Earthq Eng & Eng Vib (2015) 14: 571-578 **DOI**:10.1007/s11803-015-0046-x

# Damage characteristics and seismic capacity of buildings during Nepal $M_s$ 8.1 earthquake

Sun Baitao[1,2†] and Yan Peilei[1,2‡]

1. *Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China*
2. *Key Laboratory of Earthquake Engineering and Engineering Vibration, China Earthquake Administration, Harbin 150080, China*

**Abstract:** The extensive damage to buildings caused by the Nepal $M_s$ 8.1 earthquake has attracted much attention by the international community. After the preliminary scientific investigations on the different affected areas in Nepal, the construction and damage characteristics of five different types of buildings commonly existing in Nepal were discussed and the reasons of their disaster performance were analyzed. Types of buildings investigated include reinforced concrete (RC) frame structures, rubble structures, brick-wood structures, raw soil structures, and brick-wood structures of historic buildings. In addition, the weak links of the seismic design were pointed out, which was very important for the post-earthquake reconstruction and recovery, and gave a preliminary explanations for the damage experienced.

**Keywords:** Nepal earthquake; seismic damage of building; seismic capacity

## 1 Introduction

A strong earthquake of $M_s$ 8.1 hit Nepal in the area between capital Kathmandu and tourist town Pokhara (84.7°E, 28.2°N) at 11:56 am on April 25, 2015 (UTC +5:45), with a depth of 20 km. The earthquake caused extensive damage to buildings and thousands of deaths and injuries and was even felt in Pakistan, India, Bangladesh and China, especially in Nielamu County, Dingri County, Jilong County of Rikaze City in Tibet, China. Then, a powerful aftershock of $M_s$ 7.0 hit the area near Pokhara (84.8°E, 28.3°N) at 12:00 pm with a depth of 30 km. Another huge aftershock of $M_s$ 7.1 occurred to the southeast of the main earthquake area (85.9°E, 27.8°N) at 12:54 pm on April 26 (UTC +5:45), with a depth of 10 km. Seventeen days later, another strong earthquake of $M_s$ 7.5 struck Nepal (86.1°E, 27.8°N) at 12:50 on May 12, with a depth of 10 km. Table 1 shows the details of the main earthquake and strong aftershocks.

The extensive damage to Nepal and neighboring countries caused by the powerful aftershocks became the focus of the international scientific and engineering community. The authors along with the Nepal earthquake assessment team from China , total 22 people, went to Nepal and carried out a 15-day field investigation. The seismic assessment team conducted the seismic damage investigations on various engineering structures, especially on the buildings, in the most affected areas and other areas impacted by the earthquakes. The building inventory in Nepal consists mainly of low-rise buildings, with only few high-rise buildings. In Kathmandu, the capital of Nepal, there are less than 20 reinforced concrete (RC) high-rise buildings with more than 10 stories, most of which were with the Chinese government aid. In the mid-1990s the first edition of the seismic design code of buildings in Nepal (NBC 150, 1994) was published, though its provisions are not complete yet. The seismic design requirements have not been considered in the buildings built 20 years ago, and have not been fully considered in most of the buildings built in recent years. Therefore, the damage to the buildings was significant. The reasons for the less than expected death & injuries, and the economic losses are probably related to the following factors: quick intensity attenuation, the impacted areas with high intensity being relatively small, as well as the low population density, and the small number of the buildings in high-intensity areas.

The Nepal earthquake assessment team organized by the China Earthquake Administration (CEA) had produced the seismic intensity map of the earthquake according to the Chinese Seismic Intensity Scale (GB/T 17742-2008, 2008) shown in Fig. 1. The main shock and the strong aftershocks formed two areas

---

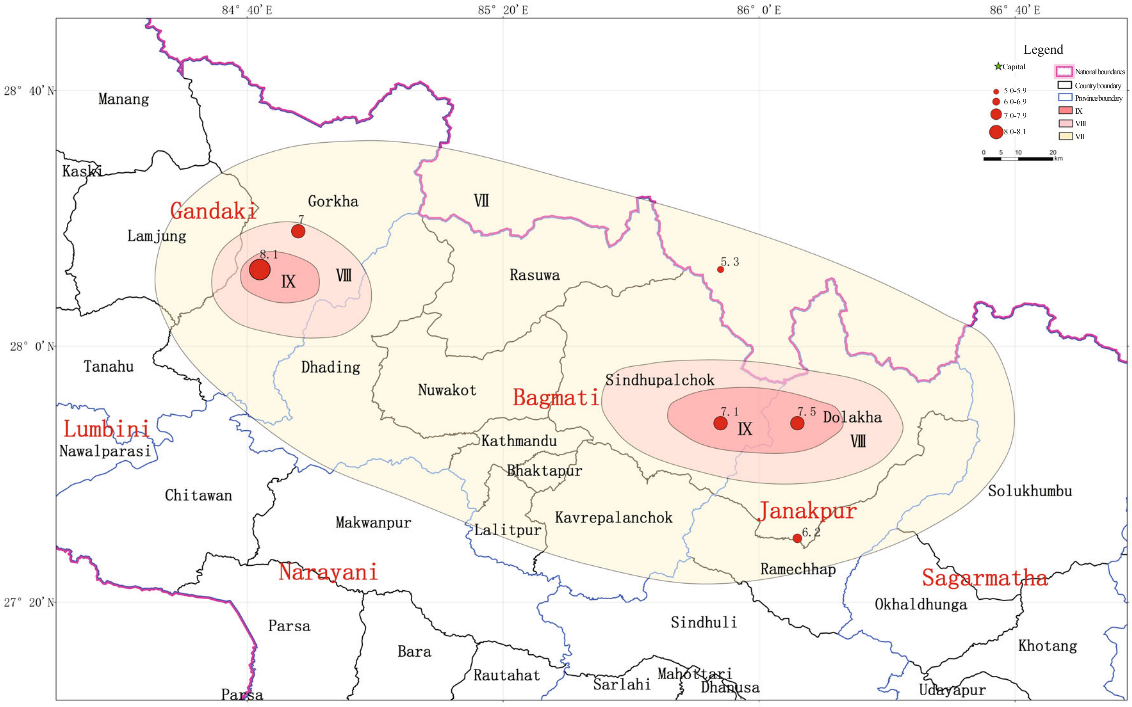
**Correspondence to**: Sun Baitao, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China
E-mail: sunbt@iem.cn

[†]Professor; [‡]Associate Professor

**Supported by:** National Science & Technology Pillar Program No. 2015BAK17B00 and Seismic Industry Research Special Fund under Grant No. 201508026
**Received** June 25, 2015; **Accepted** August 10, 2015

**Table 1 Main earthquake and strong aftershocks sequences of Nepal $M_s$8.1 earthquake**

| No. | $M_s$ | Depth (km) | Time (Nepal, UTC +5:45) | North latitude (°) | East longitude (°) |
|---|---|---|---|---|---|
| 1 | 8.1 | 20 | 11:56 am, April 25, 2015 | 28.2 | 84.7 |
| 2 | 7.0 | 30 | 12:00 pm, April 25, 2015 | 28.3 | 84.8 |
| 3 | 7.1 | 10 | 12:54 pm, April 26, 2015 | 27.8 | 85.9 |
| 4 | 7.5 | 10 | 12:50 pm, May 12, 2015 | 27.8 | 86.1 |



**The earthquake field assessment working group in $M_s$8.1 Nepal earthquake**
**China Earthquake Administration**

**Date:2015/6/18**

**Fig.1 Seismic intensity map of Nepal $M_s$8.1 earthquake**

highly impacted by the disaster.. Due to the low depths (10 km) and large magnitudes (*M*7.1 and *M*7.5) of the aftershocks (Table 1), the eastern area is larger than the area impacted by the main shock.. The intensity in the most seriously impacted areas is IX with rapid intensity attenuation restricted to relatively small area. However, some structures damaged in the $M_s$8.1 earthquake, and the damage aggravated in $M_s$7.1 and $M_s$7.5 earthquake, the damage superposition phenomenon of engineering structures occurred.

In this paper, the construction and damage characteristics and damage mechanisms for the five types of buildings are preliminarily analyzed, the weak links of seismic design are pointed out, and the suggestions on the design and construction are given, which may be helpful to the reconstruction and recovery in Nepal.

## 2 Buildings in Nepal

In Nepal, there are five most popular building types, i.e., rubble structure with timber frame, RC frame structure, brick-wood structure, raw soil structure, and brick-wood structure of historic building. Among them, the rubble structure is the main traditional type, about 50%–60% and concentrates in small towns and rural regions. In developed regions, this type of buildings are mostly old houses. However, in recent decades, a large number of frame structures has mushroomed in the comparatively developed regions and cities, such as Katmandu, Chautara and Dhunche. Most of these frame structures are self-built by the residents, without effective management and regulations by the government. In addition that the design and construction are done by the craftsmen or organizations without adequate seismic design understanding. Few buildings were constructed fully according to the Nepal seismic design code, except some important public buildings-schools, hospitals, government office buildings, etc. The brick-wood structures are mainly old houses, taking a very small proportion, about 3%–5%. The raw soil structures, where the timber frames and the raw soil walls bear the loads, comprise 5% of the inventory.

## 3 Construction & damage characteristics and seismic capacity of different structures

The rubble structures performed the worst during the Nepal earthquake, many were seriously damaged or collapsed in different intensity areas. Since this type of structures are most popular in the rural regions, the rubble structure is the chief culprit for the loss and human casualties. The second worst performing buildings were the raw soil structures, which were damaged in Intensity VII regions and were seriously damaged or collapsed in Intensity VIII regions. The traditional brick-wood structures is small portion of the building inventory, but their seismic capacity is weaker than the commonly used masonry structures. The major reason is that the masonry mortar is mostly mud or mortar. Compared with the above three types of structures, the self-built RC frame structures performed generally well during this earthquake.

### 3.1 Rubble structures

3.1.1 Structural characteristics

The history of the rubble structures can be traced back to 1600 year ago. They were used for the Xiuba Castle, which is the initial prototype of the present rubble structures. At that time, many castles were built using similar rubble structures. The rubble structures have become the major traditional structural type for local residential buildings. The main reason is that the rubble can be found easily and is widespread in both towns and rural regions.

The supporting system of the rubble structure is mixture of internal timber frame and external rubble walls. The embedded depth of foundation is lower or even, while the walls are constructed just on the flat ground base. The timber floors are laid on the longitudinal walls, with mud on them. The roof truss consists of purlins on the gabled roof. The double slope roof with light tile is widely used in the traditional wooden roof, while the single pitch roof can also be found at present. Most of the rubble buildings are two to three story structures. The rooms inside are small, the window openings are usually larger in the front longitudinal walls, with smaller windows or no windows in the back longitudinal walls.

Nepal is located in the south foot of Himalayas, where most rock strata outcrop on the surface, the vegetation coverage is poor with thick humus layer, so that almost all trees have difficulties to grow up. Therefore, the length and the sectional dimensions of the timber components are with small dimensions. The internal timber frames of most residential buildings can hardly play their primary supportive role. In addition, the timber frames are connected with steel parts, which results in poor stability of the timber. For comparison, in Tibet, China, most of the timber frames are connected with tenon-mortise joints and the sectional dimensions of the beams and columns are large. In Nepal, the major raw-material of the walls is small rubbles, which are constructed to 50–60 cm thickness by the marl mortar, so the overall ductility and stability of the walls are very poor. Besides this, there is lack of reliable connections between the timber frame and the walls, and the gables and the longitudinal walls. For the craftsmen with some seismic design understanding, the horizontal longer irregular stones may be vertically laid on the walls in space of 50–60 cm, or the higher grade of marl mortar may be used.

In general, for these rubble structures, the vertical loads are mainly supported by the rubble walls and partly by the timber frames, while the horizontal loads are mainly supported by the walls, as shown in Fig. 2.

3.1.2 Damage characteristics and seismic capacity of rubble structures

The rubble structure is one of the structure types which cannot resist earthquakes. Due to the lack of ductility and effective connection of walls and components, the overall stability is poor and the internal timber frames hardly support the system. This type of structures visibly damaged in Intensity VI areas, few collapsed and some were moderately damaged in Intensity VII areas, while most collapsed or were seriously damaged in Intensity VIII areas.

The general damage patterns consist of an initial drop of top of the gable, the connection of the gable and the longitudinal walls yields, followed by collapse of the gable the longitudinal walls, as shown in Fig. 3. Without the effective connection, the timber frames cannot support the walls. However, the internal timber frames can prevent the walls falling down inward to some extent, so most of the damaged walls collapse outward. When the timber frames collapse, the roof falls down and the buildings completely collapse (Fig. 4).

### 3.2 RC frame structures

3.2.1 Structural characteristics

The RC frame structure has been widely used in the developed regions and by the wealthy families of Nepal since the last two decades, which has become a universally accepted structural type. The buildings are mostly constructed without considering the seismic design requirements and using relatively standard construction methods. In recent years, only the government and public buildings have been constructed according to the seismic design code. However, since the local code regulations are incomplete, the RC frame structures under standard design and construction have also been damaged at different levels.

The RC frame buildings are mainly three to five story structures. For the three-story structures, the independent foundation under column is set up, and the RC columns and steel reinforcement cages for the additive floors

**Fig. 2 Typical rubble structure**

**Fig. 3 Partial collapse of a rubble structure in Intensity VIII area**

are half outcropped on the roof. The thickness of the cast-in-place floors and roof panels is about 100 mm. In almost all structures, the sectional dimensions of the beams are larger than those of columns, which obviously does not obey the seismic conceptual design principles, i.e., strong column and weak beam, as well as the minimum sectional dimensions of components, i.e., usually the sectional dimension of beams 300 mm × 230 mm, columns 230 mm × 230 mm. The infill walls of the enclosing walls are constructed by the solid bricks of 220 mm × 100 mm × 50 mm, the thickness of which is 220 mm while that of the inner walls is 100 mm. The story height is 3.0 m, and the spacing between the columns is usually between 3 m and 3.9 m (Fig. 5).

#### 3.2.2 Damage characteristics and seismic capacity of RC frame structures

The RC frame structures performed relatively well in the earthquake affected areas. These structures were basically intact in Intensity VI areas, cracks in infill walls occurred in Intensity VII areas, many of them experienced serious inclined and cross cracks in Intensity VIII areas, while in Intensity IX areas the infill walls were seriously damaged or partly collapsed, some column capitals of bottom frames were seriously damaged and few structures collapsed.

The frame structures are mostly three to five stories. The damage generally began with the infill walls (Fig. 6), and then the column capitals of the bottom frames damage, prior to the column bottom. The major reason is that almost all frame columns are directly cast in place till the beam bottom during construction (as shown in Figs. 7 and 8), and there are no dense stirrups around the joints during design, so the column capitals are easily to shear off (see Fig. 9). In addition, the upper parts of the infill walls firstly drop due to the window openings, and the bottom parts could bear the frame lateral force together with the frame columns, so the damage of the column bottom is usually lighter than the capitals. However, the lateral resistance capacity of the joints are much poorer than that of China (GB 50011-2010, 2010; GB50010-2010, 2010).

The strong beam and weak column is the primary reason that the self-built frame structures of Nepal are easy to damage, where the sectional dimensions of frame beams are often bigger than those of columns and the reinforcements of beams are stronger than those of columns (Chang *et al*., 2014; Deng *et al*., 2013; Elkady and Lignos, 2014; Liao and Goel, 2014; Lignos *et al*., 2013; Lee, 1996).

The seismic damage showed that there were no

**Fig. 4 Complete collapse of a rubble structure in Intensity IX area**

**Fig. 5 Typical RC frame structure**

**Fig. 6** Damage of the bottom infill walls of a RC frame structure

**Fig. 7** Frame column cast into the bottom of the frame beam

(a) (b)

**Fig. 8** Column - beam connection of RC frame structures

**Fig. 9** Serious damage of the column capitals at the bottom of RC frame structure

dense stirrups around the beam-column joints, which caused some serious brittle failures (Sung *et al*., 2013; Fakharifar *et al*., 2014; Chaulagain *et al*., 2014). Besides that, there were no construction bars in both the frame columns and the enclosing walls, which resulted in the walls being prone to leaning outward or collapsing, and rarely participating in the lateral force resistance with frame columns.

## 3.3 Brick-wood structure

### 3.3.1 Structural characteristics

There are two types of brick-wood structures in Nepal, i.e., one is the traditional brick-wood structure with internal timber frame, as shown in Fig. 10, that is commonly used in the major cities of Katmandu, Pantan and Bhaktapur, about 8%–10% of the structures in these areas. The other one is widely used in towns and rural regions, just about 3%–4% of the buildings, as shown in Fig. 11.

The first type of the brick-wood structure will be introduced in the section 3.5, while this section is focused on the second type. The confined masonry structures are not used in Nepal, i.e., the structures with ring beams and constructional columns. This type of brick-wood structures are usually two to three stories, and most were built 20 years ago. The supporting system of the brick-wood structure is the mixture of brick bearing walls and inner walls, as well as the timber floors and roof trusses. The foundations are mainly brick foundations, and some rubble shallow foundations. The upper structures are longitudinal walls bearing loads, and thickness of the outer walls are between 220 mm and 350 mm. In addition,

**Fig. 10 Traditional brick-wood structure in the city of Katmandu**

**Fig. 11 Serious damage of a brick-wood structure in high intensity regions**

the walls are constructed by common bricks, and mortar or mud, where the grade of the mortar is low. Besides that, there are no connections between longitudinal and transverse walls. The triangular roof truss is laid on the longitudinal walls, with double slope roof and grey tiles by mortar or light tiles. In the cities, there are few newly built masonry structures without reinforcement using the cast-in-place floors and roofs, while they are rare in rural regions.

### 3.3.2 Damage characteristics and seismic capacity of brick-wood structures

Some of the brick-wood structures were seriously damaged in Intensity VII areas, most severely damaged with some partially collapsed in Intensity VIII areas, while most severely damaged and many collapsed in Intensity IX areas.

In the lower intensity areas, it is very common that the top of the gable walls of the brick-wood structures dropped. Since the transverse walls and longitudinal walls are not confined by the ring beams and without bar connections, the top gable walls cracked and partly collapsed, and the shear inclined or cross cracking occurred at the bottom resulting in collapse. Due to the lower grade of mortar or mud used in some structures, the cracks extended along the brick joints and few cracks cut off the brick, indicating poor shear resistance capacity of the brick walls.

## 3.4 Raw soil structure

The raw soil structures mostly exist in the rural regions. They were seriously damaged in Intensity VII areas, and partly or completely collapsed in Intensity VIII areas. This type of structures comprises about of 5% of all structures.

Generally, the internal timber frames are firstly constructed during the construction of the raw soil structures in Nepal. The sectional dimensions and the stiffness of the timber frames are smaller, and there are no connections between the frame columns and the adobe walls, with a space of about 10–15 cm. The walls are constructed with adobe bricks and mud, and the dimension of the adobe bricks are the same as the local common bricks. The entire force transmission system is that the beams of the timber frames overlap the walls, then the timber floors lay on the longitudinal walls with the template beams, and the timber roof truss directly lay on the longitude walls. The traditional raw soil structures are constructed by four-slope roof and grey tiles by mud.

The seismic capacity of the raw soil structures is poorer than the brick-wood structures. Due to the internal timber frames, the overall stability is good, but the strength and ductility of the adobe bricks are poor, in addition to the lack of connections under wall construction, the seismic capacity is poorer than the brick-wood structures while better than the rubble structures (Fig. 12).

## 3.5 Historical buildings and traditional brick-wood structure

The brick-wood structures are widely used for the religious buildings, historical buildings and residential buildings in old downtown cities of Nepal. This type of structures with a history of more than 2000 years, has obvious regional characteristics long-term affected by the Hinduism and Buddhism. The joint supporting system is achieved by constructing the enclosing and inner walls by bricks and then laying the timber floors on the longitudinal walls and internal timber frames. The tenon-mortise joints are not used, but the steel joints or wedges for the timber frames. For the historical buildings, the outer walls are usually one-and-half brick walls while the inner walls are one brick walls, which are constructed by mud with small and imperfect mortar joints. The triangular roof truss, crown or multi cornice, lateral gable and hip roof and grey tiles are mostly used.

Generally, the height of the residential buildings is less than the palace and temples, but the construction methods are similar. With the long-term development, the crown cornice has mostly become the gable and hip cornice projecting the second floor, and the sectional dimensions and quality of the internal frames are poorer than those of the palaces and temples.

Since there are no reliable connections between the brick walls and internal timber frames, and there is lack of the connecting construction between the longitudinal and transverse walls (Sun *et al*., 2014; Wang, 2008; Zhang and Jin, 2008), the damage pattern usually shows that the walls collapse outward and the corner cornice damage until the buildings is completely collapsed (Fig. 13 and Fig. 14). Some Hindu temples were constructed only by the brick pedestal and brick walls with the loess sand mortar, multi cornice structures, which were seriously damaged during this earthquake, as shown in Fig. 15.

## 4 Conclusions

The Nepal $M_s$8.1 earthquake caused tremendous damage to the country and its people. It also gives us many lessons worth thinking about. For the engineering structures, the most important thing to mitigate and prevent future disaster damage is to clearly understand the seismic damage characteristics and their reasons of local buildings. The seismic capacity of the structures in Nepal also reflects the characteristics of the underdeveloped regions in South Asia and West Asia.

(1) The RC frame structures will gradually replace the traditional structures and become the acknowledged structure types by the Nepalese people. However, the damage of strong beam and weak column commonly exist, i.e., the frame columns have been cut off while the beams are without any damage. Therefore, the seismic design of the RC structures should be further improved and the design & construction should be carried out strictly in accordance with the seismic code.

(2) The frame columns of each floor are mostly directly cast in place to the beam bottom, and there are no dense stirrups around the joints, which causes the frame column capitals being directly cut off by the horizontal shear stress. In addition, the concrete and reinforcements around the joints seldom bear the shear stress together, which is another big defect of frame structures.

(3) Abandoning the traditional rubble structures would be the best choice for the reconstruction after the earthquakes, not only for their poor seismic capacity but also for the difficulty of repair. Moreover, the rubble structures are constructed by brittle materials, of which

**Fig. 12 Moderate damage of the brick-wood structure in Intensity VII areas**

**Fig. 13 Leaning outward of the wall in Hindu temple of living Buddha in Katmandu**

**Fig. 14 Inclining outward and partial collapse of the wall in a traditional brick-wood structure in Katmandu**

**Fig. 15 Collapse of the temple in Durbar Square, Katmandu**

the overall stability is poor and prone to collapse. In addition this is difficult to repair. However, the improved construction method for rubble structures with ring beams and constructional columns as used in Tibet, China could be considered, which could significantly promote the lateral force resistance capacity of these structures.

(4) The reconstruction and repair of the historical buildings and traditional brick-wood buildings are the major tasks of the Nepalese government. The traditional brick-wood buildings in the major cities, such as Kathmandu are the iconic images. However, this type of structures were seriously damaged during the earthquakes. It needs the support and contribution of the entire society to preserve the past.

This paper is based on the research conducted by the seismic investigation team of the Nepal earthquake, organized by the China Earthquake Administration.

## Acknowledgement

The authors would like to thank the Chinese Ministry of Commerce, the China Earthquake Administration, the Chinese Embassy in Nepal and the Nepalese government for their great support. The research is supported by the National Science & Technology Pillar Program No. 2015BAK17B00 and Seismic Industry Research Special Fund under Grant No. 201508026.

## References

Chang SY, Chen TW, Tran NC and Liao WI (2014), “Seismic Retroftting of RC Columns with RC Jackets and Wing Walls with Different Structural Details,” *Earthquake Engineering and Engineering Vibration*, **13**(2): 279–292.

Chaulagain H, Rodrigues H, Spacone E, Guragain R, Mallik R and Varum H (2014), “Response Reduction Factor of Irregular RC Buildings in Kathmandu Valley,” *Earthquake Engineering and Engineering Vibration*, **13**(3): 455–470.

Deng KL, Pan P, Alexandre L, Pan ZH and Ye LP (2013), “Test and Simulation of Full-scale Self-centering Beam-to-column Connection,” *Earthquake Engineering and Engineering Vibration*, **12**(4): 599–607.

Elkady A and Lignos DG (2014), “Modeling of the Composite Action in Fully Restrained Beam-to-column Connections: Implications in the Seismic Design and Collapse Capacity of Steel Special Moment frames,” *Earthquake Engineering and Structural Dynamics*, **43**(13): 1935–1954.

Fakharifar M, Sharbatdar MK, Lin Z, Dalvand A, Sivandi-Pour A and Chen G (2014), “Seismic Performance and Global Ductility of RC Frames Rehabilitated with Retrofitted Joints by CFRP Laminates,” *Earthquake Engineering and Engineering Vibration*, **13**(1): 59–73.

GB50010-2010 (2010), *Code for Design of Concrete Structures*, Beijing: China Architecture and Building Press.

GB50011-2010 (2010), *Code for Seismic Design of Building*, Beijing: China Architecture and Building Press.

GB/T17742-2008 (2008), *The Chinese Seismic Intensity Scale*, Beijing: China Architecture and Building Press.

Lee HS (1996), “Revised Rule for Concept of Strong-column Weak-girder Design,” *Journal of Structural Engineering*, **122**(4): 359–364.

Liao WC and Goel SC (2014), “Performance-based Seismic Design of RC SMF Using Target Drift and Yield Mechanism as Performance Criteria,” *Advances in Structural Engineering*, **17**(4): 529–542.

Lignos DG, ASCE AM, Hikino T, Matsuoka Y, Nakashima M and ASCE M (2013), “Collapse Assessment of Steel Moment Frames Based on E-defense Full-scale Shake Table Collapse Tests,” *Journal of Structural Engineering*, **139**(1): 120–132.

NBC105 (1995), *Nepal National Building Code,Seismic Design of buildings in Nepal,* Nepal Ministry of Housing and Physical Planning.

Sun BT, Yan PL and Chen XZ (2014), “New Characteristics of Intensity Assessment of Sichuan Lushan “4.20” $M_s$7.0 Earthquake,” *Earthquake Engineering and Engineering Vibration*, **13**(S1): 123–139.

Sung YC, Lin TK, Hsiao CC and Lai MC (2013), “Pushover Analysis of Reinforced Concrete Frames Considering Shear Failure at Beam-column Joints,” *Earthquake Engineering and Engineering Vibration*, **12**(3): 373–383.

Wang YY (2008), “Lessons Learned from the “5.12” Wenchuan Earthquake: Evaluation of Earthquake Performance Objectives and the Importance of Seismic Conceptual Design Principles,” *Earthquake Engineering and Engineering Vibration*, **7**(3): 255–262.

Zhang MZ and Jin YJ (2008), “Building Damage in Dujiangyan during Wenchuan Earthquake,” *Earthquake Engineering and Engineering Vibration*, **7**(3): 263–269.