Lessons from Damaged Historic Buildings in the Sichuan Earthquake: 
A Case Study in Zhaohua, Sichuan Province

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Abstract
Zhaohua is a historic town in Sichuan Province, in China. On 12th May 2008, a devastating earthquake measuring 8 on the Richter scale struck Wenchuan, Sichuan province. Among the 232 historic buildings in Zhaohua, the number of damaged buildings was 46; partially damaged, 74; and slightly damaged buildings, 112. The purpose of report is to study the extent of damage to these historic buildings during the earthquake, and then attempt to find the weak points which these buildings displayed.

Authors conclude that the damage to historic buildings is primarily related to the combination of main building materials and the construction used. Buildings made of wood and brick withstood the seismic forces better than did buildings made of wood and mud, which collapsed more easily. Further, the connections between the walls and the purlins and beams are the main weak points in the traditional historic buildings in Sichuan. Many of the historic buildings, particularly some made of mud, had never been reinforced.

In Zhaohua, although a disaster prevention plan was in place, this plan focused mainly on fire and did not include practical information on the historic building reinforcement and what should be done during a disaster and post-disaster.

Keywords: Sichuan earthquake; historic building; disaster prevention plan

1. Introduction
In the afternoon of May 12, 2008, a magnitude 8 earthquake hit Wenchuan County of Sichuan Province in China, a mountainous region in western China, killing about 69,226 people and leaving over 17,923 missing. Also, some historic towns and historic buildings with traditional and local identities were damaged in this earthquake.

Zhaohua, a historic town, is located in the northeast of Sichuan province, approximately 220 kilometers northeast of the epicenter, Wenchuan. The position of Zhaohua is shown in Fig.1. The detailed planning for repairing the Zhaohua historic district was finished under the guidance of the National Historic City Research Center of Tongji University from April to October 2006. With this planning, the authority of Zhaohua town had taken the corresponding measures for repairing historic buildings1.

In this planning, the historic district area was determined as 29 ha., with the population of 2750 people lived (in 2006 statistics). The 232 historic buildings in town were built using the Post-and-beam System as their main structure, which includes 41 historic buildings belonging to cultural property units that were designated by the province or municipality, and 191 predesignated historic buildings. In December 2008, Zhaohua was designated as a Historic and Cultural town by the Chinese government. After the earthquake, the damaged historic buildings in Zhaohua has been investigated conducted by national criteria.

The objective of this paper is to find the weak points of the damaged historic buildings with Post-and-beam System construction, to provide useful guidance for the reconstruction of the damaged historic district in Sichuan province. Also, the proposed advice will be rendered for improving the disaster prevention plans.
in China. The over-arching aim is to preserve the local and cultural identities in the occurrence of destructive earthquakes.

2. Characteristics of Post-and-beam System

The buildings with Post-and-beam System utilize tile roofing. The building structure consists of columns and beams. Post-and-beam System consists of three-column wooden frames or five-column wooden frames. The structure that runs across the beams and through the columns, as well as under the crossbar is named the Post-and-beam System. The Post-and-beam System is a weaving connection into the structural assembly made of wood components. The role of such structure is to connect the beams and columns to ensure the lateral rigidity and stability of the wooden frames.

The characteristics of Post-and-beam System Construction (Fig.2. and Fig.3.) are the following:

- Provide a separate load-bearing system and maintenance structure

The wooden structure is also a load-bearing system, where columns and horizontal beams are the main load-bearing elements, with the retaining wall structures being flat and flexible to fulfill different seismic loading requirements. Commonly, the substructures such as walls are composed of mud, adobe, pebble wood, walls, and bamboo, which are easily found nearby.

- Tenon-and-mortise

It is easy to maintain structural integrity with a tenon-and-mortise structure. Generally, joints made of tenon-and-mortise in the beams and columns have great capability in absorbing energy, to increase the structural integrity. The tenon-and-mortise is a kind of light structure, with small seismic loading, good elasticity, and deformation and recovery ability.

- Heavy gable walls with low deformation and recovery ability

As a gable wall does not easily adapt to deformation, vertical stability has always been weak. The buildings with Post-and-beam System are distributed in the south of China, especially in Sichuan province, Chongqing city, Yunnan province, Hubei province, and Hunan province. When some old houses in these fields were rebuilt or repaired, the owner always kept the main wooden structure.

3. Damage Condition

After investigating the 232 damaged historic buildings in Zhaohua, the data on damage conditions has been acquired as follows: (Table 1.)

The investigation discovered that among the 62 buildings built with mud walls, the number of fully destroyed buildings was 27 (43.5%); among the 162 buildings with brick walls, the number of fully destroyed buildings was 18 (11.19%). The percentage of fully destroyed buildings with mud walls appeared significantly higher than the buildings made of brick walls (Table 2.).

4. Analysis of the Damaged Condition

The classification of the damage is shown in Table 3.

4.1 Roof Surface Damage

Roof damage during seismic action is a very common phenomenon. Damage is depicted by the loosening of the tiles; where the tiles tend to dislocate individually instead of moving as a cohesive unit. The tiles eventually fell, resulting in areas of the roofing tiles collapsing. All roofs experienced damage to varying degrees (Fig.6. and Fig.7.). During construction, the tiles were attached to the rafters.
without the use of adhesives and fasteners. The tiles are thus likely to fall off the roof when experiencing quakes. The long semi-circular tiles that sit at the apex of the roof (Fig. 8.), upon construction, are not adhered with a bonding material. Subsequently, upon seismic action, the tiles and structure below the tiles break away and fall.

4.2 Structural Roof Damage

From observations of structural roof damage, we found a high percentage of rotten wood, reducing the structural integrity of the wooden supports. Rafters carry the loading of the roof tiles are generally lightweight and thin. When there is damage to the wood, it cannot be easily restored due to its position at height that posts limitation for its access. In the quake, the rotten wood column is hence likely to fail, followed by the falling of tiles (Fig. 9., Fig. 10. and Fig. 11.).

Table 1. Damaged Condition of Historic Buildings

| Damage condition | Slightly damaged | Partially damaged | Fully damaged | Total |
|------------------|------------------|-------------------|--------------|-------|
| Damaged Numbers  | 112              | 74                | 46           | 232   |
| Percentage       | 48.3%            | 31.9%             | 19.8%        | 100%  |

Table 2. Damaged Condition of Historic Buildings with Different Materials

| Type of historic building | Fully damaged | Partially damaged | Slightly damaged | Total |
|---------------------------|---------------|-------------------|-----------------|-------|
| Number                    | Percentage    | Number            | Percentage      | Number |
| Mud building              | 27            | 43.5%             | 16              | 30.7% |
| Brick building            | 18            | 11.1%             | 67              | 41.4% |
| Wooden building           | 1             | 25.0%             | 1               | 25.0% |
| Total                     | 46            | 84                | 98              | 100%  |

Table 3. Damaged Position of Historic Buildings

| Damaged condition | Slightly damaged | Partially damaged | Fully damaged |
|-------------------|------------------|-------------------|--------------|
| Roof              | Tile of the roof | Tile falls with quake (Fig. 6. and Fig. 7.) | Ridge of the roof broken (Fig. 8.) |
| Ridge of the roof | Some structures damaged, and most of them were all right (Fig. 9.) | Most of structure was damaged and collapsed (Fig. 11.) |
| Roof Structure    | Few cracks occurred on the surface (Fig. 12. and Fig. 13.) | Wall inclination (Fig. 16.) | Most of wall collapsed, particularly the mud wall (Fig. 17., Fig. 18. and Fig. 19.) |
| Wall              | Materials on the surface of wall foot fell (Fig. 15.) | |

4.3 Connection of the Wall and Roof

Purlines and beams were connected to the walls without fastening links. The dualities of the movement of the vertical and horizontal members during the quake did not worked in unison, causing failure. Materials behave differently during seismic action; together they can work in uncomplimentary ways, causing failure, and leading to cracks from these connections (Fig. 12. and Fig. 13.).

4.4 Wall Damage

During the earthquake, the brick and mud load-bearing walls failed; structural integrity was undermined, resulting in partial or complete collapse. Surface materials fell, and significant cracks occurred in the load-bearing walls during the seismic action, resulting failed connections between the walls and the purlines and beams.

During seismic action materials perform differently. Wood can absorb the energy, while brick and mud cannot. Therefore, the combination of materials worked differently in the earthquake, resulting in structural failure (Fig. 14.). The surface materials at the foot of the wall had been loosened due to precipitation. The already weakened material failed during the earthquake, and the surface materials fell away easily (Fig. 15.). The Post-and-beam System structurally performed well in the quake due to its lateral stiffness, but partial failure occurred, resulting in the leaning of the gable to one side (Fig. 16.).

Compared to the walls made of single material, some walls consisting of multiple materials combined, such as brick, gravel, mud, or soil, which collapses easily. The heavy walls of the Post-and-beam System are not
Fig. 6. Most of Tiles Fell

Fig. 7. Few of Tiles Fell

Fig. 8. Ridge of the Roof Broken

Fig. 9. Few Structures Damaged

Fig. 10. Some Structures Damaged

Fig. 11. Structures Collapsed

Fig. 12. Few Cracks in the Wall

Fig. 13. Cracks from the Connection of the Wall and Roof

Fig. 14. A New Wall and Old One Shocked

Fig. 15. Materials on the Surface of the Wall Foot Fell

Fig. 16. Wall Inclination

Fig. 17. Collapsed Wall

Fig. 18. Various Materials in the Wall

Fig. 19. Collapsed Mud Wall
the load-bearing structure, and collapse easily with less flexibility, particularly the mud walls (Fig.17., Fig.18. and Fig.19.).

5. Consideration of Disaster Prevention Plan in Historic District

It is known that a disaster prevention plan is necessary for reducing losses in a disaster. Several guidelines on disaster prevention in the preservation planning were made in 2006, specifically targeting the damages caused by fire; other disasters, such as earthquakes, were not included in the guidelines. In infrastructure planning, a substantial amount of effort has been devoted into the detail investigation of the position of fire hydrants, refractory of the historic building, principles of emergency shelter, and advice for organizing residents’ fire response, improving residents’ awareness of fire prevention, and increasing the knowledge of firefighting equipment and its applications. While this is indeed crucial due to the areas of high population density and high risks of fire (which cause a significant loss of wooden and wooden composite buildings), greater effort in addressing the critical earthquake guidelines is yet to be made.

Even though significant planning has been undertaken for fire prevention, several areas are still unclear pertaining to fire prevention: for example, detailed information such as the exact locations for emergency shelter and which road or roads should be used in emergencies. Methods on how to organize a residents’ fire group and improve the dissemination of knowledge throughout the community would also be of benefit regarding disaster planning.

Regarding standards and principles at a national urban planning level, there are some principles in place for disaster prevention planning for historic towns. It is said that fire prevention is the most important thing in historic districts, and some endangered buildings should be reinforced for seismic damage, but the original appearance must not be altered, affecting the authenticity of the building. But in this standard, there is a lack of detail regarding how exactly to reinforce the historic buildings and knowledge pertaining to the weak points that need reinforcement.

6. Conclusion

1. The historic buildings made of mud are easily damaged compared to other structures. To avoid the collapse of walls, various materials should be changed, to improve the entirety of the wall, especially for mud walls.

2. One of weak points is the connection between the wall structure and the beams and purlines. Some historic buildings were repaired during 2006 and 2007, but during the repair reconstruction, no reinforcing was used. Therefore, during the process of recovery for damaged historic buildings, reinforcement of the connections between wooden wall structures is advisable. Additionally, varied materials which work in harmony could reduce mutual collisions. For example, wooden structure knocked against mud brick wall lead to wall collapse.

3. Existing disaster planning for the prevention of earthquake disasters and the reduction of the damage made by earthquakes is not enough. For the first stage, Chinese government focused on the reconstruction of major city and resolved some residential problems post-earthquake. However, to reduce future loss, disaster prevention plans for the historic district, as the requirement of the second stage, is also important.

   Concerning the possibility of an earthquake disaster, it is necessary to provide some principles and guidelines on how to identify structural weak points and reinforce them during cyclic repair work, such as in 2006 to 2007. Thus, some method of transmitting knowledge to the owners of the important historic buildings is necessary prior to earthquakes and post-earthquakes, perhaps via public drills, printed educational pamphlets, local community exhibitions that identify structural weak points in buildings, and discussions of maintenance such as repair of rotten supporting wooden roof member structures.

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Note

1 The definition of historic building refers to the architectures with a certain value of protection which decided by the government, can reflect the historical features and local characteristics, but haven’t announced as a conservation unit, also not registered as immovable cultural relics of buildings and structures.

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