Analysis on Building Seismic Damage in the Wenchuan Earthquake

Ye Lieping, Lu Xinzheng, Qu Zhe, Feng Peng
Department of Civil Engineering, Tsinghua University, Beijing 10084 China

Abstract: On 12 May 2008, a violent earthquake with a magnitude of 8.0 occurred in Wenchuan, Sichuan Province, China. The earthquake resulted in a large number of collapses and damages of buildings, and brought huge loss to the people's lives and properties. This paper gathers the building seismic damage data in major disaster area. The data are classified according to structural type, construction time and occupancies. It is learned that the strict implementation of seismic design codes is the prerequisite to guarantee the seismic capacity of building structures. For masonry structures, the design of structural system and earthquake-resistant measures should be emphasized and the construction quality should be ensured. For RC frame structures, the construction measure of the connections between enclosure and filler walls and the main structure should be carefully designed. Measures to ensure the strong column-weak beam damage mode should be revised and improved. Furthermore, methods to increase the integral aseismic capacity of building structures are discussed in the framework of system theory. It is shown that the safety margin of building structural systems can be divided into three levels, say fundamental, integral and unexpected safety margins. The overall seismic capacity and collapse prevention of building structures are mainly determined by the integral safety margin and unexpected safety margin. Lack of unexpected safety margin is one of the main reasons of the severe building damage in the Sichuan earthquake. The unexpected safety margin of a structural system mainly comes from its robustness, stability and firmness. Researches on the integral and unexpected safety margins of building structures are still very limited. Corresponding requirements and specifications in current design code for building structures are to be improved.

Keywords: Sichuan earthquake, seismic damage, wholeness, safety margin

On 14:28:04, 12 May 2008, local time, a great earthquake located in 31.0°N, 103.4°E with Richter magnitude 8.0 by CENC and a focal depth of 14km occurred near Yingxiu in Wenchuan County, Sichuan, China. It caused great damage to an area over 100,000km^2 and was felt in most part of China. By 24 June 2008, 69185 people were killed in the earthquake, and 18467 were missing, 374170 were injured. After the earthquake, structural professional teams of Tsinghua University were sent to Sichuan province to investigate the building damage in the earthquake. Some preliminary statistics of building damage regarding the structural types, construction time, local intensity and building functions were obtained and reported in this paper. Methods to increase the overall aseismic capacity of building structures are further discussed in the framework of system theory. Some key problems and suggestions for seismic design, especially for enhancing the capacity of collapse prevention of building structures are proposed.

1 Typical building damages in the Sichuan earthquake

1.1 Masonry structure with timber roof

This type of structure is widely used in single-story factories, warehouses and residential houses in the rural area for its cheap materials. These buildings are usually old and lack of maintenance. The strength of most of their masonry walls and columns can not meet the requirements of current building codes. They are vulnerable to overall and partial collapse in the earthquake. See Figure 1.

A factory in Anxian
A folk house in Yinghua
The classroom of Hongbai Middleschool

Fig. 1 Seismic damage of masonry structures with timber roof

1.2 Reinforced masonry structures

Most residential buildings, school buildings in the rural area, and some of factories, old residential and office buildings in the cities use the reinforced masonry structures, which is the most common structure type in the earthquake area. A lot of buildings of this structure type collapsed or were heavily damaged in the earthquake. Some general reasons of its vulnerability are: poor redundancy of structural system, lack of concrete structural columns and ring beams, poor connections of pre-cast slabs and so on. Figure 2 shows some typical damages of such structures. Some undamaged or slightly damaged buildings with this structure type could also be seen in the meizoseismal area. This proved that buildings with this structure type are able to survive the great earthquake only if the earthquake-resistant measures such as concrete structural columns and ring beams are ensured. To enhance the wholeness and lateral resistance is the key issue in the design of such structures.

Collapse of the teaching building of Nanba primary school, Nanba
Severe damage in the load-bearing walls and columns of the teaching building of Huayuan St. Middle School, Jiangyou
Undamaged masonry structures with concrete structural columns and ring beams in Anxian

Fig.2 Seismic damage of RC-strengthened masonry structures

1.3 RC frame and masonry hybrid structures

There’re many hybrid layouts including vertical hybrid such as masonry structures with bottom RC frames, and horizontal hybrid structure with partial RC frames and partial masonry structures. The load-bearing system, especially the lateral load-resistant systems of these structures are generally disordered and inconsistent in deformation between different parts. The vertical or horizontal stiffness of most of these structures is also badly distributed. Some common damages of these structures are: weak story collapse and the collapse of upside masonry structures. See Figure 3.

A gas station using masonry structure with bottom RC frame, Hongbai

The damage of an office building using horizontal hybrid structure

Fig.3 Seismic damage of RC frame-masonry hybrid structures

1.4 RC frame structures

Filler wall collapsed, Dujiangyan

Collapse of a RC frame with a heavy roof, Dujiangyan

Weak story collapse of a RC frame

Shear failure of short columns in a split-level RC frames

Plastic hinges in frame columns, Nanba

Fig. 4 Seismic damage in frame structures

The damage of most of the buildings with RC frame structures was not very severe in the earthquake. The damage mainly occurred in the enclosure structures and filler walls, especially circular filler walls. Such nonstructural damage also brings considerable economic loss and is even harmful to people’s safety. Some RC frames collapsed in the earthquake due to poor construction quality or badly-designed structural system. The expected “strong column-weak beam” damage mode can be seldom found in the real damage, which may be the result of disregarding the strengthening effect of floor slabs and filler walls when the RC beams are designed. Figure 4 shows some typical damage in RC frames, including the shear failure of short frame columns in split-level buildings.

1.5 RC frame-shearwall (core tube) structures

This type of structure shows its advantage in seismic behavior in the earthquake. The damage of buildings with RC frame-shearwall (core tube) structures is very slight compared with that of nearby buildings with pure RC frame or other structures. Figure 5 is Xinyi Building in Mianyang city. Only some minor cracks were found in its enclosure walls in the earthquake survey.

However, this structure type is only used in modern cities such as Chengdu and Mianyang, where the earthquake intensity was relatively small. As a result, the seismic resistance of RC frame-shearwall (core tube) structures against severe earthquake has not been checked in this earthquake.

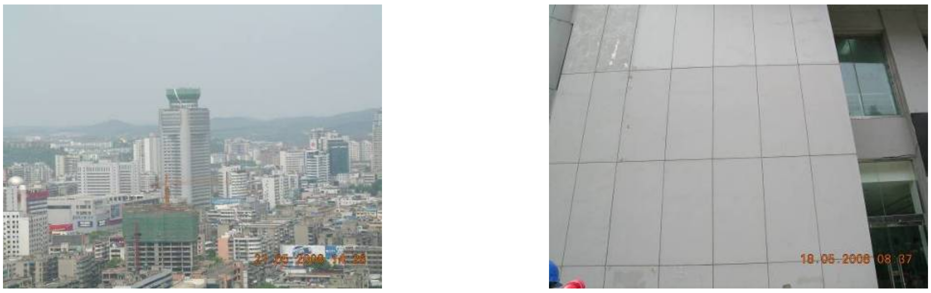

Fig. 5 Xinyi Building in Mianyang
(No damage in load-bearing structure. Only small cracks in some enclosure structures)

1.6 Large-span steel structures

The damage of this kind of structures was very slight and occurred mainly in the enclosure structures. Figure 6 shows the Jiuzhou Stadium in Mianyang city. No damage was found in its major steel structure and concrete supports. Only some damage due to collision was found in the connections between the steel truss and enclosure walls.

Fig. 6 Mianyang Jiuzhou Stadium

1.7 Other damage

Some other typical damage was found in the earthquake area including damage due to the collision in expansion joints (Figure 8) and whiplash effect (Figure 9).

A hotel in Mianyang

Fig. Collision damage in expansion joints

A public building in Dujiangyan

Fig. 9 Rooftop projection structural damage due to whiplash effect

2 Statistics of building damage

Building damaged in the earthquake is classified into the following 4 categories according to the influence to the building functions:

(1) Operational: The whole building keeps undamaged or only some nonstructural elements are slightly damaged. The normal operation will not harm the load-bearing structure and the damage in non-structural elements will not cause further economical loss and human injury.

(2) Out of service before retrofitting: The load-bearing structure is damaged, some nonstructural elements collapses. Without retrofitting, the structural damage may become more severe or the remaining nonstructural

elements are not stable and may cause further economical loss and human injury.

(3) Not reparable: The structure is severely damaged but will not collapse. The structure is not reparable.

(4) Immediate demolition: The structure is near collapse and dangerous.

Buildings in the earthquake area with different structural types, construction time and functions will be examined and classified into the above categories in order to generate the statistic data, which is helpful in discovering the courses of damage and further improving the current seismic fortification criterion.

2.1 By structural types

Table 1 shows the damage statistics of buildings with different structural types, including masonry structures, RC frame-masonry hybrid structures and RC frame structures. According to the proportions of severely damaged buildings (including “Not repairable” and “Immediate demolition”), the seismic capacities of buildings with different structure types can be concluded as the following sequence from poor to good: masonry structure, RC frame-masonry hybrid structure, RC frame structure. Except for structural difference, building quality management is another important issue influencing the seismic capacities of buildings with different structural types. Masonry structures are widely used in the rural area where the construction is not under the national supervision system. Many buildings are constructed without any design, or by disqualified constructors. As a result, these structure systems are disordered and their seismic behavior is hard to predict. In contrast, most RC frame structures have clear load paths and it’s easier to control the construction quality.

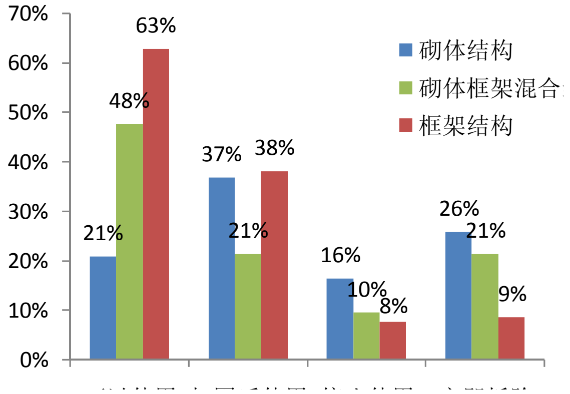

Fig. 12 Comparison of seismic damage for masonry structures, frame-masonry structures and frame structures

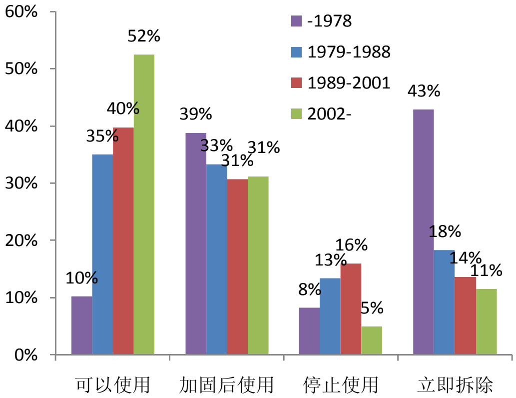

Fig. 13 Comparison of seismic damage for buildings with different construction time periods

2.2 By construction time periods

Service life and design code are the two issues relating to the construction time. Figure 13 shows the damage statistics of buildings with different construction time period. Buildings constructed before 1978 were damaged most severely. These buildings are almost masonry structures and have serviced for a long time. On the other hand, the structural safety margin specified in the building design codes at that time was relative low.

After the 1976 Tangshan earthquake, more effort has been devoted into the research of earthquake engineering in China. It can be shown that the building seismic design codes have been improved from TJ11-78[1], the early edition published in 1978, through GBJ 11-89[2] in 1989, to the latest edition GB50011-2001[3] in 2001. At the same time, since the reform and opening in late 1970s, the safety margin in structure design codes has been progressively increased through years with the economic growth. Table 4 compares the structural safety margins in the Chinese design codes for concrete structures in different time periods. The safety level and safety margin of building structures specified in TJ 10-74 in 1974 is relatively low due to the economic condition at that time, and have been increased from then on.

Table 4 Comparison for the safety levels and safety margins of different versions of concrete design codes (Source: CABR)

Codes	Safety level		Safety margin	
	flexure	compression	flexure	compression
BJG21-66[4]	2.22 (1.59）	2.10 (1.35)	2.22 (1.27)	2.10 (1.13)
TJ 10-74[5]	1.40 (1.00）	1.55 (1.00)	1.75 (1.00)	1.86 (1.00)
GBJ 10-89[6]	1.72 (1.23)	1.61 (1.04)	2.24 (1.28)	2.08 (1.12)
GB50010-2002[7]	2.15 (1.54)	2.00 (1.29)	2.80 (1.60)	2.60 (1.39)

*Take TJ 10-74 as the benchmark; Safety level: calculated by nominal values; Safety margin: calculated by design values.

2.3 By building functions

Figure 14 shows the damage statistics of buildings with different functions. School buildings and factories are damaged most severely. Large-bay masonry structure with large window openings in the load-bearing walls is generally used in school buildings in the earthquake area. Besides, some of these buildings were constructed even without any seismic design and construction measures. As a result, these structures are more vulnerable to earthquake damage. Factories in the rural area are usually small and also use masonry structures. The seismic design criterion for these structures is relatively low. The government office buildings usually use RC frame structures. So the damage is not severe.

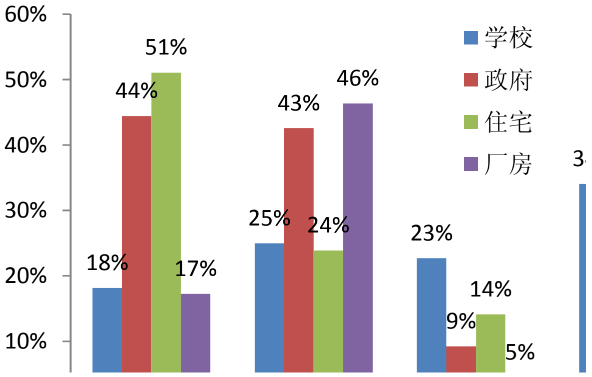

Fig. 14 Comparison of building seismic damage with different functions of usage

3 Design concepts to increase the anti-collapse capacity of building structures

Preventing the collapse of building structures in the meizoseismal area is a basic fortification requirement to save people’s lives. More research is needed to understand the mechanism of building collapse and to develop practical methods of anti-collapse design for different kinds of building structures. One of the key issues is the wholeness of building structural systems.

3.1 Robustness, integral stability and integral firmness of structural systems

Building structure is a complex system made of many different structural elements. In the framework of system science, the function of a complex system mainly relies on its characteristic of “emerging as a whole”, or its wholeness. That’s to say the whole is not equal to the sum of parts. For building structures, the function of elements relies on the whole structural system. An element will lose some of its function once it is not in the system. On the other hand, the function of the whole structural system relies on each of its elements. The system function loss when an element fails is not equal to, but bigger or smaller than the element’s function.

The influence of system wholeness over its function can be very different regarding the way to organize its elements. Sometimes, local failure of the structural system may cause disproportionate function loss of the whole system due to interactions of elements. In such cases, the whole seismic capacity of a structure system is weakened by its wholeness, so we call it “negative wholeness”. Structural vulnerability, which has been extensively studied in order to better understand the mechanism of building collapse after the 9/11 disaster, is a famous example of negative wholeness.

What is in contrast is so called “positive wholeness”. The system damage due to local failures can be effectively controlled to a minimal degree in a well-designed and organized structural system. The interrelation of elements plays a positive role in this procedure. Structural robustness and integral stability are two typical expressions of positive wholeness.

Structural robustness is the capacity of a structural system to prevent disproportionate function loss when suffered from local failures. In other words, the influence of the failure of an element over the whole structural system is very limited. Ye Lieping et al (2008)[8] discussed the important role of robustness in preventing building collapse under severe earthquake. Methods to increase the structural robustness were also proposed, including increasing the structural redundancy, clarifying the functions of different elements, using dual- or multi-lateral resistant systems, increasing the structural integral firmness and so on.

Different from structural robustness, which focuses on the degree of final damage, structural integral stability focuses on the damage procedure. Here the term “stability” is generalized to describe that the structural status changes from one to another in a stable evolving process instead of any sudden changes. Buckling is only one of these sudden changes and is not a major topic of this paper. If a sudden change happens, the collapse of building structure will be difficult to predict or control. As a result, a stable, continuous and sequential damage process is preferred, which is relatively easy to predict and control. Ye Lieping (2007)[9] discussed global and local failure modes of building structures under earthquake. The global mode has a stable damage process, where the capacities of all parts of the structural system can be taken full advantage of before the system finally fails. It’s a favorable damage mode.

Structural robustness and integral stability is actually the two sides of a coin. Robustness cares about the damage result and integral stability cares about the damage process. So design concepts and methods to increase both the robustness and integral stability should be consistent.

Furthermore, interrelation between elements is the basis of building up a system. The wholeness of a structural system will become impossible if the system is easily disassembled under the earthquake. For this reason, the structural integral firmness is the basis for structural robustness and integral stability. It requires the connections between structural elements to be strong enough to ensure the structural system stays as a whole before its final failure.

It should be noted that the integral firmness is not sufficient, but only a prerequisite to achieve the positive wholeness of building structures. Take masonry structure with bottom RC frame as an example. The connections between different parts of the structures (i.e. integral firmness) may be very strong, but the badly-distributed story stiffness determines its vulnerability to local failure mode. Thus its seismic capacity is still poor despite of its excellent integral firmness.

3.2 Safety margin of structural systems

The seismic behavior of a structure under earthquake is demonstrated as the lateral resistance to displacement curve in Figure 11. Point B indicates the effective yielding point, where the stiffness of the whole structure decreases greatly. Point D is referred as “collapse point” where the structural status changes to collapse. It is defined as such a critical point that before this point the structure can stand itself and its elastic deformation can recover if the lateral load disappears, as the path from point D to point E shown in Figure 11, but beyond this point, the lateral deformation will go on increasing due to its self weight even if the lateral load disappears, as the path from D to F in Figure 11.

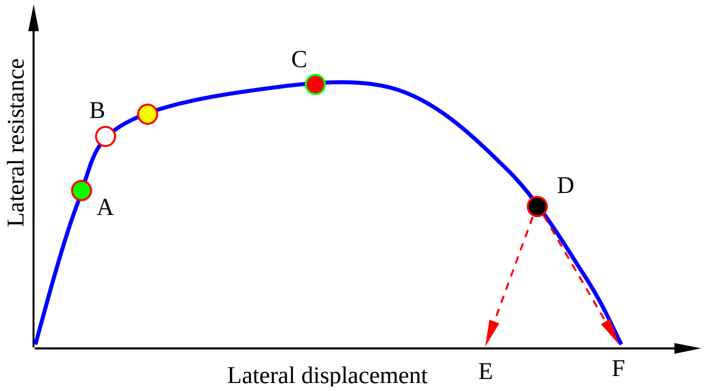

Fig 11 Lateral-load resistant behavior of structures

In the current Chinese seismic design code for building structures, the design earthquake has an exceeding probability of 10% in 50 years. The seismic design is carried out in two phases.

In Phase I, buildings are designed against minor earthquake, which is about 1/3 of the design earthquake. The structure is required not to yield under the minor earthquake with a certain safety margin. A design point demonstrated as Point A in Figure 11 is specified in the codes considering the structural safety margin and possible influence of randomness. In this phase, the safety margin of the whole structure is determined by that of each element, and is numerically equal to the smallest strength safety margin of all its elements. So it can be called “fundamental strength safety margin”, which can be demonstrated as the curve between point A and B in Figure 11. It is to ensure the safety and serviceability of building structural systems during their normal operation.

In Phase II, buildings are designed against severe earthquake, whose intensity is twice of the design earthquake. Collapse prevention is the main task for this phase. Another design point before the collapse point D in Figure 11 (e.g. point C) should be carefully specified. In the current Chinese code, this design point is defined by a maximal elastic-plastic story drift for high-rise or very important building structures. For example, the maximal story drift is 1/50 of the story height for RC frame structures and high-rise steel structures. In this phase, the structural system behaves as a whole. Parts of the structure yield or even fail. The safety margin of the whole structure is related but not equal to that of its elements. It is determined by the strength, ductility, energy-dissipating capacity of all its elements and their organization. In this sense, the safety margin in Phase II can be called “integrated safety margin”, which corresponds to the curve between point B and C in Figure 11.

There should be a third phase regarding the portion between point C and D in Figure 11 since buildings are also vulnerable to unexpected violent earthquake. So far, it’s almost impossible to determine and predict the structural behavior within this phase. But the structural safety margin between point C and D is of key importance to prevent building collapse and to save people’s lives. We call it “unexpected safety margin”, which is believed to be strongly related with the robustness, integral stability and integral firmness of structural systems. Researches on these topics are still very limited.

To improve the current seismic design method for preventing building collapse, more effort should be devoted to better understanding the structural behavior between point C and D in Figure 11. In the Sichuan earthquake, a lot of buildings are severely damaged, whose deformations are larger than point C defined in the design code, but did not collapse. Hence, there are actually many different states between severely damaged and collapse. Figure 12 shows some examples. These buildings are all severely damaged and beyond the design point against severe earthquake in the code. However, many of them are still standing, which may save a lot of people’s lives. To this end, methods to increase the robustness, integral stability and integral firmness should be further studied.

Fig 12 Different states of building damages beyond the design point against severe earthquake

Therefore, only the fundamental strength safety margin can be effectively ensured by current seismic design codes. The design concepts and engineering education about the integral and unexpected safety margins are very limited. It should be emphasized that the structural design is much more than the design of elements. But in the current engineering practice, most effort is devoted to the design of elements and the safety of building structures are not considered as an integral problem. Take the design of masonry structure for example. Brick walls are major load-bearing elements but they are brittle. So their failure is not stable. The ties between walls are usually ignored, resulting in the poor integral firmness. Concrete structural columns and ring beams can form an integral framework providing sufficient confinement to brick walls. They are very important to increase the system robustness, stability and firmness although they don’t carry much load during normal service. Therefore, the fundamental strength safety margin, which is the focus of current design procedure, relies on the brick walls, but the integral and unexpected safety margin mainly come from the concrete structural columns and ring beams. Such a mismatch makes it easy for the engineers and constructors to ignore the structural wholeness. This is very dangerous for the structure under severe earthquake.

4 Conclusions and suggestions

Buliding damages in Wenchuan earthquake are investigated and classified in this work according to the building systems, construction time periods and building occupancies. And the collapse prevention measures of building structures are discussed in depth following the framework of system science. The following conclusions and suggestions can be drawn or proposed:

(1) The seismic damage of masonry structures is generally more severe than that of RC frames; building structures complying with more recent design codes suffered less damage; buildings in developed regions like cities generally performed better than those in the rural areas; the seismic damage of public buildings such as schools and factories is generally more severe than that of residential buildings.

(2) There’re three different levels of safety margin of building structures, referred as fundamental safety margin, integrated safety margin and accidental safety margin. The fundamental safety margin can be determined by the safety margin of the structural elements, while the integrated and accidental safety margin is the characteristic of the whole structural system. The current building design codes in China mainly focus on the fundamental safety margin and do not give enough attention on the latter two.

(3) The building safety can be generally secured through its fundamental safety margin under predicted minor earthquakes. However, the integrated and accidental safety margins are crucial for the buildings to resist severe earthquakes. The lack of integrated and accidental safety margins of building structures is one of the main reasons of the severe damage and loss in the Wenchuan earthquake.

(4) For integrated safety margin, it’s suggested to further study the structural behaviors under severe earthquakes and to develop practical design procedures for the second-phase seismic design. For the accidental safety margin, it’s suggested to study the structure as a system with its unique wholeness, including the robustness, stability and firmness.

References

[1] TJ11-78, Seismic design code for industrial and civil buildings[S]. Beijing: China Building Industry Press, 1979

[2] GBJ 11-89, Code for seismic design of buildings[S], Beijing: China Building Industry Press, 1989

[3] GB50011-2001, Code for seismic design of buildings[S], Beijing: China Building Industry Press, 2001

[4] BJG21-66, Code for design of reinforced concrete structure [S], Beijing: China Building Industry Press, 1966

[5] TJ 10-74, Code for design of reinforced concrete structure [S], Beijing: China Building Industry Press, 1974

[6] GBJ 10-89, Code for design of concrete structure [S], Beijing: China Building Industry Press, 1989

[7] GB 50010-2002, Code for design of concrete structure [S], Beijing: China Building Industry Press, 2002

[8] Ye Lieping, Cheng Guangyu, Lu Xinzheng et al. Introduction of robustness for seismic structures [J]. Building Structures, 38(6) (in Chinese)

[9] Ye Lieping, Qu Zhe, Failure mechanism and its control of building structures under earthquakes based on structural system concept [A], Proceeding of The International Symposium on Advances in Urban Safety[C], Nanjing, China, Oct. 2007: 150-157