than the structural calculation. The 2008 Code stresses that (a) the integration and duplicate seismic structural systems are very important and necessary for some structures, (b) the configurations of buildings should be regular and symmetric to the extent possible, and (c) structural redundancy is a key factor in ensuring that collapse is avoided when an individual member fails.

There is no doubt that the Code should be further improved gradually. There are still many issues that need to be addressed. For example, how can the "strong column and weak beam" for a frame structure be realized? How can the partition of a building be set correctly? How can buildings avoid sequential collapse? How is the stair shaft involved in modeling of structure analyses? How are the joints of pre-cast RC slabs detailed properly? How can nonstructural members and their joints, such as infill walls, ceilings, curtain walls, etc., be designed? Can a complex structure with a bottom frame and upper masonry walls be used in seismic regions? These questions are expected to be resolved in the next revision of the code.

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