Influence of Stiffness Variation on the Performance of Houses in Earthquakes

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ABSTRACT: There are about one and half million light timber framed (LTF) buildings nationwide in New Zealand and satisfactory seismic performance of LTF buildings in major earthquakes is crucial in terms of the community’s resilience to earthquakes. Observed earthquake damage to light timber framed (LTF) buildings demonstrates that, while LTF buildings generally perform well in major earthquakes, they do suffer extensive damage if there are significant stiffness incompatibilities or there is severe land damage, including liquefaction. There can be various stiffness incompatibilities and the effects of these on the seismic performance of LTF buildings vary. This paper reports on a study of the effects of broad stiffness incompatibility issues on the seismic performance of LTF houses, based on earthquake damage observations and theoretical examinations of critical seismic aspects. The study revealed the following: (a) a timber floor diaphragm plays an important role in allocating seismic actions to different lateral load resisting systems and the floor deformation has to be considered if there is a stiffness incompatibility, (b) timber floor diaphragms need to be adequately designed to meet their required function, (c) a displacement-based design approach is more rational when there is a significant deformation incompatibility issue.

1 INTRODUCTION

The majority of residential building construction in New Zealand uses light timber framed (LTF) construction and this construction technique has lasted for many decades. There are about one and half million residential dwellings in NZ, hence research into the seismic performance of LTF buildings is very important. Past earthquakes including the recent Canterbury earthquake series have frequently shown that LTF residential houses generally perform well in earthquakes as severe as the ultimate limit state level and beyond (Buchanan et al. 2011), provided there are no implications associated with liquefaction or land damage or irregularities. However earthquake damage observations have shown that the seismic performance of LTF buildings is significantly complicated by the presence of structural irregularity resulting in stiffness incompatibility or by land damage including liquefaction (Personal communication, 2012).

Extensive studies are being carried out on the effects of land damage, including liquefaction, on LTF buildings in the recent Canterbury earthquakes. Severe liquefaction led to loss of integrity of the foundation slabs, causing extensive damage to superstructures of many LTF buildings. Discussion on the effects of land damage on the seismic performance of LTF buildings is outside the scope of this paper.

Various stiffness incompatibility issues, which were observed to have facilitated earthquake damage to LTF houses, are discussed in this paper. There are many situations where stiffness variations exist in LTF buildings, for instance, LTF buildings which have specifically designed elements in combination with NZS 3604 construction (SNZ, 2011), LTF houses on hillsides or houses which have significantly different structural systems in superstructures or in subfloor systems. People’s tastes for their dream homes are changing significantly as society changes and the presence of stiffness incompatibility in LTF buildings is more and more prevalent nowadays. Adequate seismic design of LTF buildings in this category is crucial in order that the vast housing stock is resilient in earthquakes.
This paper studies the effects of broad stiffness incompatibility issues on the seismic performance of LTF houses, based on the earthquake damage observations and theoretical studies (Liu, 2011). Discussion of the expected seismic behaviour of LTF buildings with stiffness variations is included and the paper also makes suggestions for an appropriate design approach to minimise the effects of broad stiffness variation on the seismic performance if the variations cannot be eliminated.

2 RELEVANT OBSERVED DAMAGE IN RESIDENTIAL LTF HOUSES

Stiffness incompatibilities in LTF residential buildings have many different forms and they have different implications on the seismic performance of LTF buildings. Figures 1 to 4 show earthquake damage to LTF buildings observed in the recent Canterbury earthquakes, which was more or less attributed to stiffness incompatibility.

Figure 1 shows a house which had broken front windows. There were many similar cases because large glass windows were often included on the front face of the house for the view and stiff solid walls were included on the rear side. Steel portal frames may have been designed to resist the seismic loads at the front but the designer usually has not considered (a) the associated deflections and their effects on the glazing and (b) the compatibility between the stiff sheet bracing systems in the rear of the house and the more flexible steel frame.

![Figure 1. Failure of Front Glass Elements by Unevenly Distributed Lateral Load Resisting Systems in Superstructures](image)

Figure 2 shows a house which had a mixture of pole foundations and concrete block wall foundations in the subfloor system. The building had suffered severe shaking damage and was abandoned when the photograph was taken. The stiff concrete block garage attracted the lateral load and because the pole structure was less stiff, the connections between the two were overstressed as the lateral loads from the superstructure above the poles were transferred to the garage.
Figure 2. Significant Stiffness Differences in Subfloor Framing Systems

Figure 3 shows a house which had a soft storey collapse. Soft storey is a typical case of vertical irregularity. Figure 4 shows a house which had split floor levels and severe stress concentration occurred along the junction of different floor levels. The house suffered severe damage around the junction area.

Figure 3. Vertical Stiffness Irregularity

Figure 4. Split Floor Level

It became clear to the BRANZ engineers conducting the house safety assessment checks following the February 2011 earthquake, that there were many instances of houses that did not impose a collapse threat but exhibited significant damage to the extent that they were unable to be occupied. While strength is the main consideration at the ultimate limit state condition, clearly less damage would be sustained if the stiffness compatibility of the resisting systems was also checked at this limit state.

3 THEORETICAL EXAMINATION OF EFFECTS OF STIFFNESS INCOMPATIBILITIES

3.1 Unevenly distributed lateral load resisting systems in superstructures

For architecturally designed houses, the superstructures of the houses often have very little scope for
bracing in the front and this is especially true when the site provides spectacular views. This is often referred to as in-plane stiffness irregularity. In-plane stiffness irregularity potentially could lead to significant structural torsional response in earthquakes, necessitating the torisonal resistance provided by well-arranged lateral load resisting systems in the direction perpendicular to the seismic direction.

There have been extensive publications on torsional seismic effects in buildings, particularly on reinforced concrete (RC) buildings designed to rely on inelastic deformation capacity (Paulay 1997). For RC buildings, floor diaphragms are relatively rigid, lateral deformations in earthquakes are mainly from vertical lateral load resisting systems and non-linear deformation in RC members is limited to plastic hinge regions if the members are designed to yield in earthquakes. In comparison, overall deformations of LTF buildings can be due to many sources. For example, the deformations resulting from LTF walls and floors are equally significant.

In resolving torsional response, transfer floor diaphragm plays an important role to transfer the actions across the building. Unlike RC structures or steel structures where concrete floor diaphragms are more likely to be rigid, timber floor diaphragms in LTF buildings are likely to have some flexibility and floor diaphragms have to be adequately designed, especially around openings (stairs) to meet the functional requirements. In addition, when the timber floor diaphragm needs to transfer the lateral loads from the front to the bracing system at the back, the diaphragm has to act as a cantilever. In this case, the front of the building is expected to translate significantly because of the diaphragm flexibility, potentially leading to extensive damage to the front facade.

Figure 5 shows an idealised floor plan of an LTF house where there are no bracing walls at the front of the building. CM is the centre of mass and CR is the centre of seismic resistance when seismic action is in the X direction. Seismic actions associated with the building seismic weight in the front area require the floor diaphragm to behave as a cantilever in order that the actions can be resolved by the lateral load resisting systems parallel to the seismic loading direction at the back and the generated torque can be resolved by lateral load resisting systems perpendicular to the seismic direction (i.e. the end walls). A stress concentration will occur at the junction between the floor and the walls along line A.

Timber floors constructed to NZS3604 do not generally have adequate in-plane stiffness to provide an effective load transfer as required in this case without significant displacement. As a result, the displacement of the front of the house is likely to be larger than the glazing can accommodate and failure is likely.

Figure 5. Floor Plan Showing Wall Arrangements
3.2 Mixed structural systems with different stiffness characteristics

When LTF buildings have different lateral load resisting elements with different stiffness characteristics, in-plane deformation incompatibility could potentially become an issue. This phenomenon can be present in superstructures or subfloors and the effects on the seismic performance of buildings are the same in principle. Consider a mixed subfloor system as an example. There are many occasions where the existing LTF buildings have had additions constructed and the additions have used different subfloor systems from the original building, as shown in Figure 6.

![Figure 6. Mixed Foundation System: Slab on Grade and Timber Pile Foundation](image)

In Figure 6, the original building was founded on a timber pile foundation and the later addition was founded on a reinforced concrete slab. Compared with the timber pile foundations which are flexible (Thurston 1996, Thurston 1993), the reinforced concrete slab foundation system is very rigid. In an earthquake the two different foundation systems perform very differently.

When the seismic action is parallel to the foundation interface, I-I, the two different foundation systems tend to move by different amounts and this will cause relative movement between the two systems unless they are adequately joined. When seismic action is perpendicular to foundation interface I-I, a severe stress concentration will occur at the interface between the two different foundation systems and the connections will need to be designed for this. Adequate connections between two different foundation systems are essential to maintain the building integrity at foundation level. Major structures often intentionally employ a seismic separation between old and new parts with appropriate detailing. However, this is rarely considered in residential houses, emphasising the importance of the need for a suitable connection, or otherwise the building will open up along the interface of the two systems, leading to significant damage to the entire structure.

3.3 Significant stiffness incompatibilities in subfloors of hillside LTF houses

Hillside LTF buildings, especially down-slope buildings, are likely to present the most challenges in designing buildings for seismic actions in terms of stiffness incompatibility. Down-slope houses have not only vertical stiffness incompatibilities but also in-plane stiffness incompatibility.

Figure 7 shows one common type of down-slope house where the main building structure is separated from the ground by a substantial subfloor system. Because of the nature of the sloping ground, down-slope hillside houses always have subfloor structures which are of varying “stiffness” even if they have similar types of bracing systems, such as braced piles, due to varying heights. Consequently, the stiffness incompatibilities exist not only within the subfloor systems but also between the subfloor systems and the superstructure.
A possible consequence of deformation (stiffness) incompatibility is progressive failure (Liu 2011), and deformation incompatibility in subfloor systems of hillside LTF houses significantly complicates the design approach. When the seismic action is in the up-slope/down-slope direction, progressive failure could potentially occur in the subfloor system. When the seismic action is across the slope, significant torsion can be induced. If the subfloor framing system has a mixture of different structural bracing systems, the effects of deformation incompatibilities on the building’s seismic performance will be greater.

A progressive failure mechanism in subfloor systems of varying stiffness is demonstrated below using a braced pile subfloor example but the principles will be applicable to other types of subfloor framing systems with varying stiffness. Figure 8 shows the braced pile groups of varying heights for a down-slope house. The diagonal braces are of 100mm x 50mm timber and piles are 250mm S.E.D. timber poles.

A standard braced pile group of two piles and a diagonal brace has a seismic bracing capacity of 6kN (120 BUs), according to NZS3604 (SNZ 2011). NZS3604 has assumed a ductility of 3.0 in deriving the bracing demand for the subfloor system. Therefore the horizontal loads at the ultimate limit state for $\mu_\Delta = 1.0$ are 18kN for each braced pile group.

Under the horizontal loading of 18 kN applied to each braced pile group at the floor level, the diagonal brace “2” in the short braced bent has the maximum axial compression of the braces and the compressive action is 19 kN, as illustrated in Figure 8 (ii). The 100mm x 50mm diagonal brace has a compressive axial load capacity of 11 kN and therefore the brace will fail in compression.

Assume that the diagonal brace “2” has failed in compression. What will happen to the rest of the subfloor bracing system? Figure 8 (iii) shows that the other diagonal brace “1” in the short bent has then been significantly loaded after brace “2” has failed. As a result, diagonal brace “1” will fail because its axial compression capacity is now well exceeded. At this stage, the short braced bent, which was originally stiffer than the taller bent, has lost its bracing function and all the horizontal seismic action must be resisted by the taller braced bent. Figure 8 (iv) shows the axial actions in the slender braced bent after the shorter braced bent has failed. The diagonal braces in the taller braced bent are now overloaded and they are expected to fail as well, completing the cycle of the progressive collapse scenario.

Potential progressive failure because of structural system stiffness incompatibility has been demonstrated above based on a system consisting of braced pile groups. If subfloor framing systems of
down-slope LTF houses consist of mixed structural forms, such as combinations of braced piles and sheathed walls, the consequences associated with stiffness incompatibilities would be on a greater scale and specific engineering design considerations are needed to prevent such progressive failure.

Possible progressive failure/collapse in subfloor systems could be very critical when the seismic action is down the slope due to the nature of the varying heights. Meanwhile torsional response and high local stressing could be very significant when the seismic load is across the slope, depending on the flexibility of the floor diaphragm.

Figure 8 Progressive failure in braced pile systems of varying stiffness
(iv) Members 5 and 4 are overstressed to failure after failure of stiff braced pile group

Figure 8 Progressive failure in braced pile systems of varying stiffness (contd)

4 SEISMIC DESIGN OF LTF HOUSES WITH STIFFNESS INCOMPATIBILITY ISSUES

If lateral load resisting systems have different stiffness characteristics, the adequacy of the diaphragm plays an important role in building’s seismic performance. If floor diaphragms are absolutely rigid, all the lateral load resisting systems have to translate approximately by the same amount although the relationship between the centre of rigidity and the centre of mass will cause the entire system to rotate. The load-displacement curves shown in Figure 9 are for two systems of different stiffness characteristics and they reach their peak strength at different displacements. In this case, a displacement-based design procedure is more rational than a force based procedure. Under seismic actions, all the lateral load resisting systems parallel to the seismic loading direction are assumed to translate by the same amount if the diaphragm is assumed to be rigid and there is no torsional rotation.

As shown in Figure 9, after the design displacement, $\Delta_{\text{cap}}$, is determined, based on the desired performance requirements, the summation of the force capacities of all the lateral load resisting systems at the designated displacement, $\Delta_{\text{cap}}$, will be the seismic load resistance, $R$ $(R=V_A+V_B)$, of the entire system at that displacement level. The combination of $R$ and $\Delta_{\text{cap}}$ will give the reliable seismic capacity. In detail, the effective period, $T_{\text{eff}}$, can be found, based on $R$ and $\Delta_{\text{cap}}$. By referring to the design spectra, the required base shear capacity, $V_{\text{required}}$, for $T=T_{\text{eff}}$ can be determined. Iteration may be required until the criterion of $V_{\text{required}} < R$ is met. For LTF buildings, floor diaphragms have some flexibility and lateral load resisting systems will not translate by the same amount because the floor will deform as well. The amount of floor deformation depends on the construction of timber floors, especially around the edges, and this differential displacement has to be allowed for when allocating the seismic actions to the different lateral load resisting systems. Figure 10 illustrates the impact of timber floor flexibility on the building’s seismic performance when the lateral load resisting systems are eccentric. In the case of a stiff floor, the horizontal seismic action can be resisted by the long wall at the back and the induced torsion can be resisted by the walls perpendicular to the seismic action direction. However, if the floor diaphragm is flexible, seismic action transfer across the building will cause significant distortion in the floor diaphragm, potentially causing failure of the front glazing under large deflections.
5 CONCLUSIONS

Presented in this paper is a study on the effects of stiffness incompatibilities on the seismic performance of LTF houses. Observed earthquake damage to LTF buildings clearly showed that stiffness incompatibilities present in lateral load resisting systems can potentially cause much more damage to buildings, in comparison with similar buildings without stiffness incompatibility issues. Examples have been given of houses which had sustained significant damage to glazing because of wide stiffness incompatibilities between the front and rear of the house and significant damage to the structure because of unaccounted for stiffness incompatibilities between foundation elements.

Because of stiffness incompatibilities present in some forms in LTF buildings, lateral load resisting systems of different stiffness characteristics will achieve different strength levels at the same deformation magnitudes. In this case, displacement-based design procedures, rather than the commonly used force-based procedures, should be used.

Floor diaphragms play an important role in the distribution of seismic actions to parallel vertical structural systems of different stiffness characteristics and the deformation compatibility between the lateral load resisting systems and the floor diaphragms have to be allowed for appropriately. Timber floor diaphragms used in LTF buildings are not rigid elements and their stiffness and strength performance depend on floor construction details, especially the edge members. In determining floor stiffness properties, construction details must be properly specified in order that the designed floors match the intended design objective.
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