Establishing the resilience of timber framed school buildings in New Zealand

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ABSTRACT: Following the Canterbury earthquakes, the Ministry of Education has applied significant effort and resources to better understand the seismic performance of its existing buildings. Approximately 90% of its building stock is timber framed low-rise construction, with the majority of these being constructed prior to modern structural design codes. Many of these buildings feature elements such as fully glazed facades that have little quantifiable strength, often leading to low assessment ratings. However from a structural perspective, it has been a common view amongst engineers that these buildings pose little life safety concern.

This paper provides a summary of a programme of work undertaken by the Ministry of Education to consolidate and build upon the lessons from the Canterbury earthquakes in relation to timber framed structures. This work included the detailed seismic analysis of a range of the Ministry's standard classroom blocks, and culminated in the full scale physical testing of standard classroom blocks in Carterton, Wairarapa and Christchurch in 2013.

These tests have confirmed the general engineering expectation that timber framed buildings with older glazed facades have strength and resilience significantly in excess of their calculated capacity. Results from the tests indicate that failure of the glazing in the longitudinal direction occurred at more than five times the nominal calculated overall ultimate capacity of the building. These studies are considered to confirm that single storey timber framed structures with light roofs on flat ground are not earthquake-prone as defined by the current legislation. The results of this work have significant implications for similar type structures across New Zealand and are being fed directly into the update of the NZSEE's 2006 seismic assessment guidelines.

1 INTRODUCTION

It is challenging for structural engineers to evaluate the seismic performance of timber framed buildings with features such as fully glazed facades that have little quantifiable strength. It has been a common view amongst engineers that these buildings pose little life safety concern. However, the difficulty the Ministry and other similar property portfolio owners have been faced with is that most of these structures were being assessed by engineers as below 33% New Building Standard, and in some cases significantly below this level. This was resulting in some very difficult decisions on whether

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they should be continued to be occupied. It was also impacting on current and future funding, with a large portion of future funding being allocated to structural strengthening rather than maintenance and modernisation of the portfolio.

To address these challenges, the Ministry established an Engineering Strategy Group (ESG) in November 2012. The ESG has systematically worked through a series of inter-related activities aimed at providing the Ministry and engineers with a more realistic and consistent approach to assessing the seismic performance of timber framed buildings. These activities have included reviewing the application of Building Importance Levels to school buildings and the development of guidelines for the seismic evaluation of timber framed school buildings. Detailed reviews of a range of standard timber framed classroom blocks have been undertaken, culminating in the destructive testing of two typical timber framed classroom blocks.

This paper summarises the activities by the Engineering Strategy Group and engineers working for the Ministry, and the key outcomes. It draws upon the extensive information obtained by the Ministry's engineering consultancy panel for the Detailed Engineering Evaluation programme in greater Christchurch.

2 PERFORMANCE OF SCHOOL BUILDINGS IN THE CANTERBURY EARTHQUAKES

Timber framed buildings are known to have a relatively low risk of damage in earthquakes. This was demonstrated in the September 2010 Darfield and February 2011 Lyttelton earthquakes. In these events, damage to timber framed buildings was largely limited to sites that sustained ground deformations from liquefaction or landslide, or to vulnerable elements such as chimneys and tiled roofs (e.g. Buchanan et al., 2011).

Despite high levels of ground acceleration across a range of school sites throughout Canterbury, no school structures collapsed, and no serious injuries or fatalities were recorded. Timber framed school buildings performed well in the Canterbury earthquakes from a life safety perspective, confirming previous expectations. Significant damage was however caused by lateral spreading and liquefaction.

Results from the Christchurch Detailed Engineering Evaluations (DEEs) have shown both one and two storey timber framed buildings have generally performed very well. Key observations include:

- Minimal racking or permanent deformation and very few cases of broken glazing
- Most permanent deformation attributable to settlement, and usually not significant with respect to life safety.

Given the severity of the earthquake loading experienced at many Christchurch schools, DEE results to date have shown timber framed buildings have performed far better than traditional methods of structural analysis would suggest. Timber framed structures generally have many additional load paths (not easily quantifiable) that are able to carry significant loads in a seismic event providing both diaphragm and bracing action.

Previous work by the Ministry resulting from the 1998 National Structural and Glazing Survey replaced most heavy roofs, removing a significant mass driver for seismic action. This has also undoubtedly improved the performance of the lightweight building stock.

3 BUILDING IMPORTANCE LEVELS

In December 2012, the Ministry's Engineering Strategy Group produced the document *Recommendations for Design Levels for the Structural Evaluation and Design of School Buildings.* This report set out the background to design levels used for the assessment and design of school buildings, including Importance Levels (ILs).

Recommendations were made by the ESG to update aspects of the Ministry's policy provisions to bring them into closer alignment with current Building Code provisions. The Ministry adopted ESG's recommendations in late December 2012, and revised previous policies for assessing and strengthening existing buildings.

In summary, the key elements of the Ministry's current policies in relation to Importance Levels are:

i. The lateral load levels to be used for the *assessment* and *strengthening* of school buildings of light floor and roof construction are to be the same as defined in the AS/NZS 1170 Part 0 (SNZ, 2002) and the Building Code (clause A3).

   This alignment of requirements is intended to reflect a consistent approach to risk (as indicated by Importance Levels) as intended by New Zealand building regulations.

ii. For the *assessment* and *strengthening* of school buildings of two or more storeys with heavy suspended floor and roof construction, a higher Importance Level of IL3 should be used. For buildings of lower occupancy this exceeds the IL2 requirements of the Building Code.

   This requirement is intended to ensure that such structures receive more specific risk consideration in view of the consequence of failure.

iii. For *new design*, a higher Importance Level of IL3 should be used for all new school buildings. For buildings of lower occupancy this exceeds the IL2 requirements of the Building Code.

   This requirement is intended to provide additional resilience to new school building stock at typically nominal additional cost.

The Ministry of Business, Innovation and Employment (MBIE) and the Ministry of Civil Defence & Emergency Management (MCDEM) were consulted and support the Ministry's view on applicable design levels.

4 TIMBER FRAMED BUILDING EVALUATION GUIDELINES

The New Zealand Society for Earthquake Engineering *Guidelines for the Assessment and Improvement of the Structural Performance of Buildings in Earthquakes* (NZSEE, 2006) currently provides only limited guidance for evaluating timber framed buildings as they are generally regarded as being low risk. Timber walls and diaphragms are covered as elements, but mainly in relation to supporting Unreinforced Masonry (URM) buildings. Moreover, the Initial Evaluation Procedure (IEP) method from Section 3 of the 2006 NZSEE Guidelines typically provides unduly conservative results if applied to timber framed buildings without consideration of their generally good seismic performance.

In response to the situation that many timber framed classroom blocks in Canterbury and other regions were assessed as earthquake-prone buildings, the Ministry's ESG prepared a document *Guidelines for the Seismic Evaluation of Timber Framed School Buildings* (June 2013). This document includes qualitative and quantitative seismic evaluation methods, both based on the NZSEE's 2006 Guidelines. Clarification is provided on the specific values of key parameters to be used in both levels of evaluation, including higher representative ductility factors.

The Ministry's document is intended primarily for use as a guideline for professional structural engineers working on school building assessments. In particular, the document provides guidance for engineers carrying out Detailed Engineering Evaluations for school buildings in greater Christchurch, as required by the Canterbury Earthquake Recovery Authority.

The Ministry's guidelines are generally applicable to one or two storey classroom, administration and ancillary buildings of the types that would present some similarities with the current and/or previous standards for timber buildings not requiring specific engineering design. New Zealand Standard (NZS) 3604:2011 is the current version of this standard.

For reasons covered in the following sections, it is envisaged that engineers will only need to undertake specific seismic evaluations of timber framed school buildings for non-standard buildings or where there has been previous extensive re-modelling.

The November 2013 update by NZSEE of Section 3 of its 2006 Guidelines (now entitled *Initial Seismic Assessment*) has embodied the parameters proposed by the Ministry's ESG for qualitative assessments of timber framed buildings. It is intended that the Ministry's guidelines will be updated in

2014 to reflect the lessons and conclusions from the Ministry’s destructive testing programme and the updated NZSEE Guidelines.

5 REVIEW AND INVESTIGATIONS OF STANDARD TIMBER FRAMED CLASSROOM BLOCKS

A key element of this overall programme of work was a detailed study of a number of the Ministry’s standard classroom blocks. These blocks were subject to both qualitative and quantitative assessment using engineering parameters provided in the Ministry’s guidelines for the seismic evaluation of timber framed school buildings. They also utilised the NZSEE Guidelines in their analysis in terms of methodology.

The standard blocks included in this study were:

- Avalon block
- Dominion block
- Formula block
- Nelson blocks: one and two storey classroom blocks, and library blocks
- Canterbury block
- CEBUS block

Front (fully glazed) Back: High-level glazed (or “clerestory”) section

Figure 1. Avalon block (examples)

Front (fully glazed) Front Back

Figure 2. Dominion block (examples)

To gather further evidence of the performance of timber framed school buildings, the Ministry commissioned testing of standard classroom blocks of timber framed construction. This includes a destructive test of an Avalon block in June 2013 and an invasive examination of Nelson Two Storey blocks. A further destructive test of a Dominion block was undertaken in December 2013. This confirmed the principal findings of the Avalon block test, and the results are currently being further analysed and written up.

5.1 Avalon and Dominion blocks – destructive testing

The Ministry commissioned the BRANZ Ltd to undertake the destructive test of an Avalon block in June 2013, with the Engineering Strategy Group overseeing the test.

The test involved two classrooms that formed part of a four-classroom “Avalon” block at South End School, Carterton, Wairarapa. Commonly constructed in the late 1950s and early 1960s, this timber framed classroom block features a front wall that is essentially fully glazed, with no recognisable structural bracing panels. The classroom ceiling features a high-level vertical glazed (or ‘clerestory’) section, again with no identifiable form of bracing to connect the diagonally braced higher section to the tongue and grooved braced lower section of ceiling over a section of each classroom and the cloakroom area. Extensively glazed facades and clerestory windows are also present in a number of other standard classroom designs.

Two classrooms were tested from the block of four to ensure that the strength of the building could be reached with the available test equipment. Lateral loads were applied cyclically to both ends of the two classrooms at roof level (Figure 33) and also an isolated transverse wall using hydraulic actuators integral to house moving trucks connected to the 5th wheel of each truck. The loads were distributed to three attachment points on each end of the building using steel pre-stressing tendons. The 5th wheel attachments were connected directly to hydraulic actuators having 30 tonnes of pulling capacity and a stroke length of approximately 1.4 m. They could also be held at displacements corresponding to target load increments to allow for displacement recording using surveying station equipment.

Figure 3. View of the Avalon block during testing

Figure 4. Building at end of longitudinal test

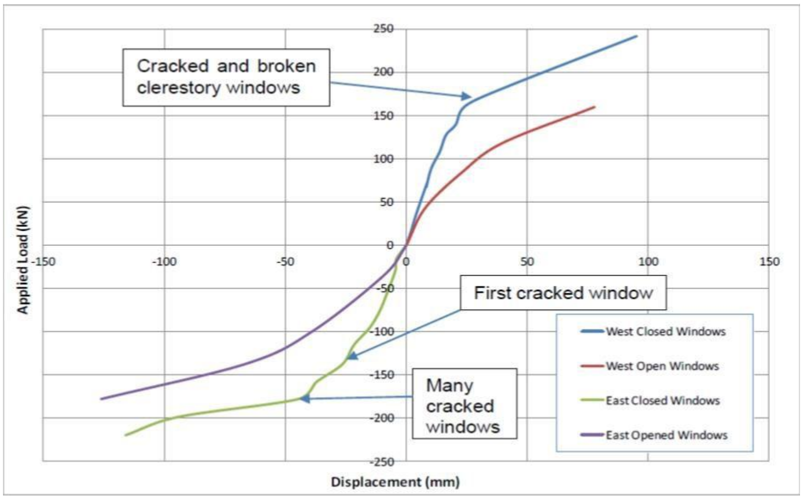

Figure 5. Load-displacement backbone plots for windows closed and windows open

Throughout the testing of the classrooms, loads were recorded using load cells on each of the steel tendons and the displacement was recorded near the roof apex using a rotary potentiometer. In addition, displacements of selected locations on the end walls were recorded at peak loads and zero loads using surveying station equipment. Load levels were increased in approximately 20 kN increments at each end of the building and held at each increment so that displacement measurements could be obtained. The majority of testing was undertaken with the windows closed but at different times during testing load was applied with all of the windows open for comparisons of stiffness. Figure 5 shows the two load-displacement backbone plots for pulls to the east and the west with windows opened and closed. Loads were increased up to the point of significant building damage, but at no time was there imminent collapse of the building.

A similar process was employed by BRANZ to test two classrooms of a Dominion block at Hammersley Park school in Christchurch in the longitudinal direction and a single classroom in the transverse direction in December 2013 (Figures 6 and 7). For these test buildings, the load was applied at the wall top plate level on both sides of the building because the roof was well braced in the ceiling plane and not expected to have any greater weaknesses than the side walls.

Figure 6. The Dominion block in early stages of the longitudinal test

Figure 7. Building showing high levels of drift during the transverse test

The destructive tests confirmed the general engineering expectation that timber framed buildings with older glazed facades have strength and resilience significantly in excess of their calculated capacity. Test results for the Avalon block indicated that failure of the glazing in the longitudinal direction occurred at more than five times the nominal calculated probable capacity of the building. A margin of three to four times was achieved in the associated single direction test of a transverse wall. The Ministry’s report on the test provides further information, with the BRANZ report providing full details of the test (BRANZ, 2013). For the longitudinal direction, the Dominion block tests indicated a margin of more than eight times the calculated probable capacity and in the transverse direction two to three times (BRANZ, 2014).

In November 2013, Housing New Zealand commissioned BRANZ Ltd to undertake a similar full scale test of a two-storey timber framed housing unit in Upper Hutt. The results have also indicated significant resilience in these buildings, at a level of over five times the calculated strength.

5.2 Nelson Two Storey block – invasive examination

In October 2013, an invasive examination of a two-storey Nelson block at Mairehau High School, Christchurch, was undertaken in conjunction with a demolition process. It provided a good opportunity to inspect key structural elements in order to gain a better understanding of how Nelson block structures were constructed and how that compared to the original design drawings. A further examination of a Nelson block was undertaken at Upper Hutt College in January 2014.

These inspections found that the structures were largely built as per the original drawings and specifications from the early 1960s, which included specific bracing provisions and engineered elements. The assessment of the connectivity at floor and roof levels between the sections of the buildings and the specific bracing connection details confirmed that the building has effective load paths that had received particular attention during its construction. This included specific connection capability between the wings of the “H” block and the central classroom portion.

Like other early low-rise timber framed structures, these blocks have a relatively low *%NBS* rating when evaluated using current engineering approaches. However as indicated by the generally good performance in the Canterbury earthquakes and knowledge gained from the other destructive tests outlined above, these structures are not at risk of collapse in strong ground shaking. Figure 8 shows the structural framing elements of the Upper Hutt College Nelson block following removal of the exterior cladding. This image also highlights the large footprint and hence low aspect ratio of these buildings.

Figure 8. Nelson block structural framing

6 SEISMIC CAPACITY RATINGS FOR STANDARD CLASSROOM BLOCKS

The analysis of the results of the destructive test of the Avalon block indicated that a factor of two can conservatively be applied to the calculated probable strengths of single storey timber framed buildings with light roofs in order to better reflect actual expected performance. The Engineering Strategy Group have subsequently revised the quantitative assessment of the Ministry of Education standard blocks using an S_p factor of 0.35, confirming that all of the blocks have a seismic capacity rating considerably greater than 34% NBS, even in locations of higher seismicity.

This work, along with the findings of the investigation of Nelson Two Storey blocks, has led to the establishment of reference calculated capacities for standard blocks (refer Table 1 following). Whilst acknowledging that there are many variations of such buildings, having these base values established means that only in unusual circumstances will there be a need for specific engineering evaluation of these buildings.

It is noted that in the NZSEE's recently released update to the Initial Evaluation Procedure (now entitled *Initial Seismic Assessment*), an S_p factor of 0.5 is recommended for use for *qualitative* assessments. The first column of Table 1 therefore shows the values corresponding to the use of an S_p of 0.5 (as currently recommended by NZSEE for *qualitative* assessment purposes), with the second column showing capacities currently recommended by the ESG for timber framed school buildings using an S_p of 0.35.

These seismic capacity ratings are based on a Wellington location (Z=0.4) with a category "C" for site flexibility. This is comparable to Christchurch seismicity (Z=0.3) with a soil type of "D". For Auckland scenarios (Z=0.13, soil class "D"), all of those standard types of timber framed buildings are rated as near, or in excess of, 100% NBS.

The preliminary results of the second test undertaken by the Ministry of Education in December 2013 and Housing New Zealand's destructive testing further support the values recommended by the ESG in Table 1.

In early 2014 the ESG will further discuss its recommendation of an S_p factor of 0.35 with the NZSEE's Project Technical Group, which is undertaking a review of the 2006 NZSEE *Guidelines for the Assessment and Improvement of the Structural Performance of Buildings in Earthquakes*.

Table 1. Seismic Capacity Ratings for Standard Classroom Blocks, Taking Into Account Destructive Testing Results

Building Type	Seismic Capacity Rating	
	Using NZSEE Factors (S_p = 0.5)	**ESG Recommended** (S_p = 0.35)
Avalon	46% NBS	66% NBS
Dominion	70% NBS	>100% NBS
Formula	>91% NBS	>100% NBS
Nelson Two Storey (“T” Block) • Unstrengthened • Strengthened	46% NBS >100% NBS	66% NBS >100% NBS
Nelson Two Storey (“H” Block)[1] • Unstrengthened • Strengthened	36% NBS 80% NBS	52% NBS >100% NBS
Nelson Library	67% NBS	96% NBS
Nelson Single Storey	70% NBS	>100% NBS
Canterbury	41% NBS	58% NBS
CEBUS[2]	49% NBS	49% NBS

Note 1: Nelson Two Storey (“H” Block) is designated as Importance Level 3 due to its level of occupancy (more than 250 people). The other standard blocks in Table 1 are designated as IL 2.

Note 2: CEBUS blocks are relocatable classrooms and are likely to be on piles only, with no concrete perimeter foundation to transfer shear loads to the ground. Due to their construction type, they are not influenced by the Carterton/Hammersley Park test results and therefore a lower S_P factor cannot be applied.

7 ENHANCING THE SEISMIC RESILIENCE OF TIMBER FRAMED SCHOOL BUILDINGS

The Ministry’s short-term goal is to ensure all buildings are not earthquake-prone, with any critical vulnerabilities addressed as soon as practical. The medium-term goal is to ensure that all school buildings are at or above 67% NBS.

Although timber framed buildings are considered low risk from a life safety perspective, and are not a priority to assess and strengthen, there are resilience enhancement opportunities to consider when modernisation projects are being undertaken. These include measures such as relining with seismically-rated plasterboard and installing the associated floor and ceiling connections. These enhancements, which often add little cost to projects, will increase the performance of buildings in earthquakes and result in less damage. The ESG has developed block-specific guidance for enhancing the resilience of the most common standard block designs, including rated seismic capacities once the work has been undertaken.

Where a timber framed building has a seismic capacity of less than 67% NBS, the standard seismic performance enhancement measures outlined above are typically all that is necessary to achieve the Ministry’s policy targets. Additional bracing elements are required for some generic blocks in higher seismic zones to achieve this level of seismic strength. These standard seismic performance enhancement measures should also be applied as part of modernisation even where a building already has a seismic capacity of greater than 67% NBS, in order to achievd greater resilience at modest cost.

8 CONCLUSIONS

During 2013, the Ministry of Education’s Engineering Strategy Group co-ordinated a programme of work aimed at improving the understanding of the seismic performance of timber framed classroom buildings. This work included firstly a detailed analysis of a set of half a dozen standard classroom blocks using available assessment methods and parameters, and secondly, destructive testing of two different standard classroom blocks along with the invasive investigation of a third block type during its demolition.

The detailed analysis, in conjunction with observations from the many assessments undertaken on behalf of the Ministry following the Canterbury earthquakes, established that standard blocks were not earthquake-prone. The destructive tests have taken this finding further, confirming the view held by many engineers that timber framed buildings with light roofs constructed prior to modern seismic codes have an inherent lateral resistance and ductility well beyond that which can be readily calculated.

Timber framed buildings with heavy roofs are also unlikely to be earthquake-prone, but the potential dynamic effects associated with elevated heavy masses need further consideration. Replacing heavy tile roofs with lighter materials is an important risk mitigation measure. Most early school buildings with heavy roofs were identified as part of the 1998 National Structural and Glazing Survey of schools, with either replacement or specific structural strengthening having been undertaken since.

As consequence of the analysis and testing work undertaken during 2013, timber framed buildings are not considered to pose life safety threats in terms of their overall structure. This has allowed the Ministry to assign a lower priority to undertaking seismic assessments for timber framed buildings. In most cases, these buildings will be assessed in conjunction with programmed asset management, and active seismic assessment will not be undertaken by the Ministry. When classroom blocks undergo programmed upgrades, the opportunity will however be taken to incorporate seismic resilience enhancement measures. This has had a very significant financial impact allowing the funding available to focus on the whole of the asset not just the structural aspects.

This work has provided broader insights into the performance of low-rise timber framed construction in New Zealand in general. The outcomes of the Ministry's work are being further consolidated with similar results from Housing New Zealand Corporation's testing of a two-storey house in November 2013 as part of the wider project to update the 2006 NZSEE Guidelines for assessing the seismic performance of existing buildings.

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