TECHNICAL NOTE

Seismic Damage of Masonry Infilled Timber Houses in the 2013 M7.0 Lushan Earthquake in China

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Masonry infilled timber frames are widely used for residential houses in underdeveloped rural and mountainous areas in southwestern China. As suggested by the identified dynamic properties of three typical timber houses of this type, the structure can be taken as a dual system in which the masonry infills provide most lateral resistance while the timber frame withstands the vertical loads. The seismic damage of the houses, either of masonry or of masonry infilled timber structure, in a small town near the epicenter of the 2013 M7.0 Lushan earthquake in southwestern China was inspected and compared to show that the masonry infilled timber houses exhibited much better seismic performance than un-reinforced masonry ones during the earthquake.

INTRODUCTION

Masonry infilled timber frames are being widely used for small-scale residential houses in earthquake prone regions such as in Turkey, Greece, Italy, Portugal, Romania, Pakistan and China (Gulkan et al, 2004; Makarios et al, 2006; Ruggieri, 2005; Mascarenhas, 2005; Dutu et al, 2012; Langenbach, 2006). With a few exceptions (e.g., those in Portugal and Italy), most of the structures are un-engineered and were built following local historical practice of construction. In some countries, this form of construction only exists in old buildings (e.g., Portugal, Turkey, Haiti), while it is still a current construction practice in other countries like Romania, Pakistan and China.

The seismic performance of masonry infilled timber frames has been reported after several major earthquakes. In the 1999 M7.4 Kocaeli earthquake in Turkey, the houses with this type of structure sustained less damage in comparison with poorly constructed reinforced concrete ones with masonry infills (Gulkan et al, 2004; Langenbach, 2011). Vintzileou et al (2007) reported the survival of timber framed houses in Greece during the 2003 M6.2 Lefkada earthquake, even when not properly maintained. In the 2010 M7.0 Haiti earthquake, the local

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traditional timber frames with masonry infills, referred to as Gingerbread houses, sustained significant damage but very few collapsed (Langenbach et al, 2010).

These observations on various types of masonry infilled timber frames lead to a common impression that such structures do not easily collapse during earthquakes, although they may sustain various levels of damage especially in their masonry infills. This stimulated the interest of better understanding the seismic behaviour of such a structural system. Experimental studies were conducted on timber frames with either clay brick masonry infills (Ferreira et al, 2012; Poletti et al, 2013; Dutu et al, 2013) or stone masonry ones (Ali et al, 2012; Ruggieri et al, 2013; Vieux-Champagne et al, 2014). The lab tests confirmed the excellent in-plane behaviour of masonry infilled timber frames under cyclic lateral loading, highlighting the significant deformability as a result of the confinement provided by the timbers for the masonry infills.

Although brick masonry structures predominate in low-rise residential houses, the Chuandou timber frame is still a current practice and is very popular in rural and especially mountainous areas in southwestern China for residential houses. The Chuandou timber frame system is one of the two major timber structural systems in China and has a history of at least 500 years. Chuandou timber frames were historically infilled with timber panels as partitions, while clay brick masonry has been overwhelmingly preferred for the infills over the past few decades, for its low cost and easy construction. The joint details of recent timber houses have also been gradually over-simplified over the years.

This paper summarizes the observed damage to Chuandou timber frames with masonry infills during the 2013 Lushan earthquake in China and compares their damage statistics with those of masonry structures during the same earthquake. Before that, a brief review of the strong ground motions obtained during the earthquake is followed by an introduction to the three structural systems concerned, namely un-reinforced masonry (URM), confined masonry and masonry infilled Chuandou timber frame structures, with better details for the last one which is the focus of this paper.

THE STRONG GROUND MOTIONS IN LUSHAN EARTHQUAKE

In April 20, 2013, an Ms7.0 earthquake hit Lushan County in western Sichuan province in China. 196 people were killed, 21 missing and 11470 injured during the earthquake as of April 24, 2013 (CEA, 2013a). Several reconnaissance reports are available online for general information regarding the seismology and impacts of the earthquake (e.g., EERI, 2013; Wang and Mooney, 2013).

Four strong ground motion stations (namely, LSF, YAM, QLY and BXD) maintained by China Strong Motion Networks Center are located within 40 km from the epicenter. Figure 1 shows their locations on the seismic intensity map released by China Earthquake Administration (CEA, 2013b). The seismic intensity was measured on a scale from I (not felt) to XII (total destruction) in accordance with 'The Chinese Seismic Intensity Scale' (GB/T 17742-2008, 2008), which is a revised version of the Modified Mercalli Intensity scale. The nearby active faults and major cities are also depicted on the map. Table 1 summarizes the characteristics of the ground motion records at the four stations. The low PGV to PGA ratios reveal the near field nature of those records and indicate that they are rich in high-frequency contents while poor in low-frequency ones (McGuire, 1978). This can also be seen from their response spectra.

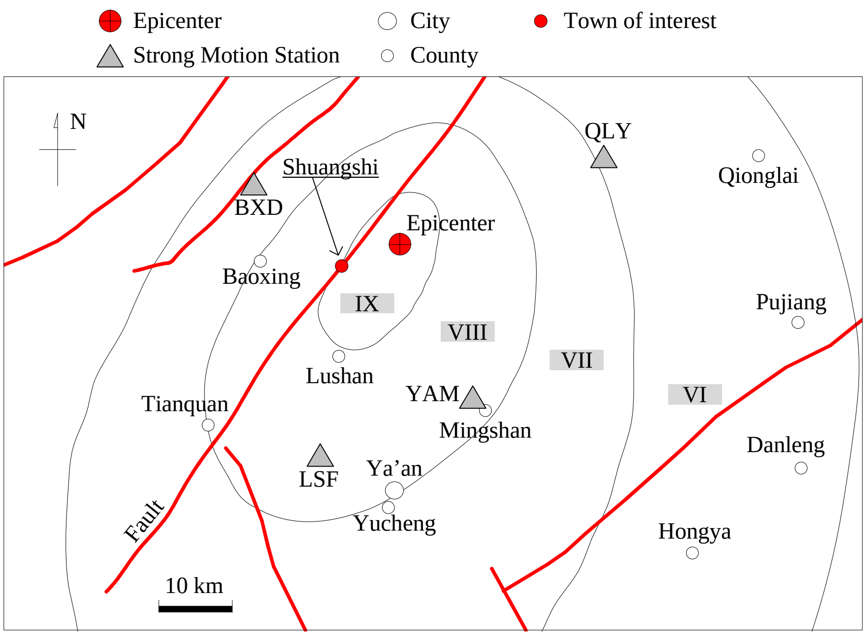


Figure 1. Intensities, faults and strong motions stations in near field area of Lushan earthquake.

Table 1. Properties of strong ground motion records obtained in Lushan earthquake

Station	PGA (g)*			PGV (m/s)*			T_d (s)**		
	NS	EW	UD	NS	EW	UD	NW	EW	UD
BXD	1.050	0.767	0.539	0.204	0.258	0.157	5.7	5.4	8.0
YAM	0.428	0.365	0.108	0.123	0.115	0.079	25.2	24.8	24.9
LSF	0.384	0.388	0.282	0.153	0.123	0.119	23.4	22.0	19.4
QLY	0.274	0.317	0.111	0.179	0.107	0.055	13.3	20.2	22.9

* Acceleration time histories are corrected by linear baseline correction and filtered by fourth order band pass Butterworth function of 50 Hz LP and 0.1 Hz HP before integrating into velocities.

** The significant durations between 5% and 95% earthquake input energy of the corrected records (Trifunac and Brady, 1975).

Figure 2 compares the pseudo acceleration response spectra of the records with the design spectrum for Lushan County in the Chinese seismic provisions (GB50011, 2008). The spectral pseudo accelerations of the records are several times greater than the design spectrum in short period range while are comparable or even less than the design spectrum for periods around 1 s or longer.

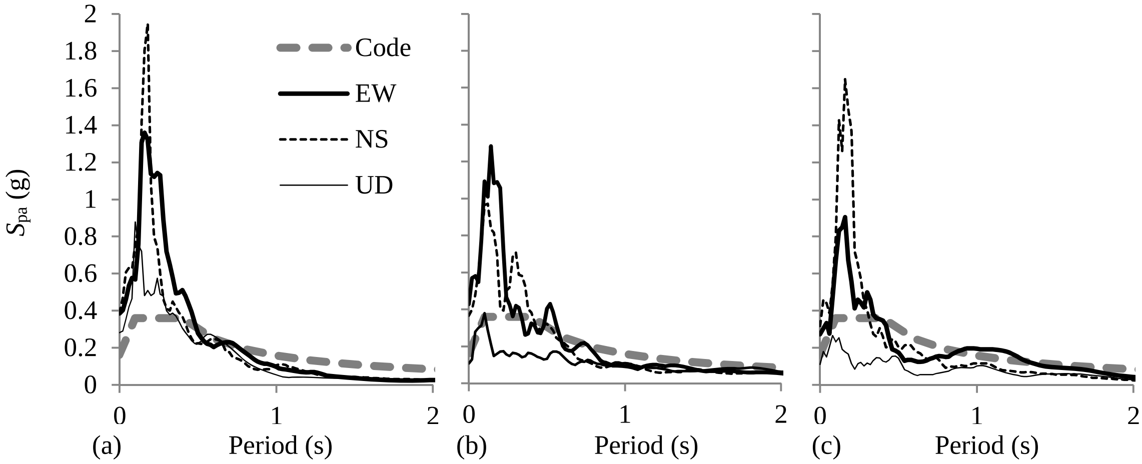


Figure 2. Pseudo acceleration spectrum of ground motion records at (a) LSF station; (b) YAM station and (c) QLY station.

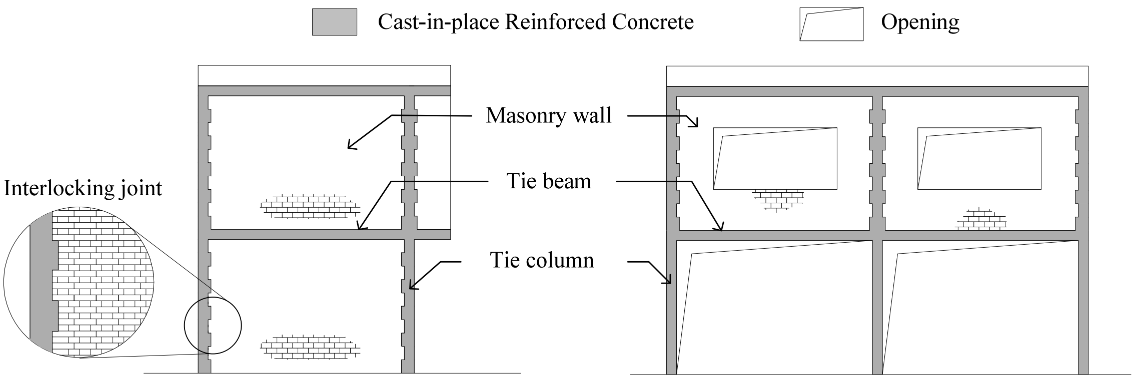
Most of the area affected by the earthquake is mountainous, where the proportion of timber framed houses was relatively high. As a case study, the seismic damage of the houses in the town of Shuangshi, a mountainous town about 8 km southwest of the epicenter (Figure 1), was examined during the emergency inspection immediately after the earthquake and a more detailed reconnaissance three weeks later. Before introducing the reconnaissance results, it is necessary to first define the three structural systems concerned in this paper.

UN-REINFORCED MASONRY AND CONFINED MASONRY HOUSES

Back to 1970s, un-reinforced masonry (URM) structures predominated in low-rise buildings and houses in rural areas throughout China, regardless of the seismic risk. In such structures, clay brick masonry walls are the primary load-bearing components, which are usually 120 mm to 360 mm thick, depending primarily on the economic condition of the owner rather than structural concerns. Precast concrete slabs were usually used as floor slabs due to its low cost, easy transportation and fast construction. As a result of the vast collapse of URM buildings and houses, especially those with precast concrete floor slabs, during the deadly Tangshan earthquake in 1976 (Housner and Xie, 2002), confinements such as reinforced concrete (RC) tie columns and tie beams were introduced to URM structures to enhance their integrity and thus the seismic performance.

In a typical confined masonry house as shown in Figure 3, clay brick masonry walls are, as in a URM house, the primary load-resisting components. Cast-in-place RC columns, referred to as tie columns, are placed at the corners as well as at the joints of perpendicular brick walls. The dimensions of the tie column cross section are usually predetermined by the thickness of the intersecting walls, but should be no smaller than 240 mm by 180 mm as per GB 50011 (2008). A minimum of 4 ϕ12 longitudinal rebars and ϕ6 hoops at 250 mm spacing is required for the tie columns. During construction, brick walls are first laid with about 60 mm setbacks every other 300 mm along the edges. RC columns are then cast to form interlocking joints with the brick walls as shown in Figure 3(a).

When precast concrete floor slabs are used, RC tie beams are also required on top of all brick walls at every floor level and the roof level. The cross sections of such tie beams should be no smaller than 240 mm by 180 mm and a minimum reinforcement of 4 ϕ12 longitudinal rebars and ϕ6 stirrups at 250 mm interval should be provided.



(a) Transverse direction (b) Longitudinal direction

Figure 3. Structural configuration of confined masonry house

Like in other underdeveloped areas lacking of governmental regulation, URM and confined masonry houses were mixed in the rural area affected by the Lushan earthquake. In addition, many of the confined masonry houses were not engineered to fully conform to the code requirements. In some cases, there were only tie beams. In some other cases, both tie beams and tie columns were present but the tie columns were either placed at too large interval or were absent at critical locations. In the following discussion, however, a masonry house is categorized into a confined masonry one if only tie columns are present, no matter if they satisfy the code requirement or not.

CHUANDOU TIMBER FRAME HOUSES

STRUCTURAL CONFIGURATION

The configuration and detailing of the Chuandou timber frame houses in the earthquake affected area were quite uniform. Two story houses as shown in Figure 4 were most commonly seen. Round timber columns are erected on top of independent footings made of stone, or in a few cases brick masonry. They are supposed to be anchored in the footings by extending tenons into mortises on the footings. However, this traditional detail seems to have been abandoned in the inspected area. Instead, the columns are simply put on the top surface of the footing without anchorage, making friction the sole source of shear resistance at the column base.

The columns in the transverse direction are spaced in relatively small spans, and some columns are terminated at the second floor level instead of reaching to the ground (Figure 4(a)). The transverse beams usually have deep rectangular cross sections and frame into the columns by penetrating the columns as shown in Figure 5(a). The transverse beams are usually 100 to 200 mm in depth and the depth-to-width ratio varies from 2 to 4. In the longitudinal direction, the column span can be as large as 3 ~ 4 m. Round beams, on which the timber floor slabs are placed, frame into the columns by mortise-and-tenon joints (Figure

5b).

As observed in the cyclic loading test by Gao (2007), the mortise-and-tenon joints exhibited very low lateral stiffness until as large as 0.05 rad. deformation angle, owing to the initial gaps between the mortise and the tenon. This kind of initial gaps may also be expected in the penetration joint in the transverse direction of the Chuandou frame. In the past, wedges were typically used for tightening the mortise-and-tenon joints in order to eliminate the initial gap as well as to prevent the pull-out of the tenons (Figure 5b). Another way of preventing the pull-out of the tenons is to use out-of-plane wood dowels as shown in Figure 5(c). Unfortunately, either wedges or dowels were hardly seen in the beam-to-column joints of timber houses constructed in recent years in the earthquake affected area.

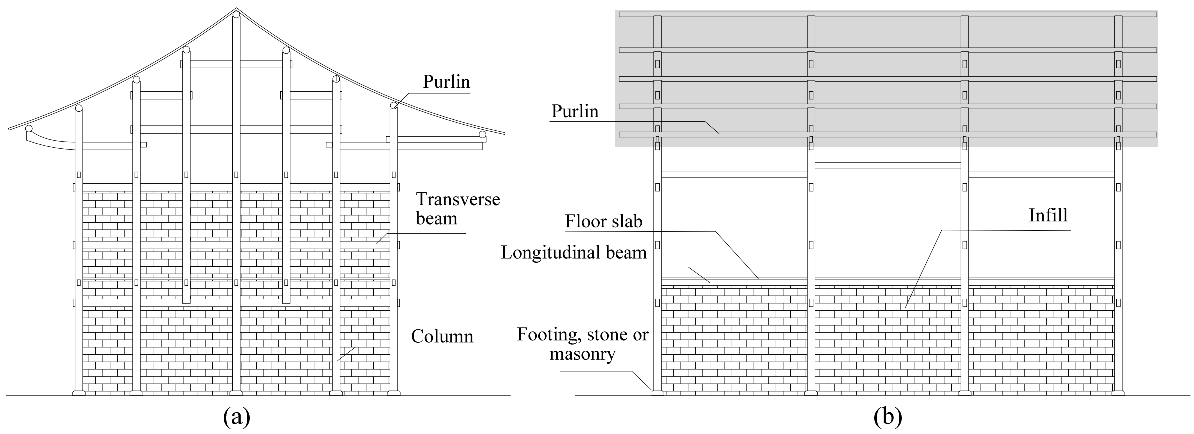


Figure 4. Structural configuration of Chuandou timber houses with infills: (a) transverse elevation and (b) longitudinal elevation.

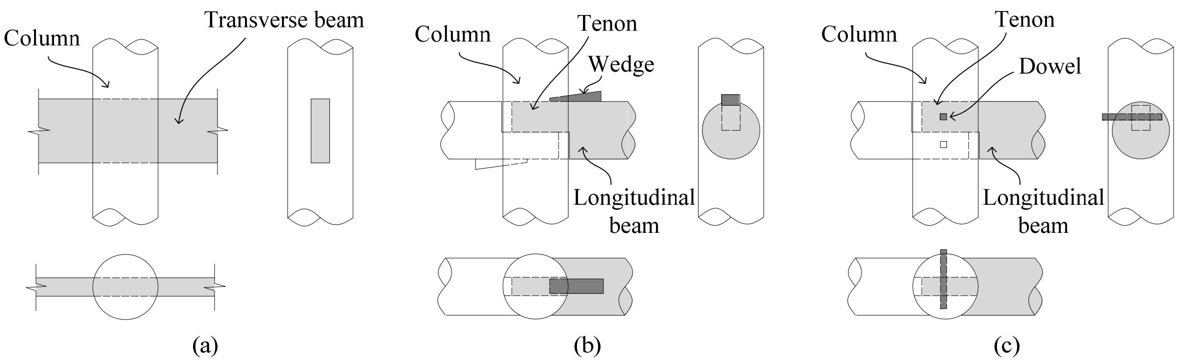


Figure 5. Typical beam-to-column joints in Chuandou timber houses: (a) transverse beam-to-column penetration joint; (b) longitudinal beam-to-column mortise-and-tenon joint with wedge and (c) longitudinal beam-to-column mortise-and-tenon joint with dowel.

The first floor of the timber house is usually occupied as living space, which is enclosed and partitioned with clay brick masonry, or in very few cases, timber panel infills. On the other hand, the second floor is usually for open storage, and infills are built in only the transverse frame. Brick masonry infills are laid after the whole timber frame is erected. On both ends of each brick masonry panel, the gaps to the timber columns are filled with mortar. As a common local practice to tie the brick masonry, nails of about 50 mm in length are nailed on the timber columns and embedded in the mortar between brick layers. In such a manner, the timber frame provides some in-plane as well as out-of-plane, although very limited, constraint to the masonry infills. On top of the masonry walls, gaps to the timber beams are hardly avoidable for the mortar may sustain considerable shrinkage. Such initial gaps would prevent vertical load from transmitting to the masonry infills, leaving the timber frame carrying most, if not all, the vertical loads. On the other hand, such gaps would also weaken the confinement, both in-plane and out-of-plane, of the timber frame for the masonry infills.

DYNAMIC IDENTIFICATION

The fundamental dynamic properties of three typical detached Chuandou timber houses near the town of Shuangshi were identified through on-site tremor observations. These houses (denoted as House A, B and C, hereinafter) were similar in their timber frames but different in the infills (Figure 6). House A was a rare case of a Chuandou timber house without any infills. The owner of the house said that most masonry infills of the house collapsed or badly cracked during the earthquake and were completely demolished after the earthquake with the help of the neighbors. Several timber logs were set up around the house as temporary lateral supports in case the aftershocks or strong wind might tilt the bare frame (Figure 6a), which, as mentioned above, had little lateral stiffness itself as a result of the detailing of the column base and the beam-to-column joints. House B was said to have been built over fifty years ago and is featured by its timber panel infills (Figure 6b). The timber frame of House C was infilled with brick masonry, which sustained minor to moderate damages during the earthquake (Figure 6c).

A portable accelerometer was installed on the topmost floor (i.e., 3rd floor for House A and 2nd floor for B and C) close to a column at the center of each house to capture the horizontal tremor of the houses (as denoted by the solid triangles in Figure 6). The method developed by Tanaka et al. (1969) was adopted to identify the vibration periods and damping ratios of the houses from the tremor observations, in which the power spectral density (PSD) function of the response signal is first smoothened by convolution with a Hamming window function. The period corresponding to the maximum density, S_0, on the smoothened PSD is taken as the fundamental period of the house, and two characteristic frequencies, f_a, f_b at which the spectral densities become $1/\lambda$ of S_0 are found and used to calculate an apparent damping ratio, ζ', by Equation (1), where λ is taken as 2. The thus-obtained damping ratio is called ‘apparent’ because it is strongly influenced by the smoothing process and is always larger than the ‘true’ damping ratio. The graphic relationship suggested by Tanaka (1969) is then adopted to convert the apparent damping ratio to the true damping ratio, ζ. Three runs of observation were conducted for each house and the identification results for both the longitudinal (x) and the transverse (y) directions are summarized in Table 2.

$$\zeta' \approx \frac{A}{2}\left(1-\frac{3}{8}A^2\right) \tag{1}$$

where the parameter A is calculated by Equation (2) as below.

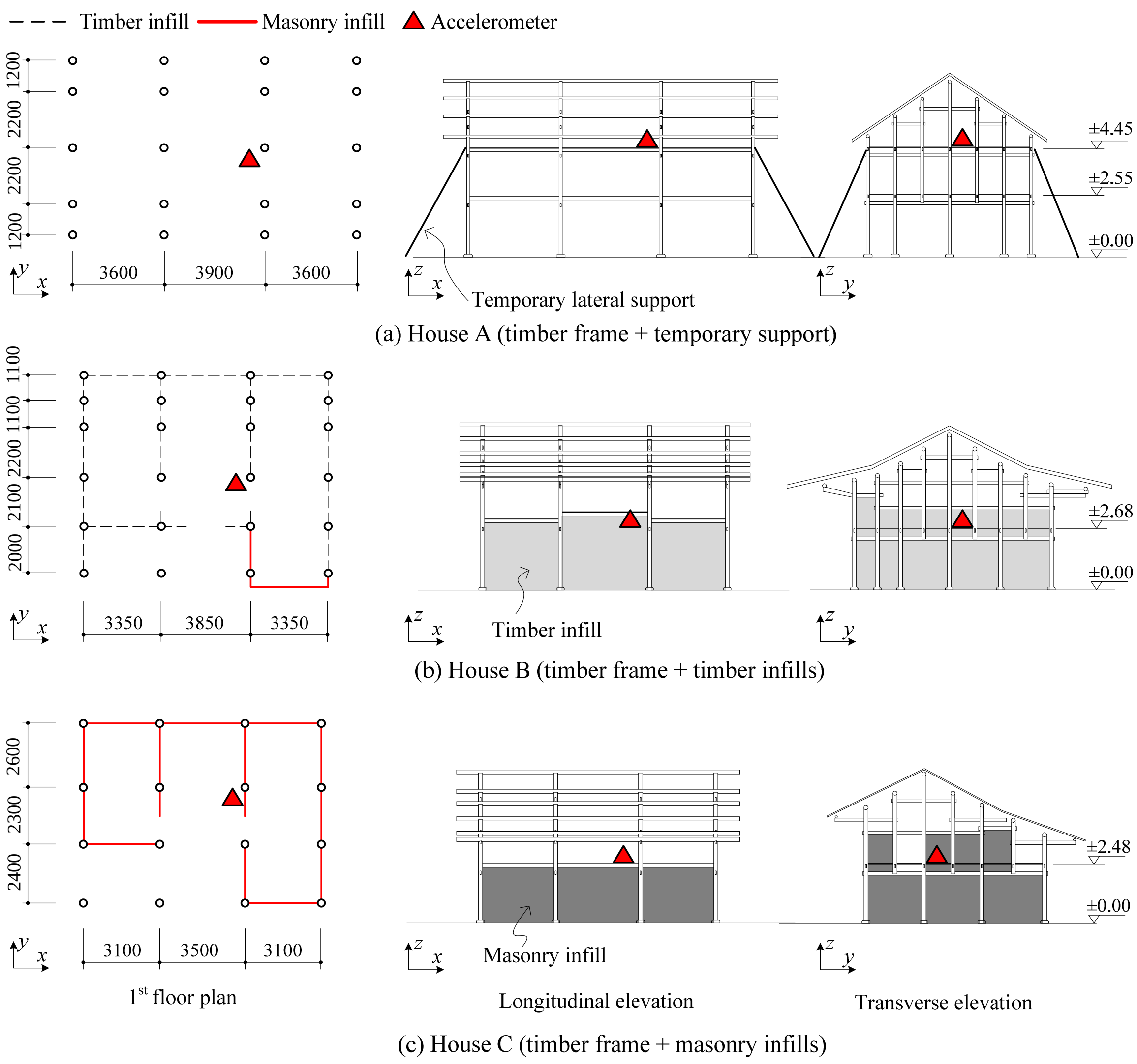


Figure 6. Structural layout and locations of accelerometers of (a) House A; (b) House B and (c) House C.

$$A = \frac{f_a^2 - f_b^2}{f_a^2 + f_b^2} \cdot \frac{1}{\sqrt{\lambda - 1}} \tag{2}$$

Table 2. Identified dynamic characteristics of typical timber houses

House		Fundamental period, T_0 (s)				Damping ratio, ζ (%)			
		Run 1	Run 2	Run 3	Average	Run 1	Run 2	Run 3	Average
A	x	0.75	0.73	0.74	0.74	0.8	1.1	3.4	1.8
	y	0.73	0.72	0.75	0.73	6.7	2.8	2.4	4.0
B	x	0.09	0.08	0.10	0.09	6.6	23.2	21.0	16.9
	y	0.12	0.10	0.12	0.11	9.8	20.0	2141	17.1
C	x	0.08	0.08	0.12	0.09	12.6	22.9	8.0	14.5
	y	0.12	0.12	0.12	0.12	5.4	15.3	15.2	10.3

The fundamental vibration period of House A, which was not infilled by any walls, was more than 0.7 s in both directions, while those of House B and C were only about 0.1 s. It can be expected that the period of House A could have been even longer if there were not the temporary lateral supports. The marked difference in period between House A and House B and C could partly be attributed to the fact that House A was one story higher than the other two. But more importantly, such difference suggests that most lateral stiffness of the Chuandou timber houses comes from the infill walls.

The identification results also show that the presence of either masonry or timber infills may significantly increase the damping ratio of the timber houses. The increased damping may come from the interaction between the infills and the frame, as well as from the inner friction of the infills themselves.

SEISMIC DAMAGE CHARACTERISTICS

In a masonry infilled timber frame house, two parts of very different mechanical properties are combined to form a dual structural system, in which the stiff masonry infills provide lateral resistance while the flexible timber frame carries the vertical load. In such a dual system, the seismic damage can also be discussed in two parts, i.e., that of the masonry infills, and that of the timber frame itself.

Cracking and collapse of masonry infills were the most commonly-seen damage to the masonry infilled timber frame houses. In the two examples shown in Figure 7, both houses lost many of the masonry infills in their longitudinal direction but neither of them fully collapsed, partly owing to the dual nature of the structural system. Such behavior is substantially different from that of URM structures, in which the masonry walls provide the sole resistance for both the vertical loads and the earthquake lateral load. Severe shear cracking of the masonry walls due to lateral load would at the same time greatly degrade their vertical load-bearing capacity and may eventually lead to the collapse of the house.

(a) (b)

Figure 7. Collapse of masonry infills in masonry infilled timber frame houses: (a) moderate damage and (b) severe damage.

Different from the timber frame in Figure 7(a), which was almost intact and needed no repair after the earthquake, the one in Figure 7(b) leaned so significantly towards one side that it became very difficult to repair. The residual drift ratio was about 1/8. At such large drift, the timber frame must have also sustained some damage. Most commonly seen damage patterns of the timber frame are demonstrated in Figure 8(a) to (c). They include the frictional sliding at the column base, the fracture at timber beam end, and the pull-out of the tenon from the mortise. Such damage might be attributed to the poor detailing, corroded materials or other factors like the loss of too many masonry infills. Once they took place, it is not easy to restore the full occupancy of the house without substantial repair efforts.

(a) (b) (c)

Figure 8. Typical damage to timber frame: (a) sliding at column base; (b) fracture of beam tenon and (c) pull-out of beam tenon.

DAMAGE STATISTICS OF INSPECTED HOUSES

Shuangshi is a small mountainous town with a population of about one thousand. The only connection between Shuangshi and the outside is a two-lane mountain road. For lack of means of transportation and the underdeveloped economy, there were no RC structures until the reconstruction following the 2008 Wenchuan earthquake was launched. A total of six RC moment frame buildings (three for schools, two for government and police, and one for hospital) were built as part of the reconstruction. These RC frame buildings were designed in accordance with the latest seismic code available at that time. All these RC frames remained almost intact during the Lushan earthquake while the masonry infills and suspended ceilings in them sustained some damage.

In contrast to the satisfactory performance of the RC buildings, the rest of the buildings in Shuangshi sustained significant damage or even collapsed during the Lushan earthquake, the majority of which was made of either unreinforced masonry or timber frames and was un-engineered. Figure 9 gives a map of the buildings in Shuangshi, most of which lined up along the streets. Two areas were arbitrarily selected as the inspection zones, within which the seismic damage of every single building was inspected with a few exceptions when the access to the building was unavailable (the doors were locked). As a result, a total of 32 masonry houses (either URM or confined) and 14 timber frame houses were inspected. All inspected houses in the two zones are depicted in the zoom-in maps in Figure 9(b) and (c), where the structural types are distinguished by different fill patterns.

The seismic damage of each house is classified into five levels, that is, slight, minor, moderate, severe and collapse. The classification was based on on-site observations and highly relied on expert judgment. To provide some standard, the classification criteria recommended in the Chinese Seismic Intensity Scale (GB/T 17742, 2008) were adopted as a reference for masonry structures. For timber frame houses, on the other hand, the criteria listed in Table 3 were followed for there is yet no such guideline available in China. Like the criteria for masonry structures in GB/T 17742 (2008), the criteria in Table 3 are also primarily based on the functionality of the houses after the earthquake, so that the damage levels of the different structural systems can be compared.

Table 3. Classification of damage levels of masonry infilled timber frame houses

Damage	Functionality	Timber frame		Masonry infills
Slight	Immediate occupancy	Intact	and	Minor cracking
Minor	Safe to occupy after emergency repairs	Intact	and	Moderate cracking, very few collapsed
Moderate	Safe to occupy after substantial repairs	Very few column bases slide; minor to moderate damage to beams or joints	or	Severe cracking, a few collapsed
Severe	Difficult or costly to repair	A few column bases slide, severe damage to beams or joints	or	Most collapsed
Collapse	Worthless or impossible to repair	Collapse, partial collapse		

The criteria for timber frame houses as listed in Table 3 take into account the damage of both the timber frame and the masonry infills, while the latter is given less importance than the former. This is because in the dual system of a masonry infilled timber house, removing some or even most of the masonry infills would not immediately lead to the collapse of the house and thus the cracked or damaged infills could be more easily repaired or replaced. House A in the previous section well demonstrated this advantage of timber framed houses over masonry ones.

The geographical distributions of the damage levels of the inspected houses are shown in Figure 10 for URM and confined masonry structures and in Figure 11 for the masonry-infilled timber structures, respectively. Houses of different damage levels were mixed together without obvious tendency of concentration in specific geological areas, such as riverside or hillside. This observation suggests that the seismic damages were not much affected by the differences in either geological conditions or ground motion characteristics in the current case study.

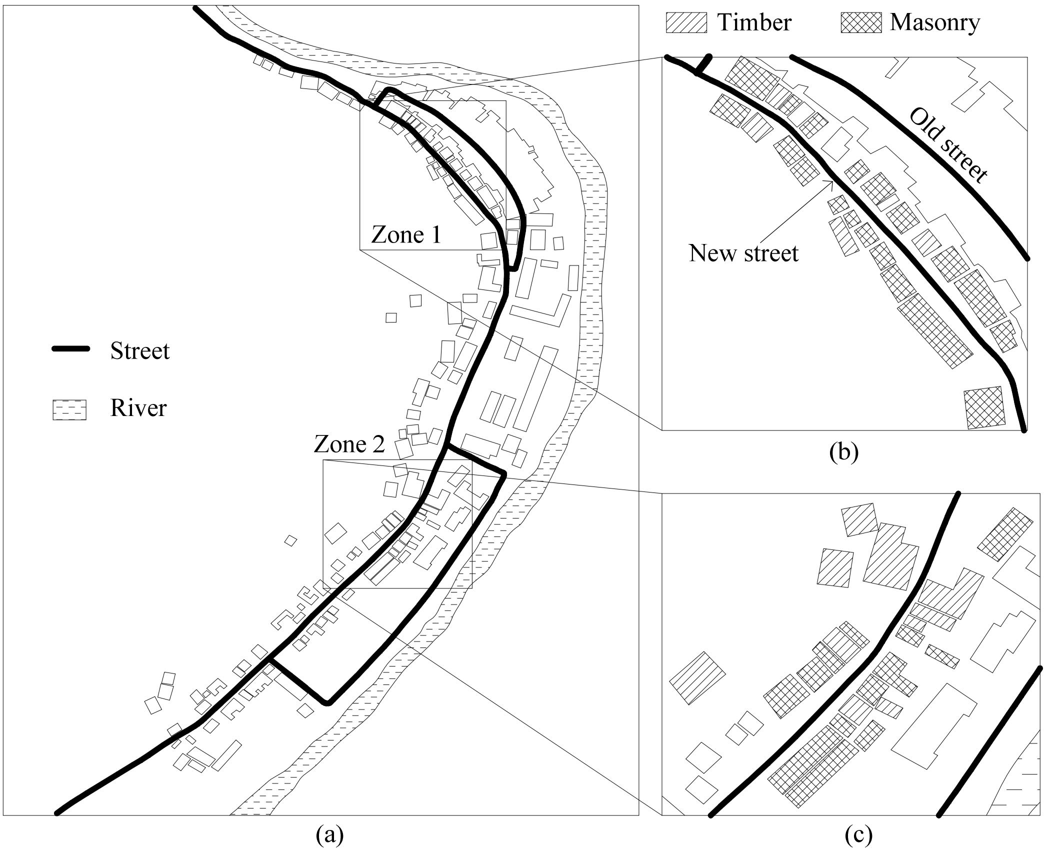


Figure 9. Map of inspected town of Shuangshi (a) overall view; (b) inspected houses in Zone 1 and (c) inspected houses in Zone 2.

Among the 32 inspected masonry houses shown in Figure 7, six were classified as confined masonry (denoted by 'C'). The results indicate that such confining elements, although not necessarily rigorously designed, were quite effective in reducing the seismic damage of the masonry houses. In contrast to the considerable damage to the URM houses, 5 out of the 6 confined masonry houses sustained only slight or minor damage.

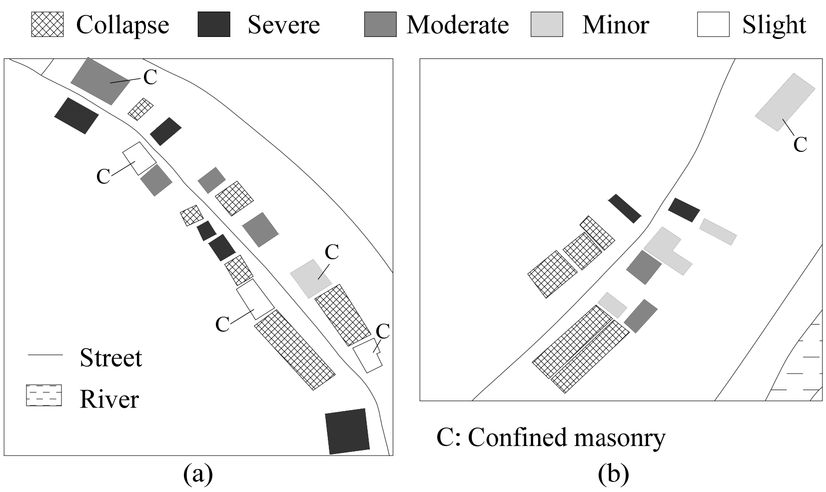


Figure 10. Damage levels of inspected masonry structures in (a) Zone 1 and (b) Zone 2.

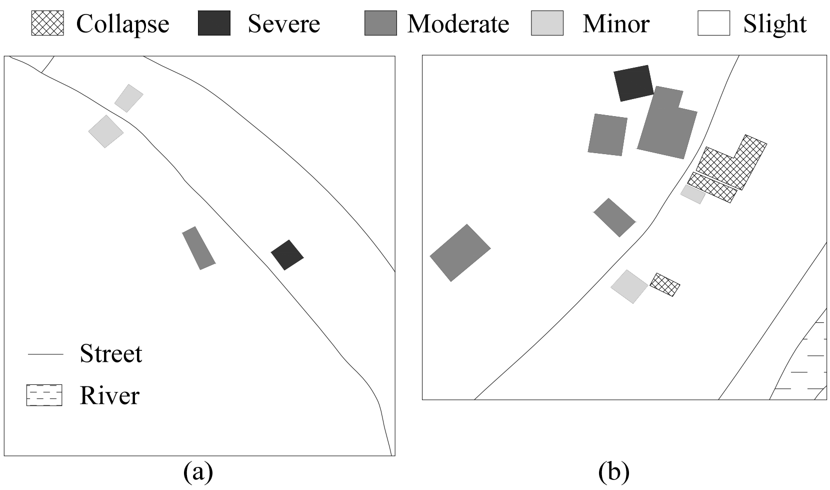


Figure 11. Damage levels of inspected masonry infilled timber houses in (a) Zone 1 and (b) Zone 2.

The structural system of masonry infilled timber houses were subjected to less uncertainty as compared to masonry houses. Statistics of damage levels of the inspected houses shows that moderate damage predominated in masonry infilled timber frames in the current case study (Figure 11), which may be either minor damage of the timber frame itself or substantial damage of the masonry infills, or both, as per Table 3. The ratio of severe damage and collapse of timber houses is only 34%, much lower than that of the URM houses (75%).

Masonry infilled timber frame houses and URM houses are the two most widely used and un-engineered structural systems in underdeveloped rural areas like Shuangshi in southwestern China. The comparison in Figure 12 clearly shows the advantage of timber houses in terms of seismic performance over URM ones, although the joint detailing has been oversimplified through the history. This can be attributed to the inherent dual system of masonry infilled timber frame houses. A lot can be learnt from this ancient structural system and improved detailing should be encouraged to further enhance its seismic performance and to restore its vitality as a practical solution for small scale residential houses in underdeveloped regions.

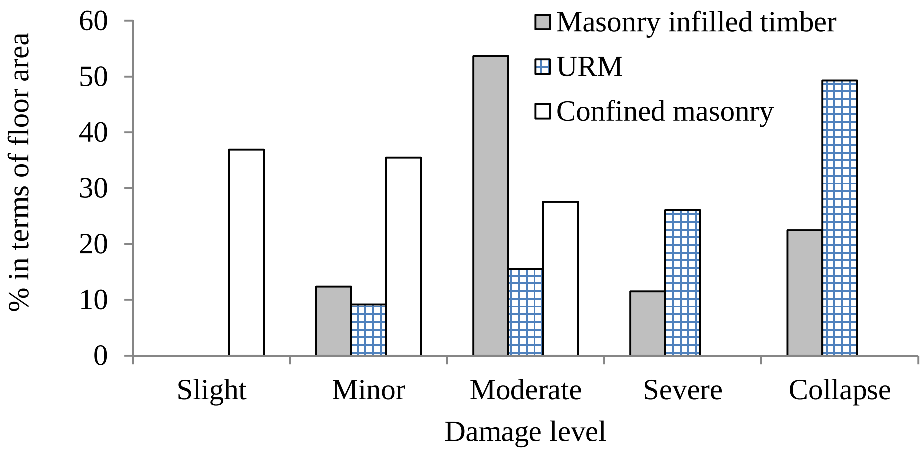


Figure 12. Damage level statistics of masonry houses and masonry infilled timber houses in the inspection zones

SUMMARY

The masonry infilled timber frame structure is inherently a dual structural system. Tremor observations show that the masonry infills would significantly shorten the vibration period of a Chuandou timber frame, indicating that the masonry infills provide most of the lateral stiffness of the structure. Meanwhile, the timber frame alone is capable of carrying all vertical loads even if most masonry infills collapse or are removed after the earthquake. This feature makes it easier to repair and to restore the occupancy of the houses.

The seismic damage of 14 masonry infilled timber houses and 32 masonry houses in the town of Shuangshi near the epicenter of the Lushan earthquake was inspected and summarized. The comparison between the statistics of their damage levels show that masonry infilled timber houses sustained much less damage during the earthquake than the URM ones, while the confined masonry ones exhibited better seismic performance in general. Before losing the masonry infills, the timber frame houses generally have vibration periods as short as those of typical masonry houses, either URM or confined masonry. Therefore, rather than the difference in vibration periods, the different seismic performance among the three structural systems was more a consequence of the innate structural properties, such as the higher damping ratios and clearly defined dual system of the masonry infilled timber frames, and the enhanced integrity of the confined masonry houses.

Although the Chuandou timber frame houses of the current state of practice are vulnerable to seismic damage, they rarely collapse. The structural system with moderate improvements to further suppress its seismic damage could represent a good solution of low cost and easy construction for earthquake-resistant buildings. Such improvements may include, but not limited to, strengthening of the timber beam-to-column joints with metal parts to prevent tenon pull-out, and embedding horizontal steel wires in the mortar layers of the masonry infills to provide better out-of-plane constraint.

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