Challenges in achieving seismic resilience of light timber -framed houses

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ABSTRACT

Performance-based seismic engineering is widely used around the world. The essence of performance-based seismic design of buildings is to design a building for multiple performance requirements such as damage controls, collapse prevention (life safety).

New Zealand (NZ) has a performance-based code environment. However, the current seismic design standards are generally prescriptive and were developed primarily to achieve life safety at ultimate limit state (ULS), it is often not clear what performance levels, apart from life safety, could be expected of the buildings.

Most of residential buildings in NZ are low-rise light timber-framed (LTF) buildings. Construction of LTF residential buildings is very different from non-residential buildings. Current LTF house construction standard is NZS3604:2011 (SNZ 2011). NZS3604 is a prescriptive standard and has an engineering basis. However, the engineering basis of NZS 3604 is significantly less vigorous than those of other structural systems.

In the Canterbury earthquake sequences, the LTF houses all achieved life safety but the house damage varied significantly from no damage to a total write-off. Greater house damage was often associated with ambitious house designs, mixed compliance pathways for a house, and/or inadequate load paths. Significant discrepancies in seismic performance of residential houses indicates significant rooms for the improvement of NZS3604.

To advance seismic designs and gain insights into seismic damage mitigation strategies of LTF houses, the fundamental engineering principles used in the engineering basis of NZS3604 are examined by desk-top studies and experimental studies. This paper reports revealed issues, which potentially exacerbated seismic performance of LTF houses.

1 INTRODUCTION

Performance-based seismic engineering of building structure is widely used around the world. The essence of performance-based seismic designs of buildings is to design a building for multiple performance requirements such as damage controls, collapse prevention (life safety) to achieve cost effective seismic resilience of built environment. New Zealand (NZ) has a performance-based code environment, but the current seismic design standard, NZS1170.5:2004 (SNZ 2004), is generally prescriptive and was developed to achieve life safety at ULS only.

Earthquake observations in recent earthquakes in NZ showed that the buildings designed to modern codes often achieved life safety in an event equivalent to the ULS intensity, but buildings often had significant damage, causing enormous interruptions in earthquakes. This brough about the realisation that current seismic design settings are unable to provide meaningful information on what levels of seismic damage are expected of the buildings designed to the current standards. Clearly there is a gap between the current design settings and the performance-based seismic engineering philosophy.

In recent year, there has been significant research efforts about damage-controlled seismic designs of buildings but these efforts have been mainly limited to non-residential buildings, such as, concrete buildings. There has been only very limited research on damage-controlled seismic design of residential buildings commonly built in New Zealand (NZ).

Residential houses in NZ are primarily low-rise light timber-framed (LTF) buildings. Construction of LTF residential buildings uses a platform construction technique and it is very different from non-residential buildings. In the 2010/11 Canterbury earthquake sequence, residential LTF houses achieved the New Zealand Building Code objective of "life safety". However, earthquake damage observed to LTF buildings was prevalent and unprecedented. The financial losses associated with LTF residential buildings in this earthquake sequence alone costed NZ over $30 billion, about 18% of NZ GDP. One apparent evidence from the 2010/2011 Canterbury earthquake sequence is that seismic performance of LTF houses did not meet societal expectations (Brown 2022).

Clearly there is a need for advancing seismic engineering of LTF houses to enable seismic performance requirements of LTF houses to include damage control requirements as well.

In this paper, the fundamental engineering principles used in constructing LTF houses are examined by desk-top studies and experimental studies. This paper reports the potential issues, which could exacerbate seismic performance of LTF houses. Subsequently this paper also suggests the work needed to bridge the knowledge gaps to advance the seismic resilience of LTF houses.

2 SEISMIC ENGINEERING CHARACTERISTICS OF LTF HOUSES IN NZ

2.1 General

Construction of LTF houses in NZ primarily follows the cook-book standard NZS3604, which was introduced in 1978. The current version of NZS3604 standard is NZS3604:2011.

NZS 3604 has been developed for constructing simple small-scale LTF buildings. For typical LTF buildings, the lateral seismic-resisting systems are sheathed LTF walls, and therefore, LTF houses perform in a similar way to other wall structures in earthquakes. The sheathed LTF walls are also the gravity load-carrying elements of LTF buildings. The lateral deflections experienced by these walls in design earthquakes would be small in comparison with the wall lengths. In addition, low-rise LTF residential buildings are generally light in nature, and subsequently, P-Δ effects usually are not significant enough to cause instability for LTF houses in earthquakes.

The reported collapse limit state for low-rise wooden buildings overseas could reach a storey drift of greater than 7%(Paevere, Foliente & Kasal, 2003; Bahmani & van de Lindt, 2013), which is significantly higher than the ULS deflection limit of 2.5%, as specified in the New Zealand seismic loading standard NZS 1170.5:2004 Structural design actions – Part 5: Earthquake actions – New Zealand. Therefore, the LTF buildings of mainly NZS 3604:2011 construction could easily achieve life safety requirements in design earthquakes, as evidenced in the Canterbury earthquakes.

While LTF buildings have a low probability of collapse in earthquakes, they are vulnerable to earthquake damage because plasterboard walls, commonly used as bracing systems in LTF houses, start to get damage at a very low drift level (lower than 1%). As such, damage control limits are more relevant and meaningful for LTF houses in NZ. As observed in the 2010/2011 Canterbury earthquake sequence, seismic performance of the LTF houses varies markedly from building to building, showing enormous uncertainties of the seismic damage potentials of LTF houses. In this section, the engineering basis of LTF house construction standard NZS3604 is examined and potential seismic issues of LTF houses are then identified for further discussions.

2.2 Engineering basis of NZS3604

2.2.1 Platform construction method

Construction of LTF residential buildings uses a platform construction technique and it is very different from non-residential buildings. A platform construction technique means that the structure of a house is like stacked boxes. In this case, valid load transfers between levels are crucial to ensure that discontinuity of the structural systems along the building height will not compromise the seismic performance of the building.

2.2.2 Determination of seismic demand according to NZS 3604:2011

Timber frame building standard, NZS3604, for constructing low-rise LTF houses was first introduced in 1978 and it has been revised a few time although the underlying principles have remained basically unchanged. NZS3604 is a cook-book standard and it specifies both seismic demand and seismic bracing provision. Current version of NZS3604 is NZS3604:2011.

According to the engineering basis of NZS3604:2011, the seismic bracing demand of an LTF house was derived using an equivalent static method as recommended by NZS 1170.5:2004, assuming a fundamental period of 0.4 seconds and a ductility of μ=3.5. The model used is an elemental lumped mass model as shown in Fig. 1 (Shelton 2013). The derived seismic demands for each storey are tabulated in NZS3604.

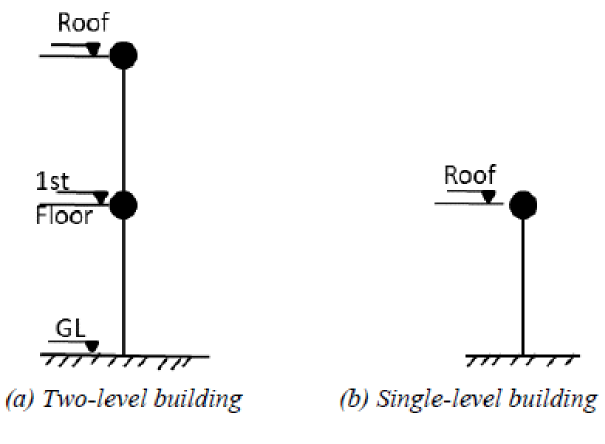

Figure 1. Model used in deriving earthquake demand

2.2.3 Determination of seismic bracing capacity of proprietary bracing elements

The lateral seismic resisting systems of LTF houses are proprietary sheathed LTF walls. NZS3604:2011 does not specify the sheathing materials of LTF walls. Instead, NZS 3604:2011 mandated the P21 test procedure (Shelton 2010), developed by BRANZ, to evaluate the seismic bracing capacity of proprietary sheathed LTF wall elements. The test arrangement for a typical P21 test is illustrated in Figure 2. The P21 test setup simulates a 2.4 m high LTF wall on a rigid foundation. The seismic bracing rating of an LTF wall obtained by P21 testing is the seismic bracing capacity of the wall, regardless of the wall being on concrete slab foundations or being on suspended timber floors, as far as the bracing rating is less than 6kN/m. Clearly P21 test setup gives no considerations to the effect of wall discontinuity at suspended floor level, including the effect of wall base conditions on the wall bracing behaviour or the load path to resolve the reactions at the wall base.

The P21 test is a slow cyclic racking test on a cantilever proprietary LTF wall element, applying a load at the top of the wall. The seismic rating of the wall element is determined as the force strength at a deflection of 15 mm, 22 mm, 29 mm or 36 mm, depending on when significant strength degradation occurs. P21 test procedure does not validate the ductility capacity of 3.5 as assumed in the derivation of the bracing demand.

P21 tests are often conducted on standard wall lengths, 0.4 m long, 0.6 m long and 1.2 m long. The determined rating may be applied to walls up to twice the length of the tested wall. There are no considerations given to the potential deformation incompatibility of LTF walls with different lengths.

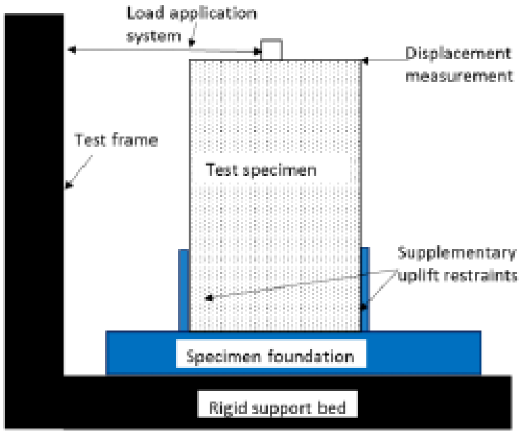

Figure 2. P21 test arrangement

2.2.4 Seismic bracing provision of LTF houses according to NZS3604

With regards to the seismic bracing designs of LTF buildings within the scope of NZS 3604, the designers just need to ensure that the total seismic bracing capacity provided within the concerned storey of a building is at least equal to the total seismic demand for that storey as derived from the tables in NZS 3604.

In terms of bracing distribution requirements in NZS 3604, allowance is made for limiting plan irregularity but not vertical irregularity. Plan irregularity of a building is accounted for by placing limits on the distribution of bracing elements, and these limits were established based on engineering judgement rather than scientific evidence.

2.2.5 Discussions

The elemental force-based approach as shown in Figure 1 is simple to use and it is only suitable for regular buildings with no critical structural weaknesses, such as, irregularities, load path discontinuities.

It is well known that many critical seismic issues, as suggested by NZSEE Advisory group, could exacerbate the seismic performance of building structures and cause great deviation of the actual seismic performance from the predicted performance. These issues include

- Deformation incompatibility
- Discontinuity and disproportionality of load paths
- Irregularity
- Soil, foundation and structure interactions

The engineering basis underlying the NZS3604:2011 uses the simplest form of seismic design methods and it is potentially insufficient to consider the effects of the-above stated crucial seismic issues. As such, NZS3604 needs to be reviewed in order to achieve seismic resilience of LTF houses.

In the following sections, these issues are examined, some issues being examined in greater details, but other issues being examined conceptually and being suggested for further investigations.

3 UNCERTAIN SEISMIC BEHAVIOUR DUE TO AN ELEMENTAL FORCE-BASED APPROACH

3.1 Overly simplified the relationship between elastic response and non-linear response

As described above, the seismic bracing design basis of LTF houses in NZ is based on a simple elemental approach. There are a few shortcomings associated with the elemental approach used by the engineering basis of NZS3604:2011.

Buildings are damaged in earthquakes because these buildings undergo significant non-linear deformations. However the current seismic design standard uses a force-based approach, which focuses on forced strength, rather than the seismic displacement. The force-based approach assumes that a non-linear seismic response of a building can be evaluated using a 'snapshot' of structural response at the peak base shear for an equivalent elastically responding structure. The peak base shear is the reduced elastic seismic design action of the building, based on the assumed ductility, which is the indicator of energy dissipating capacity of the building. The reality is that the relationship between peak displacement response of elastic and inelastic systems is complex, and more variable than commonly accepted (Priestley 1993). There are many confusions in formulating the relationships between elastic response and non-linear response. These confusions help contribute to the discrepancies of the predicted seismic responses. As a consequence, the force-based approach focuses on force strength, rather than on the seismic displacements (deformations) and therefore is inadequate to predict the actual seismic response of a building.

3.2 Emphasis on elastic stiffness characteristics of the structure and its elements

The starting point of the force-based approach is to determine the elastic stiffness characteristics of the structure and its elements in order to calculate the fundamental period of the equivalent elastically responding structure. The estimation of the elastic stiffness characteristics of the structure and its elements is a very difficult task because most building elements usually do not behave in a perfect elastic-plastic manner and in fact, most of building elements behave in a highly non-linear manner. A great deal of research and engineering practice show that the determination of elastic stiffness characteristics of the structure and its elements has significant uncertainties, subsequently leading to very different seismic response predictions.

3.3 Crude approximation of energy dissipation capacity of the building at the system level

The force-based approach uses the displacement ductility to calculate the elastic seismic design action. The displacement ductility is used as an indicator of the energy dissipation capacity of the building. It is not straight-forward how to evaluate the displacement ductility of the building at the systems level, especially when the lateral load resisting systems of the building have different load-displacement behaviour.

For LTF residential buildings, approximation of energy dissipation capacity is even cruder. The lateral load resisting systems of LTF residential houses are LTF walls, constructed of light timber framing lined with sheet materials. The energy dissipating capacity of LTF walls vary, depending on the sheet materials, sheet fixing details, wall lengths, wall base fixing details and the systems under the base of the wall so on. The engineering basis of NZS3604 assumes a ductility of 3.5 in determining the seismic action but the bracing capacity ratings of proprietary LTF walls using P21 test procedure does not validate the assumed ductility of 3.5 and does not give any considerations about the deformation/stiffness incompatibility of LTF walls of different lengths.

An elemental study on energy dissipating capacity of LTF plasterboard walls was carried out, based on the available P21 test data (Liu etc). The study revealed that energy dissipating capacity of the commonly used plasterboard bracing walls is significantly less than the assumed ductility of 3.5 in the engineering basis of NZS3604. The study suggests that a displacement ductility of not greater than 2 be used in a force-based approach domain.

Apart from the use of an over-stated ductility, the elemental 2D force-based approach in the engineering basis of NZS3604 is not able to adequately evaluate seismic response evaluation of a LTF house. Typically, LTF residential buildings have more deformation sources, more severe structural weaknesses, such as, discontinuity, irregularity. It is necessary to develop seismic bracing requirement of LTF houses based on three-dimensional seismic considerations.

3.4 Summary

In summary, the elemental force-based approach currently used by NZS3604:2011 is crude in many aspects and will not be able to provide uniform predictions of house damage performance in earthquakes.

4 CAPACITY DESIGN PHILOSOPHY

Seismic engineering has significantly advanced in last decades and the most important advancement is the development of capacity design philosophy. The fundamental philosophy of the modern seismic engineering standards around the world has been the capacity design philosophy since 1970s. The key elements of the capacity design philosophy include

A. Clearly defining the intended energy-dissipating regions within the building.
B. Ensuring the elements with no energy-dissipating regions to remain elastic when the energy-dissipating regions yields and undergoes the over-strength phases.
C. Designing and detailing the designated energy-dissipating regions adequately so that the building elements and the building as a whole could sustain their strengths while experiencing significant non-linear deformations, namely a ductile performance. As such, capacity design philosophy in designing buildings for earthquakes focuses on global behaviour of a structure in earthquakes, which is at the systems level, rather than at the elemental level.

LTF houses are wall systems, but they are different from other wall structures. For concrete wall structures, capacity design philosophy requires the lateral load resisting walls to continue from the foundation level to the wall tops. In addition, the wall foundations need to be designed adequate to resolve the reactions at the wall bases. The energy dissipating region of a RC wall is designated to be a small region above the wall base from the foundation. Capacity design philosophy ensures that the walls won't develop premature shear failure or premature foundation failure.

Construction of low-rise LTF houses usually uses a platform construction technique, as illustrated in Figure 11. As illustrated in Figure 11, the bracing systems in LTF houses only span between adjacent floors/roof and these LTF walls also often have misalignments between storeys. As such, seismic performance of the walls on upper level(s) is strongly dependent on the suspended floor conditions, especially when the walls on upper level are offset from the walls below. According to the capacity design philosophy, the suspended floor of a two-storey LTF house needs to be strong enough to resolve the overturning reactions from the walls on the upper level and it is important to prevent the suspended floor from premature failure. It is not clear how the current NZS3604:2011 or the P21 test procedure has addressed these issues.

An experimental study was conducted at BRANZ to investigate the effect of the LTF walls being on a suspended timber floor rather than on the ground floor, on the seismic behaviour of the walls. In this study, four LTF plasterboard walls on suspended timber joist floor were cyclically tested and the test results were compared with the test results of identical LTF walls but tested using P21 procedure. The study revealed that the bracing behaviour of LTF walls on suspended timber floors is different from that obtained from P21 testing. For the conventional P21 tests on LTF plasterboard walls, the failure is often initiated by the failure of screw attachments. However, the failure of the LTF plasterboard walls on suspended timber floors in this study was initiated within the floor and the damage progression was primarily limited to the floor system in this study. Shifting the damage from the screw attachments of the plasterboard walls to the floor framing is belied to be undesirable. This study suggests (1). that the current P21 test procedure be revised to ensure realistic bracing rating for LTF walls on suspended timber floors; and (2) that the floor framing under LTF bracing walls be improved to prevent the floor from premature failure.

5 IRREGULARITY

It is well-known that structural irregularities, either plan irregularity or vertical irregularity, exacerbate the earthquake damage in buildings but the effects of irregularities on the seismic response assessment of a building structure is very hard to quantify. (Uncertainty paper, Assessment guidelines).

Earthquake damage in LTF houses, observed in the 2010/11 Canterbury earthquake sequence, demonstrated that simple regular LTF houses performed well while irregular houses often had significant damage that was uneconomical to repair. This demonstrated that the irregularity of LTF buildings was an important factor responsible for the exacerbated earthquake damage.

For the bracing arrangements in low-rise LTF houses, NZS3604:2011 specifies irregularity limits but the irregularity limits were established based on engineering rules of thumb rather than scientific evidence.

A BRANZ study was carried out to quantify seismic effects of permissible irregularities in NZS 3604:2011. Model LTF houses were designed according to NZS3604:2011 and three single storey LTF buildings with varying degrees of permissible plan irregularities were designed and their seismic performance was studied by conducting three-dimensional non-linear push-over analyses. For the non-linear push-over analyses, the in-plane behaviour of LTF walls and ceiling diaphragms were modelled using the hysteresis models, developed based on test data, as reported in previous research.

The study revealed that permissible irregular bracing arrangements in NZS 3604:2011 could amplify lateral seismic deflections by 4 to 5 times in comparison with the regular counterparts, resulting on earthquake damage in irregular LTF houses well beyond economical repair. Subsequently, this study suggests that the irregularity limits in current NZS 3604:2011 be reviewed and tightened.

6 INADEQUATE CONSIDERATION FOR SOIL-FOUNDATION-STRUCTURE INTERACTIONS

As described above, the seismic engineering basis of NZS3604 of low-rise LTF houses follows an elemental force-based approach as illustrated in Figure $$. It needs to be appreciated that this elemental model in Figure $$ only simulates the super structure. Although not explicitly stated in the engineering basis of NZS3604, the seismic bracing design basis of NZS3604, in constructing low-rise LTF houses on subfloor framing systems, is based on a two-staged analysis (BRANZ SR58). The seismic bracing provision of the subfloor frames is derived from a single degree elemental study where the superstructure is assumed to be rigid and be represented by a lumped mass at the ground level, namely the top of the pile foundation, as illustrated in Figure RR. The single-degree elemental study (SR58) demonstrated that the predicted seismic deflections of anchor pile systems were influenced significantly by the assumed damping levels. The analysis results were also compared with the test results of anchor piles tested on field and the study revealed that the damping level of 14% matched the test results very well. However it is not clear what deflections level this damping level of 14% was derived because the measured pile deflections of the tested pile systems at ULS ranged from 30 mm to 80mm.

The commonly used conversion equation from damping level to the reduction of elastic seismic action is $\sqrt{\frac{7}{2+\xi}}$. A damping level of 14% means that the seismic design actions for the anchor piles are about 66% of the elastic seismic action and it is approximately equivalent to a displacement ductility of 2 if T_1=0.4s. This could be the evidence in the engineering basis of NZS3604:2011, which states that the ductility of 2 is used in providing the subfloor bracing provision.

However there are issues to be addressed before people can have confidence to use this two-staged analysis method for LTF houses on subfloor framing systems. At first, the single degree elemental approach with the lumped mass at ground level will not be able to capture the overturning effects of the subfloor framing systems and won't be able to properly demonstrate the principles of capacity design philosophy.

In addition, seismic damage observed in LTF houses on pile foundations in recent earthquakes was often limited to pile systems (SR58), indicating a failure mechanism similar to a soft storey mechanism. As such, the fundamental period of an LTF house on pile foundations could be longer than that of the identical LTF house on a concrete slab foundation. The consequence is that the seismic demand on the superstructure of an LTF house on pile foundations could be less than that of the identical LTF house but on a concrete slab foundation. This is contrary to the seismic requirements in the current NZS3604:2011, which shows that the seismic demand is higher for pile foundations in comparison with the concrete slab foundations.

7 CONCLUSIONS

Residential houses in New Zealand are designed according to a prescriptive design standard "NZS 3604:2011" and are constructed using a platform construction technique. Earthquake damage observed in recent earthquakes showed that LTF houses can easily meet the current code requirement "life safety", but the damage was very inconsistent and some houses had damage well beyond economical repair. This suggests that the current housing standard NZS3604 be examined, subsequently enabling the advancement of performance-based seismic design of LTF houses.

The underlying seismic design basis used by NZS 3604:2011 is examined in this study and the examination revealed many critical seismic issues, which are crucial for the seismic resilience of LTF houses. These issues are summarised as follows:

1. The elemental force-based approach used in the engineering basis of NZS3604:2011 is crude and inadequate to capture the seismic performance of LTF houses at the systems level, potentially leading to remarkable discrepancies of seismic damage performance of LTF houses.
2. The P21 test procedure, a companion document of the engineering basis of NZS3604, should also validate the energy dissipating capacities of tested proprietary LTF wall systems.
3. Damage control, rather than, life safety, should be the meaningful seismic performance requirement of LTF houses. Thorough review of the seismic design basis of NZS3604 is needed to enable the advancement of LTF house construction to be truly a performance-based design standard.
4. Damage control designs of LTF houses would require the engineering basis of NZS3604:2011 to shift the seismic design focus from force strength only to include force, damage and deflection.

5. The engineering basis of NZS3604 should be reviewed, in terms of the consideration for capacity design philosophy, which has been the fundamental seismic engineering since 1970s.
6. The floor framing requirement in current NZS3604 should be reviewed to ensure that the LTF bracing walls on suspended timber floors will not cause the premature floor failure.
7. Current irregularity limits in NZS3604 should be reviewed to mitigate earthquake damage to houses.
8. More research is needed to adequately quantify the effect of subfloor framing system on the seismic provisions of LTF houses

8 ACKNOWLEDGEMENTS

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