Seismic Retrofit solutions for light timber frame buildings with soft first story

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ABSTRACT: Building structures with the first story of relatively low stiffness compared to the upper stories has the potential to develop significant deformation at the first story during earthquakes. Engineers have been well aware of the phenomenon and it has been generally accepted that such arrangements should be avoided due to high ductility demand.

Past earthquakes in different countries have produced many examples of light-weight timber buildings with significant drifts and subsequent damage at the first story level. Available retrofit techniques for timber buildings with soft first stories are reviewed. An alternative novel solution with timber shear walls added to the first story and energy dissipation elements connecting the shear walls to the building frames is presented. Effectiveness of the proposed concept is demonstrated through simple numerical analysis. Detailing requirements of the scheme are also discussed.

1 INTRODUCTION

A story of a building significantly less stiff than adjacent stories is termed ‘soft story’. Structural Engineers Association of California has defined it as the story with lateral stiffness of 70% or less than that of the story above, or less than 80% of the average stiffness of the three stories above (SEAOC, 1996). Building structures with the first story of relatively low stiffness compared to the upper stories are known to have the potential to develop significant deformation at the first story during earthquakes. Engineers have been aware of the phenomenon since the 1920s (Nishkian 1927, Snyder 1927, Martel 1929). Although in some cases the existence of such a level within the structure may be turned beneficial through careful detailing, it has been generally accepted (Chopra, 1973) that such arrangements should be avoided due to high ductility demand.

Performance of light-weight timber buildings in past earthquakes in have been presented here to show examples of significant drifts and subsequent damage at the first story level. Available retrofit techniques for timber buildings with soft first stories have been reviewed and a novel solution is presented as a simple alternative.


a) b)

Figure 1: Soft first story in a) Loma Prieta (ATC 2009) and b) Kobe earthquake (Ghosh 1995)

2 OBSERVATIONS OF LIGHT FRAME TIMBER BUILDINGS IN PAST EARTHQUAKES

Performance of light timber frame buildings during earthquakes has been observed since the 1930s. One of the general conclusions after the Long Beach, CA earthquake of 1931 was that buildings with more than one stories suffered more damage than single-storied houses (Martel, 1964).

More detailed studies have been done after the major earthquakes in the last few decades. In the 1971 San Fernando earthquake the total financial looses in single family dwellings was larger than losses in any other building category in the private sector (McClure, 1973). Similar to prior findings, two-storied and split level houses suffered increased damaged compared to single-story houses with lack of adequate lateral structural bracing identified as the primary cause of overall damage.

The 1994 Northridge earthquake demonstrated the damage potential of timber buildings even more clearly with 24 out of the 25 fatalities caused by building damage were in timber buildings. About half the $40 billion in property loss was in timber buildings and 48000 housing units were uninhabitable (Schierle, 2003).

Other earthquakes in California and Japan (Figure 1) have produced many examples of light-weight timber buildings with significant drifts and subsequent damage at the first story level. A number of instances of the phenomenon have also been found in recent Canterbury earthquakes (Figure 2, 3).

Figure 2: Soft first story observed in Christchurch earthquake (Buchanan 2011)

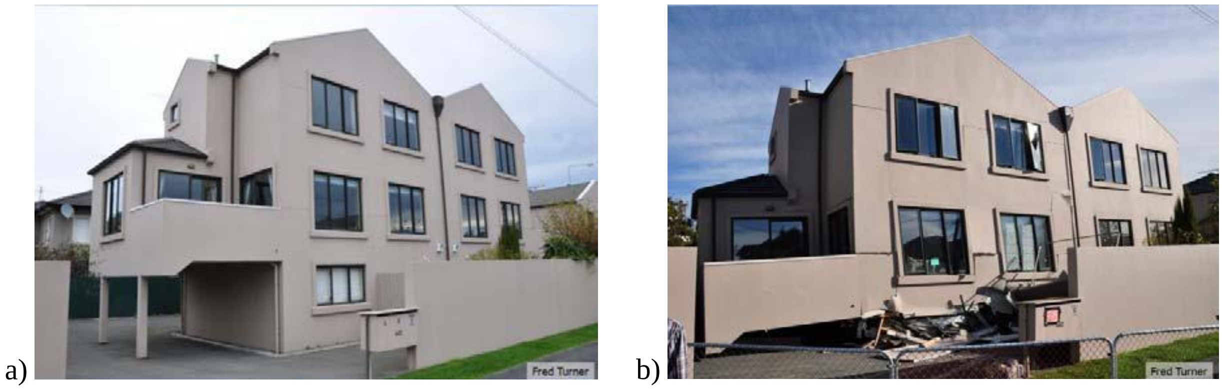


Figure 2: Progressive collapse due to soft first story: a) before and b) after (Buchanan 2011)

3 PREVIOUS AND ONGOING RESEARCH ON LIGHT FRAME TIMBER BUILDINGS

As mentioned before, damage potential of timber buildings have been known for the last few decades and some individual studies have been performed their seismic behaviour during that time. The first major collective research initiative was called CUREE-Caltech program was launched in the late 1990s (Hall, 1996). The five-year long research covered a number of fundamental aspects like dynamic characteristics of woodframe buildings and building-specific seismic vulnerability and loss estimation, demand aspects and reliability studies. At the same time it looked into structural components and details such as behaviour of shearwalls, inter-story shear transfer in woodframe buildings, design methodology for diaphragms, anchorage of woodframe buildings and connection studies. Novel techniques like application of fluid viscous dampers in woodframe structures were introduced.

The extensive testing regime also covered loading protocol and rate of loading effects, development of testing protocols and organization of an international benchmark.

In addition to experimental studies of the structural components shake table tests were performed on full scaled complete building models e.g. simplified two-story single-family house and multi-story apartment building.

The experimental research was complemented by development of seismic analysis software for woodframe construction. The findings of the research were disseminated through an education and outreach component.

The next major project on timber buildings was the NEESWood project (van de Lindt et al., 2008) which was conducted in the second half of the last decade. Although the objective was to develop performance-based seismic design philosophy for mid-rise construction, there was significant research on light-weight timber building including shake table test of a full-scale two storied building in 2006 (Christovasilis et al., 2007). The test showed, among other findings, that structural walls with gypsum wallboard can improve the seismic response of the building specially in the shear direction of the walls. At the final stage of the project a full-scale six-story apartment building was test on a shake table in Japan (van de Lindt et al., 2010).

In continuation of the NEES-funded research on timber the NEESSoft program was launched in 2010 (van de Lindt et al. 20102) particularly aimed at reduction of seismic risk for soft-story buildings. A number retrofit options are being investigated including steel moment frame, inverted moment frame, timber shear walls, combinations of steel frames and timber shear walls, knee-braces. Non-traditional techniques such as fluid viscous dampers and shape memory alloys are also investigated as well as cross laminated timber (CLT).

In 2009 the Applied Technology Council (ATC), with funding from the United States Federal Emergency Management Agency (FEMA) commenced development of simplified guidelines to address seismic retrofit requirements for weak first-story wood-frame buildings in seismically active regions of the United States, with a particular focus on Northern and Southern California and the Pacific Northwest. The guidelines, identified as FEMA P-807 (FEMA 2012), focus on multi-family, multi-story buildings with weak first stories and apartment buildings with tuck-under parking.

4 AVAILABLE RETROFIT OPTIONS FOR TIMBER BUILDINGS

A number of types of retrofit measures have been investigated and applied in practical timber buildings in recent years. The most common type of retrofit measure is to add steel moment-resisting frames to the original structure (Figure 4). It has been widely used particularly in North America. But it is often expensive and requires significant on-site intervention and careful connection detailing to integrate the steel frame with the original structure. Another common type of retrofit is to add additional plywood-sheathed shear walls (Figure 5). This is also expensive and not applicable in some structures due to the size required. It may require blocking of large openings which is unacceptable in some cases.

Base isolation is a logical concept for retrofit of soft story buildings. It is a proven technology and becoming increasingly common (Figure 6) in important and heritage structures (Reed and Kircher 1986, Sakamoto et. al. 1990, Zayas and Low 1997). However, it is not ideal for lightweight buildings, specially for elastomeric bearings due to lack of dead load. It also normally requires a rigid concrete diaphragm above the isolator plane. Base isolation is expensive and requires significant intervention as a retrofit measure. It is therefore not feasible a regular timber building unless the structure is unusually important or valuable.

Another technology that has been investigated recently is application of viscous dampers to reduce displacements in structures (Symans et. al. 2002). The dampers have been tested in diagonal and toggle-brace arrangement (Figure 7). The force exerted by the dampers is velocity dependent and therefore difficult to predict. They may also exert significant additional load on the original structure. The connections between the dampers and structures have to be detailed carefully.

Figure 4: Steel moment-resisting frame for retrofit (ATC 2009)

Figure 5: Timber shear wall for retrofit (ATC 2009)

Figure 6: Base isolator under timber building (Sakamoto et al. 1990)

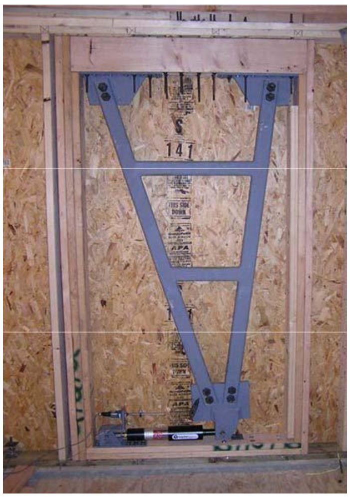


Figure 7: Viscous damper within timber shear wall (Symans et al. 2002)

Some other options that have been studied include friction connections, viscoelastic dampers, shape memory alloys, steel hysteretic braces. Although some of them have shown promising results in research, they are yet to be widely accepted for practical applications.

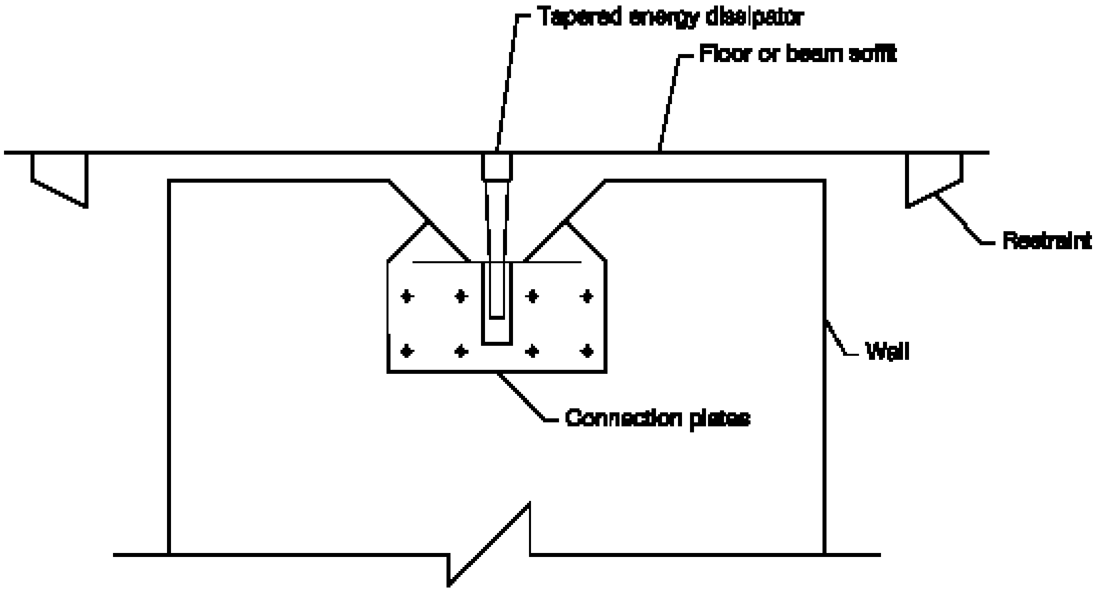
5 RETROFIT WITH TIMBER SHEAR WALLS AND ENERGY DISSIPATION ELEMENTS

A new solution with solid timber walls and mild steel energy dissipation elements is proposed here as an alternative for retrofit of light-weight timber buildings. The concept includes addition of new shear walls within existing structure and connecting that with mild steel energy dissipating elements. The shear walls will otherwise be independent of the existing structure. The ductile elements connecting the new walls and the original structure will be engaged during relative movements of the two during earthquake and will dissipate energy through deformation and yielding of the mild steel (Figure 8).

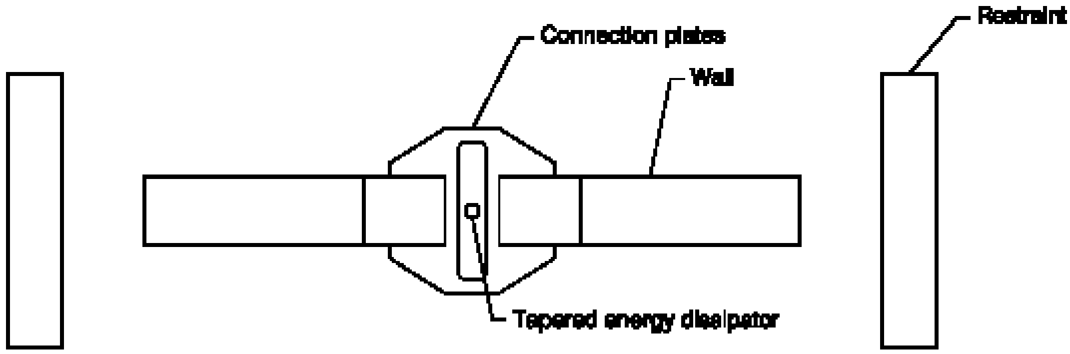
The additional elements will increase the stiffness of the first story and thereby reduce relative displacement with the stories above. The mild steel elements will remain elastic in small to moderate earthquakes but they will yield during major earthquakes. The displacement allowance provided in the system will be enough for design earthquakes. Additional restraints are provided to limit relative displacements between the stories in case of events well above the design level.

Tapered steel elements proposed by Tyler (1978) are an efficient type of energy dissipator. Although originally conceived and applied in bridge structures (e.g. King Edward Street Underpass in Dunedin), they have been used in at least one other different type of structure (Robertson, 2010). A major feature of the proposed system is that yield force of the mild steel elements is known and the maximum force transferred through the connections can be predicted irrespective of the expected ground motion. Another key advantage is that the added shear walls can act to support gravity loads in case the original structure losses some or all of the gravity load carrying capacity. This is essential to prevent progressive collapse of the structure observed in some cases in recent Canterbury earthquakes (Buchanan, 2011).

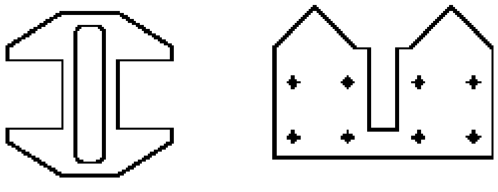
The energy dissipating elements can be replaced reasonably easily after they are damaged in a major earthquake. Most of the component added for the retrofit except the foundation can be prefabricated and therefore should be economic. Amount of intervention for the whole scheme is expected to be limited with no major strengthening of the original structure is anticipated. The newly added walls can be hidden behind claddings to protect the look of original structure.



Elevation



Plan



Horizontal plate

Vertical plate

Connection plates

Figure 6: Base isolator under timber building (Sakamoto et al. 1990)

6 DETAILING REQUIREMENTS FOR THE PROPOSED SCHEME

The shear walls have to be independent of the main building structure at the ground level. Seismic gap is required at the ground level. If the wall is at the exterior, façade has to be detailed to allow the relative displacements. Services going across the two systems have to be able to take the relative displacements.

The floor diaphragm energy dissipators connected to have to be strong enough to transfer the interstory shear forces without damage. Strengthening of the floor may be required to avoid any potential damage during an earthquake.

The energy dissipators have to be designed to act in distinct ways for different performance levels for the structure. In a minor earthquake, they will remain elastic with no or very little residual reformation. In a moderate earthquake, some of them may yield but displacement limits should be exhausted. In a major earthquake, most or all of the dissipators may yield and the connection plates may be engaged but any major damage to the walls has to be prevented.

Since the system does not have enough re-centering capacity to bring the structure to the original position, there may be some residual deformation after a major event. In case of unacceptable residual displacements the offsets have to be reduced by external interventions. Cables with turnbuckles and light jacking are two possible alternatives. These are to be considered and necessary provisions made from before.

The steel bars have to be easily replaceable after damage. One end should be threaded and there should be space within the slot at other end. The base fixing plates should have multiple provisions for bolts in case the relative positions of the two end fixing change. The fixing plates should not be damaged under any circumstance. Although the concept will remain the same, the dissipators have to be detailed carefully to suit each structure individually to act in the intended manner during an earthquake.

The bases and foundations of the shear walls have to be designed to transfer the full forces including that from any possible impact of the original structure on the floor. Particular attention has be given to the possible rocking at the base causing uplift of the foundation.

In case the movement allowance exceeded, the area of the wall expected to come into contact with the steel connection plate do not have to be armored. It is intended to have some local damage to absorb energy but global damage and potential instability of any wall is unacceptable.

CONCLUSIONS

The soft first story behaviour in light frame timber buildings during recent earthquakes is investigated. A brief review of the retrofit options is performed. A novel solution with timber shear walls and mild steel energy dissipators is proposed. The concept is practical and should be reasonable as a retrofit option. Further analytical investigations of the behaviour of the system are currently underway.

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