PRELIMINARY RESULTS OF NUMERICAL MODELLING OF TIMBER-FRAMED HOUSES LOCATED ON SLOPES

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ABSTRACT

A questionnaire distributed to homeowners of wooden-framed houses in the Wellington region has found that minor damage to houses is to be expected after undertaking structural strengthening. In order to analyse whether the actual condition of wooden-framed houses on slopes align with anticipated damage for future earthquakes by homeowners, a follow-up structural survey was carried out to develop numerical models based on such data collection. Preliminary results indicate that 1% of inter-storey drift - defined as immediate occupancy and expectation of damage by owners - is likely to be exceeded during an Ultimate Limit State earthquake and homeowners' expectations of damage might not be met.

1 INTRODUCTION

Typically, community seismic resilience has been assessed by engineers considering socioeconomic and demographic factors (Abeling et al., 2019; Sutley et al., 2017). However, those studies generally do not refer to any systematic analysis examining the alignment of social expectations of the extent of damage and the severity of damage after an earthquake (Tanner et al., 2020). This study seeks to combine the physical science of structural engineering with social science by looking to align and understand the performance levels for wooden-framed houses located on slopes in major seismic events with expected damage from the perception of homeowners.

To quantify both the societal and engineering expectations of building damage, physical infrastructure, and the users must be defined (Sutley et al., 2017). Wooden-framed houses located on slopes in the Wellington Region of Aotearoa New Zealand and their homeowners, were selected. Timber housing in Wellington was selected due to the combination of three key factors that have the potential to increase its seismic vulnerability. First, the region is likely to experience a major earthquake in the near future based on rupture return periods of major faults in the area (Orchiston et al., 2018; Tarbali & Bradley, 2014). Second, a large proportion of residential houses are located on slopes, which increases the risk of suffering damage compared with similar houses located on flat ground (Thomas & Finc, 2017). Third, Wellington has an aging building stock and a large quantity of timber houses were built before the introduction of timber standards or seismic loading standards, which makes them likely to be missing key seismic load paths (Miskell, 2008; Thomas & Finc, 2017).

Most of Wellington houses are not structurally retrofitted (EQC, 2019; Johnston et al., 2013; Miranda et al., 2021). Research has shown this is likely because people voluntarily tend to undertake more survival actions (e.g., storing food and water) than mitigation actions mainly because the cost associated with mitigation actions tends to be higher (McClure et al., 2015; Shapiraa et al., 2018). In addition, there has been a lot of research conducted and policy introduced on building strengthening but both have focused on mostly the commercial space (e.g., Building - Earthquake-prone Buildings - Amendment Act 2016) (Egbelakin, 2013).

Through a questionnaire, the first part of this study examined motivating factors triggering preparedness and homeowners' expectations of damage to their wooden-framed houses (Miranda et al., 2022; Miranda et al., 2021). In order to answer whether the house will satisfy homeowner expectations of seismic performance the second phase of this project involves assessing, modelling and numerically predicting the likely performance of wooden-framed houses located on slopes

2 DATA COLLECTION

The first questionnaire distributed in the Wellington Region (567 successfully completed questionnaires which is 19% response rate over the total distribution) provided data on how prior earthquake experience influences the retrofit decision-making process and what the expectations of damage are after undertaking structural strengthening (Miranda et al., 2022; Miranda et al., 2021). The questionnaire also asked participants whether they would like to take part in a follow-up structural survey. The survey results contributed data to developing a building typology which was used to inform numerical modelling of timber houses on slopes (Miranda et al., 2023a). Of the 567 completed questionnaires, 376 participants (66%) showed interest in participating in the structural survey, from which 80 samples were chosen randomly.

3 KEY QUESTIONNAIRE FINDINGS

The questionnaire results were analysed and presented by Miranda et al. (2021) and Miranda et al. (2022) but some key results are shown herein. Analysis of the questionnaire responses found that 66% of participants were aware of the possibility of structurally strengthening their house, and among those aware participants, 41% stated that strengthening had been undertaken (i.e., prepared participants). Questions about expectations of damage before and after strengthening indicated that participants who stated that they had undertaken structural strengthening expected significantly worse seismic performance from their house without the strengthening, moving from moderate damage to minor damage (see Table 3-1) following strengthening. Similar responses were given by unprepared participants, who expected a worse structural seismic performance of their houses without strengthening than after imaginarily undertaking strengthening.

Level of Damage	Description
Undamaged	No damage at all
Minimal	Internal hair-line cracks in walls, which can be solved by painting over
Minor	Cladding or stucco detached, or some windows broken
Moderate	Some walls replaced or repaired. The chimney collapsed. Cracks in floor or damage to foundations
Major	The houses would not collapse but it would be inhabitable
Extreme	Total Collapse

Table 3-1 Scale of Damage (Miranda et al., 2022)

Outcome expectancy of undertaking structural strengthening represents the extent to which participants think that strengthening will reduce damage to their house in the event of an earthquake. A higher score represents stronger perceptions of outcome expectancy. The outcome expectancy was found to significantly differ between prepared participants and aware but unprepared participants. This suggests that prepared participants think that structural strengthening is more effective in improving the seismic performance of their houses than aware but unprepared participants (Miranda et al., 2022).

An interesting finding from the survey was that builders were found to play an important role on strengthening timber houses. Homeowners who have seismically upgraded their houses indicated that they had acquired the information mainly from builders. Differently, unprepared participants stated they would look for information through the Wellington City Council or the Earthquake Commission (EQC) rather than builders (Miranda et al., 2022).

4 STRUCTURAL SURVEY FINDINGS

The follow-up structural survey considered 80 samples of wooden framed houses where 69 were located on slopes. The collected data, illustrated in Figure 4-1, Figure 4-2, Figure 4-3, and Figure 4-4 shows that the majority of the timber houses were one and two storey houses, more than 50% were 100 years old, and the vast majority had bearers directly supported by a row of timber piles or by jack studs and the perimeter walls at the foundation level were built using mainly weatherboards fixed to stud framing (see Figure 4-5). More than half of the houses did not have any sub-floor bracing (see example in Figure 4-6). This lack of sub-floor bracing was also observed on foundation perimeter walls (see example in Figure 4-7).

Some of the participants of the structural survey indicated that their house had been seismically strengthened. Structural strengthening identified by participants included replacement of rotten piles, addition of new connections between piles, footings and bearers, and addition of bracing (diagonal) elements (examples of which are shown in Table 4-1).

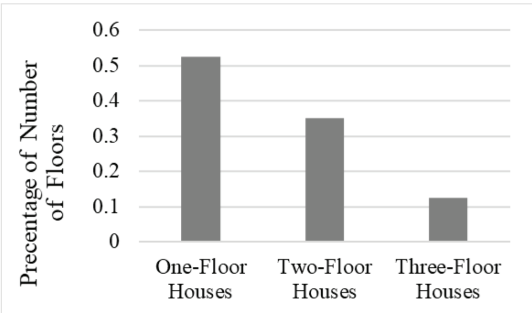


Figure 4-1 Percentage of Storeys

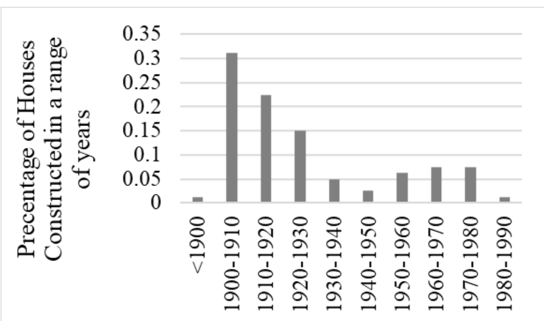


Figure 4-2 Percentage of Year of Construction

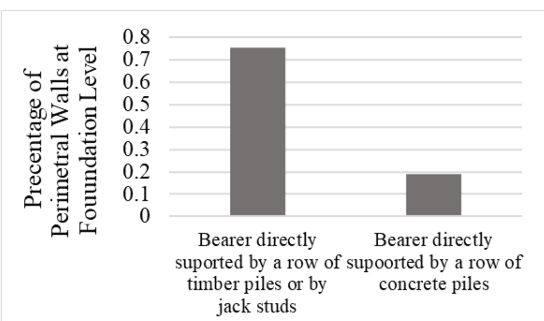


Figure 4-3 Percentage of Foundation Materials

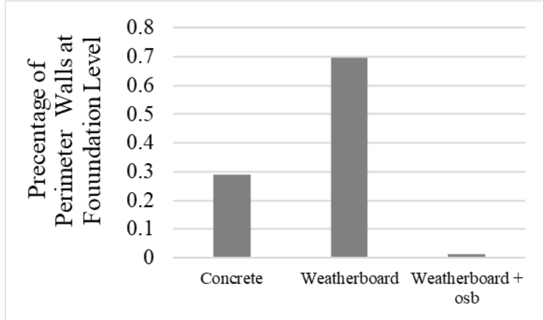


Figure 4-4 Percentage of Materials of Perimeter Walls at Foundation Level.

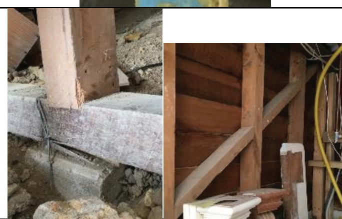
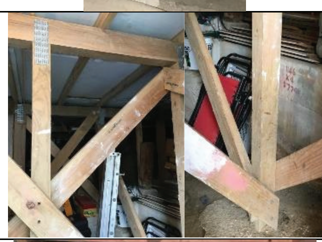
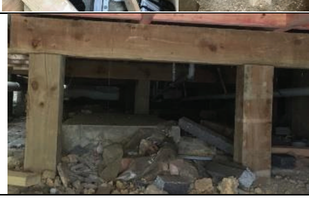
Figure 4-5 Examples of Weatherboard on Perimeter Walls at Foundation Level.

Figure 4-6 Examples of Unbraced Foundations

(a) *(b)*

Figure 4-7 Example of Perimeter Walls at Foundation Level (a) with and (b) without Diagonal Bracing.

Table 4-1 Examples of Strengthening Solutions Identified by Homeowners

Type of structural strengthening stated by owners	Photos	Carried out by (e.g., engineer, builder, or homeowner)	Comments
Replaced rotten old piles and added wire tie to bearer		Builder	Extreme slope. Two-level house.
Replaced rotten old piles and added extra bracing		Builder	Extreme slope. Two-level house.
Added wire tie to bearer		Homeowner	Perimeter piles replaced and strengthened. No access to central piles.
Replaced rotten old piles and added wire tie to connect concrete footings and timber piles.		Engineer	Included total renovation of the house.
Added bracing.		Engineer	Homeowner wanted to strengthen the house beyond the code.
House was completely re-piled		Builder	Recommendation of re-piling by builder while undertaking different work within the house

5 INDEX REPRESENTATIVE HOUSE ON A SLOPE

Considering that the majority of surveyed houses were one-storey, key parameters were measured to define a representative index house located on a slope (see Figure 5-1), where *L* represents the length of the house across slope, *a* is the length of the house parallel to slope, and *b* is the height of the sub-floor on the down slope side. A wall parameter was defined to represent the eccentricity between the centre of mass and the centre of rigidity resulting from the often-asymmetric distribution of shear walls including internal and external walls (up slope side, down slope side and parallel to slope sides). A more detailed typology of houses can be found in Miranda, Toma, Stephens and Elwood (2023).

While for the *a*, *L* and *b* the mean and standard deviations was considered (nine values in total), the superstructure's wall distribution considered three combinations of walls parallel and perpendicular to slope. *L* has a mean of 9.6 m and standard deviation equal to 3.0 m while *a* has a mean equal to 14.8 m and standard deviation of 5.2 m. The height of the foundation on the down slope side *(b)* has a mean value of 1.6 m and standard deviation of 0.8 m. The plan distribution of walls on the upper storey is calculated by the percentage of wall length that is full height divided by the total length. The mean of walls on the four sides of the house were 55%, 47% and 76% which are up slope walls, down slope walls and parallel to slope walls (both sides), respectively. Considering the standard deviation of wall distribution, two extra wall distributions were also analysed considering 50%, 47% and 73%; and 100%, 47% and 73% which are up slope walls, down slope walls and parallel to slope walls, respectively.

In order to understand how the geometric parameters (*L, a, b* and shear wall distribution) affect the peak seismic performance of the house, simplified numerical parameters based on the statistics: means (M) and positive and negative standard deviations (+-SD) for each parameter; from the sample measured were used to develop 81 simplified index houses, a matrix of which is shown in Figure 5-2.

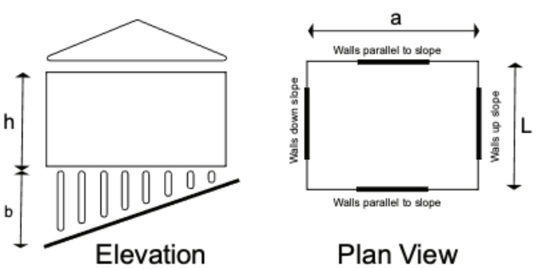


Figure 5-1 Index House - Sketch Elevation and Plan View

(a)

a_{-sd} x L_{-sd}	a_{-sd} x L_M	a_{-sd} x L_{+sd}
a_M x L_{-sd}	a_M x L_M	a_M x L_{+sd}
a_{+sd} x L_{-sd}	a_{+sd} x L_M	a_{+sd} x L_{+sd}

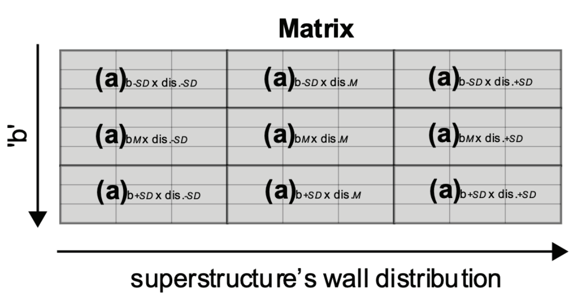


Figure 5-2 Matrix of Houses Models

6 NUMERICAL MODELLING

The structural survey provided data to confirm that there are potential weaknesses in the sub-floor bracing since the majority of house foundations have unbraced weatherboarded timber framed walls and floors supported by timber piles. In addition and due to slope, the height of the foundation varies resulting in a potential for torsion, which can be activated by the irregularity in the bracing at the superstructure. Hence, modelling primarily looks to capture the structural behaviour of the sub-floor framing.

Based on the data collection, the models represented in the building matrix (Figure 5-2) were analysed using the open-source software OpenSeesPy (McKenna & Fenves, 2001). In the development of the models, validation of a 2D model was carried out with a weatherboard wall previously tested by Thurston (2013), since most the surveyed houses had weatherboard walls as perimeter walls.

The numerical model used Elastic Beam Column Elements to model the framing and weatherboard elements. Nails to connect weatherboards and framing acting as hinges were modelled using ZeroLength Elements. Nail connections were modelled using the SAWS material which is a one-dimensional hysteretic model developed as part of the CUREE-Caltech Woodframe Project (2002). These ZeroLength Elements have been employed to characterize the non-linear behaviour of the weatherboard-to-framing connections. The 10 parameters to define the SAWS material were initially obtained from the literature and later calibrated based on the experimental results of the full 2D wall test.

Thomas and Shelton (2021) carried out a pushover test of full-scale typical New Zealand timber framed sub-floor structures on a sloping site which was used to calibrate a 3D numerical model. The 3D model used the same elements as the 2D models. Diaphragms were modelled as rigid to avoid force concentrations and out of plane deformations. This study focuses on how the structure at the sub-floor level influences the overall performance of the house – the non-linear and detailed modelling has been limited to the sub-floor structure. The upper story walls were modelled using linear Elastic Beam Column Elements based on Thurston (2013) tests.

6.1 Ground motion selection

Probabilistic seismic hazard analysis was performed for Wellington using New Zealand-specific rupture forecast models (Stirling et al., 2012). Based on the NZS 1170.5:2004 (SNZ, 2004), eight intensities were chosen, with 40 ground motion records each. The ground motions were scaled based on the spectral acceleration (Sa) of a single degree of freedom system with a damping ratio of 0.05 and a natural period of 0.7 s. In order to analyse the weakest directional response of the house ground motions were applied in the across slope direction.

7 PRELIMINARY RESULTS AND DISCUSSION

Minimum seismic performance requirements for New Zealand timber housing are set by life safety criteria within the Building Code, however, economic losses are still high as damage after earthquakes results in needed repairs (Buchanan et al., 2011). Research and testing have correlated damage of timber houses with inter-story drift by associating 1% of inter-storey drift as immediate occupancy and 3% of inter-story drift as severe damage (Lucksiri et al., 2012; Sutley et al., 2017). Timber houses, however, have high ductile response with reported collapse drifts higher than 6% (Paevere et al., 2003). Physical testing has shown New Zealand gypsum braced timber framed walls exhibit strength degradation beyond 1% of drift, suggesting that shear walls exceeding 1% drift might need to be replaced after a moderate earthquake in order to provide the minimum capacity for a future major earthquake. Considering that the shaking and displacements at the sub-floor will have a direct correlation with the drift response of the upper levels, similar limit states were considered to those analyses undertaken for foundation seismic response.

Although a detailed analysis can be found in Miranda et al. (2023a) and Miranda et al. (2023b), preliminary results of the research are shown in Figure 7-1, Figure 7-2 and Figure 7-3. Models were subjected to an ultimate limit state earthquake (i.e., 500-year return period) with resulted in 0.6g PGA in Wellington. In general, the majority of houses (>90%) are likely to exceed 1% drift at floor level (i.e., b height) and at the top of the upper-floor level (i.e., b + h height) during an Ultimate Limit State (ULS) earthquake. Figure 7-2 shows that the vast majority of the models exceeded 1% drift at the upper floor on the down-slope side compared with a more even distribution of 1% drift exceedance measured at the floor level, and at the up-slope upper level shown in Figure 7-1, and Figure 7-3, respectively. This confirms that houses located on slopes are more likely to show torsional responses, even at lower displacements.

Considering that the vast majority of homeowners expected a moderate level of damage to their house before undertaking structural strengthening (described as "some walls replaced or fixed up…"), we could say that their expectations are not likely to be met. When structural strengthening was undertaken the expectations of damage reduced to an average of Minimal, however, if strengthening as the ones shown in Table 7-1 are undertaken – which are more a gravity support upgrade rather than a horizonal load upgrade expectations of damage will most likely not be met.

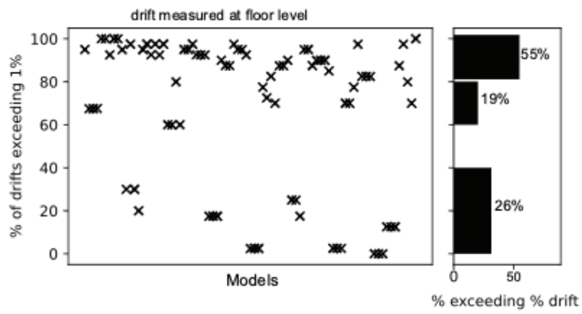


Figure 7-1 Drift exceeding 1% ULS at floor level down-slope side.

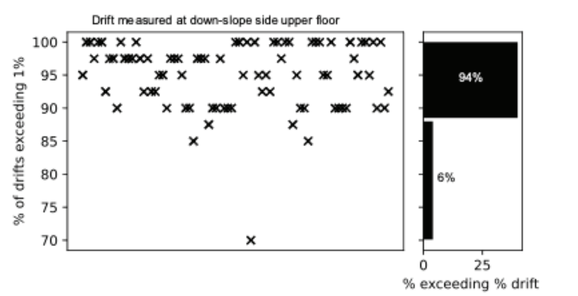


Figure 7-2 Drift exceeding 1% ULS at the top of the upper story down-slope side.

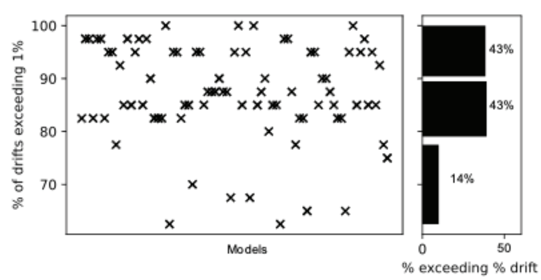


Figure 7-3 Drift exceeding 1% ULS at the top of the upper storey up-slope side.

8 CONCLUSIONS AND FUTURE WORK

This paper examinates preliminary results on the vulnerability of wooden-framed houses in Wellington which will be further analysed to better understand peoples' expectations of structural damage to their houses. Preliminary findings show that 1% drift would be exceeded by the vast majority of the houses during shaking at an intensity of ULS hence repairs are likely to be needed after a major earthquake in Wellington. Future work will be presented in two companion papers. The first paper will describe and analyse the seismic vulnerability of wooden-framed houses located on slopes in the Wellington Region. This paper will also include a parametric analysis on factors influencing the final seismic performance of houses, such as plan shape relative to the slope, slope variations and wall distribution on the superstructure.

Since preliminary results indicates that houses on slopes are likely to suffer torsion and large displacements, the second paper will analyse the benefits of sub-floor strengthening. Sub-floor strengthening was chosen since observations in the survey confirmed a lack of stiffness in the sub-floor structure and it is generally easy to access for houses on slopes causing less impact during potential strengthening works. Results will be presented using fragility functions and will be compared against homeowners' expectations of structural damage to their house before and after undertaking strengthening.

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