Establishing the Transverse Load Capacity of a Timber-framed Classroom Block

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ABSTRACT

In 2013, testing of single storey timber-framed classroom blocks was initiated by the Ministry of Education and completed by BRANZ to better understand the seismic resilience of timber-framed buildings within the Ministry's portfolio. The tests demonstrated a significantly greater lateral load capacity than could be derived from engineering calculations at the time, and led to new assessment parameters being included in the revision of the national seismic assessment guidelines in 2017.

An opportunity arose during 2021 for the Ministry to evaluate the transverse performance of classroom blocks by undertaking tests on another type of standard block from the 1970s. These blocks feature timber portal frames, and had performed well during the Canterbury Earthquake Sequence.

The tests undertaken by BRANZ involved laterally loading the central portal frame in each of two blocks constructed at Tauhara College in Taupo in 1975 and 2000. The in-situ testing was carried out to levels of force greater than the ultimate seismic and wind loads applicable for the building, but generated very low levels of horizontal displacement at eaves levels. A subsequent phase of the testing involved testing of the bare frames at the BRANZ laboratory in Judgeford following extraction from the buildings. These frames deflected significantly more than the in-situ frames.

As well as providing further evidence about the resilience of single storey timber-framed buildings, this testing highlights that fully clad light-framed buildings have a much greater transverse stiffness than provided by the individual portal frames.

1 INTRODUCTION

The Ministry has the second-largest social property portfolio in New Zealand, with a large representation of light timber-framed buildings. Following the Canterbury Earthquakes, the Ministry studied the performance of timber-framed classroom blocks and halls in the Greater Christchurch area, and confirmed that they performed well, particularly from a life safety perspective. This wasn't however being reflected in the early engineering assessments undertaken following the earthquakes during 2012 and 2013. This led the Ministry to initiate destructive testing of two different classroom blocks to enable a better understanding and quantification of the observed performance. These tests (Brunsdon et al., 2014; Carradine et al., 2015) demonstrated a significantly greater lateral load capacity than could be derived from engineering calculations at the time, and led to new capacity parameters being included in the revision of the national seismic assessment guidelines in 2017 (MBIE et al., 2017).

Due to general building condition and non-structural damage from a major weather event in 2020, several blocks at Tauhara College in Taupō were to be demolished. Canterbury Education Board Unit Systems (CEBUS) blocks had been used extensively at the college as classroom blocks, both as standalone buildings and interconnected via courtyard structures. CEBUS blocks are a widely used standard block from the early 1970s that feature timber portal frames, and had performed well during the Canterbury Earthquake Sequence. An opportunity therefore arose for the Ministry to further evaluate the transverse performance of these classroom blocks by undertaking destructive tests.

BRANZ was commissioned to test two blocks on-site and then to extract the two tested portal frames and further test them in the BRANZ Structures Lab.

As well as verifying the lateral load capacity of this type of building, these tests provided the opportunity to gather evidence to demonstrate the increased stiffness provided by the cladding of light-framed buildings with otherwise flexible diaphragms.

2 BACKGROUND

2.1 Performance of Timber-framed School Buildings in Recent Earthquakes

Timber framed school buildings throughout Greater Christchurch performed extremely well during the more severe February 2011 earthquake with no collapses or loss of life reported (Brunsdon et al., 2014). The lack of damage that would affect life safety was further supported by more detailed engineering evaluations, which also noted minimal damage in timber framed school buildings (Opus 2015).

Where significant damage to the buildings was observed it was primarily a result of differential ground movement and settlement. It is worth noting that the majority of school buildings had heavy roofs replaced with lighter roofing materials following a 1998 national survey of school buildings.

2.2 Previous Testing of Timber-framed Buildings

In 2013/2014, longitudinal testing of single storey timber-framed classroom blocks was initiated by the Ministry of Education and completed by BRANZ to better understand the seismic resilience of the predominant building type within the Ministry's portfolio.

Examples include two different types of school buildings that were tested on-site in 2013 as described in previous papers (Brunsdon et al., 2014; Carradine et al., 2016) in Carterton and Christchurch. Full-scale testing allowed for a more complete picture of how buildings perform during an earthquake and took into account the extra strength that buildings possess but that can often be difficult to quantify when assessing them for earthquake resistance.

2.3 Requirements for the Seismic Assessment of Timber-framed Buildings

The findings from the full-scale testing outlined above plus the observations of good performance of timber-framed buildings in the Canterbury Earthquakes were a significant input into the 2017 revision of the seismic assessment guidelines (MBIE et al., 2017). More favourable factors than in previous versions were included in Part B of the Guidelines for use in Initial Seismic Assessments of timber-framed buildings, including the use of a lower Structural Performance factor (S_p) of 0.5. Section C9 covering the Detailed Seismic Assessment of timber-framed buildings was a new section, which also included capacity parameters that drew upon the Ministry's tests.

There is still an underlying premise even for lighter weight structures that the capacity of a building comprising several lateral load resisting elements requires a structural diaphragm to connect the elements and distribute the lateral forces between them. While the earlier destructive tests confirmed that secondary systems undertook this function, including the roof sheeting, they primarily related to buildings with wall elements.

3. CEBUS BLOCKS

3.1 Overview

The Canterbury Education Board Unit Systems (CEBUS) buildings that were developed during the 1970s featured innovative modular design, and were used extensively as both permanent and relocatable classroom buildings in schools and polytechnics throughout New Zealand.

CEBUS blocks are based on a 3m module that is structurally self-sufficient in terms of bracing, and capable of being joined together and then subsequently split apart to enable a full range of future modifications. CEBUS blocks typically feature four or five modules, but have been constructed to incorporate more than a dozen bays. Each module is based on 300x50 (nominal) No. 1 Framing Pinus Radiata timber portal frames at 3m centres, and when joined via bolts to adjacent modules at 900mm centres together they present as a 300x100 gross section portal.

These portals typically span 7 to 8m depending on the model, and are externally expressed, as indicated in Figure 1. One of the key features of the portals is that they run under the floor to form a continuous frame of the same section size. The end frame is a single 300x50 timber portal from the base module, with the end walls not being designed as bracing walls.

The structure is tied together longitudinally with 10mm diameter tie rods at roof and foundation level, and every fourth bay typically has a full-height 7.5mm external plywood sheeting panel for longitudinal bracing.

The blocks are typically located on short timber piles without perimeter concrete foundations. Seismic assessments of these buildings are typically governed by the lateral capacity of the foundations where unbraced or lacking in anchor piles.

Roof bracing comprised let-in 50x75 timber diagonals or proprietary cross bracing with tensioners depending on the CEBUS version. The ceilings are typically pinex rather than plasterboard lined, and the ceiling framing is typically not connected into the portal frames. Accordingly, the roof diaphragms are regarded as being flexible (Opus 2013), noting that the modular design means that the diaphragms are only transferring loads transversely over a 3m distance.

The roofs are formed from steel sheeting on timber purlins spanning between the portal frames. While the original roof sheeting of CEBUS blocks is corrugated iron, some have been re-roofed in different steel profiles. The roof sheeting of all the blocks at Tauhara College is Brownbuilt with concealed fixings (Figure 2).

The portal frame elements are joined by externally exposed gang nail plates at apex, knee and floor levels (Figures 1 and 3). The external exposure of the gang nail plates represents a departure from more recent durability practice, and there were signs of delamination and corrosion to several plates in buildings at the school where the testing was undertaken.

Figure 1– CEBUS block exterior (note exposed portal columns)

Figure 2 – CEBUS block roof sheeting

Figure 3 – Exposed portal base gangnail connections

The first of the two school blocks at Tauhara College that were tested was a Mark IV CEBUS block that was designed and constructed in 1975 (Block A). Mark IV CEBUS Blocks are in common usage in schools around the country in addition to Canterbury. The building comprises four bays with three portal frames and two end frames, with an interior span of approximately 7.3m. A second block that was constructed around 2000 with similar characteristics to a CEBUS block was also tested (Block R). Block R featured solid timber sections and a steel tie-rod between the rafters above eaves level.

Figure 4 illustrates the Block A frame, with dimensional differences for Block R indicated. The plan section of the Block A columns is shown in Figure 5.

The individual portal frames of Block A were calculated to have a lateral load capacity corresponding to an eaves point load of 14kN. This lateral load capacity corresponds to a seismic rating for the superstructure of greater than 100%NBS (Opus 2013) based on a building in a high seismicity area, using an overall ductility of 1.25 limited due to the nail slip at the member joints. The corresponding knee deflection under this applied load is estimated at 17mm. The actions from wind loads were typically approximately half those from earthquake loading.

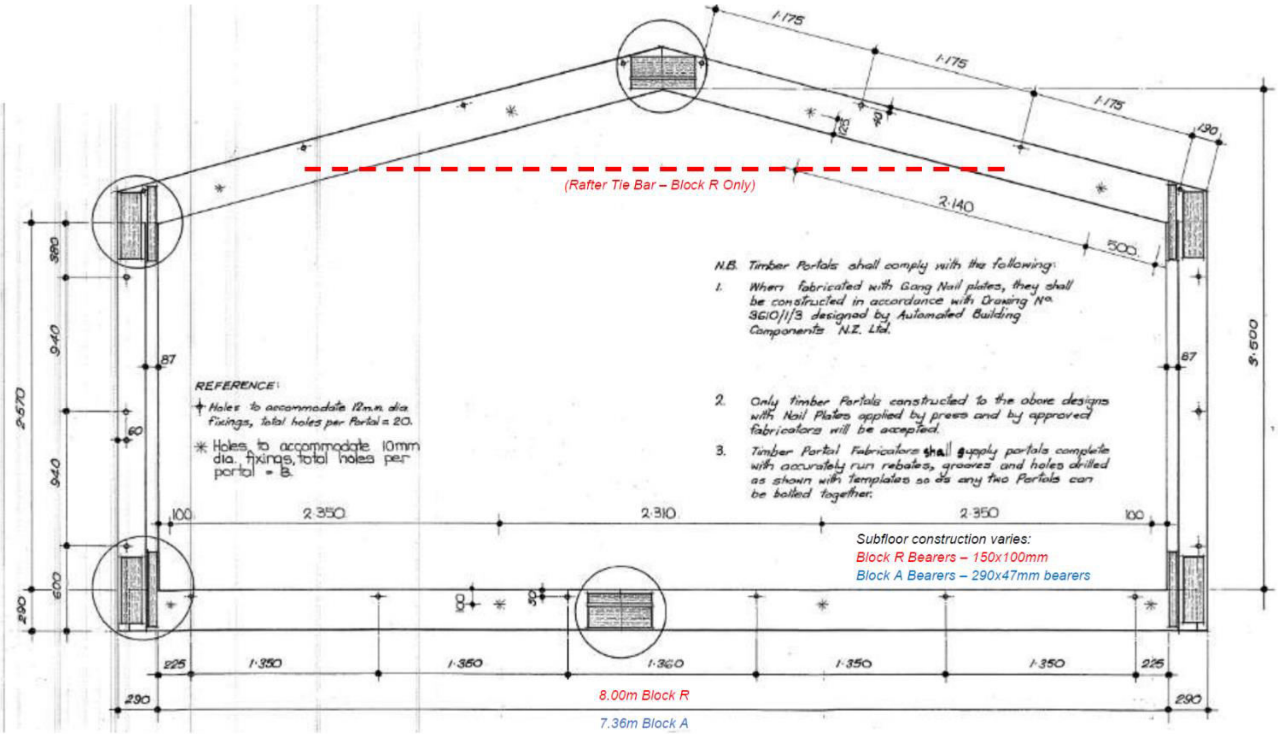

Figure 4 – CEBUS Block cross section (Block A shown, with dimensional differences for Block R indicated)

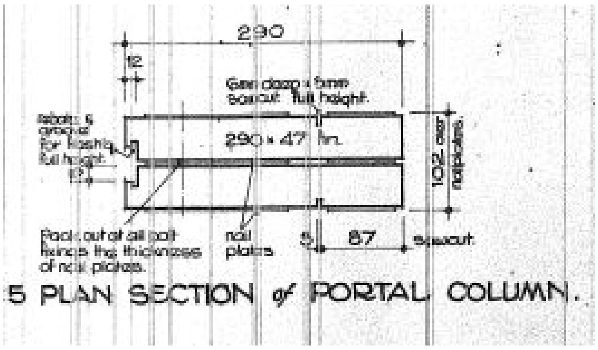

Figure 5 – Plan section of Block A portal column (the Block R column was a solid section of equivalent size)

3.2 Performance in the Canterbury Earthquakes

As part of the study of how school buildings performed in the Canterbury Earthquakes referred to in section 2.1, twelve CEBUS blocks across eleven schools with a range of ground conditions were evaluated (Opus 2015). Ten of these blocks were considered to have experienced *High* or *Severe* shaking intensities, but were all rated as having performed *Well* or *Very Well* (with only minor non-structural damage).

No damage to the gangnail plate connections were observed, suggesting that the key frame connections had not experienced high levels of force.

4. TEST PROGRAMME

The testing was undertaken in two phases. The first phase of in-situ testing was undertaken at Tauhara College during 2021, with the central frames of Block R and Block A being tested in May and July 2021, respectively, prior to their demolition. All of the structural and non-structural cladding elements were in place for this phase of the testing. The second phase involved the extraction of the same two frames that were subject to the in-situ testing, transporting them to the BRANZ laboratory in Judgeford and re-testing them as bare frames. This was considered appropriate given the relatively nominal deflection and damage recorded in the first phase tests in-situ.

4.1 Testing of Frames In-situ

On-site testing was undertaken using two hydraulic actuators fixed to the floor beams and connected to cables which applied loads near the tops of the columns to simulate earthquake loads from the roof in both directions. Connections to the beams and columns were made with screws through steel plates and threaded rods to avoid adding stiffness to the frames while ensuring minimal slippage of the loading connections (Figure 6). The frames were loaded in each direction to increasing load levels and extensive displacement measurements were recorded throughout testing to quantify the loaded performance of the buildings.

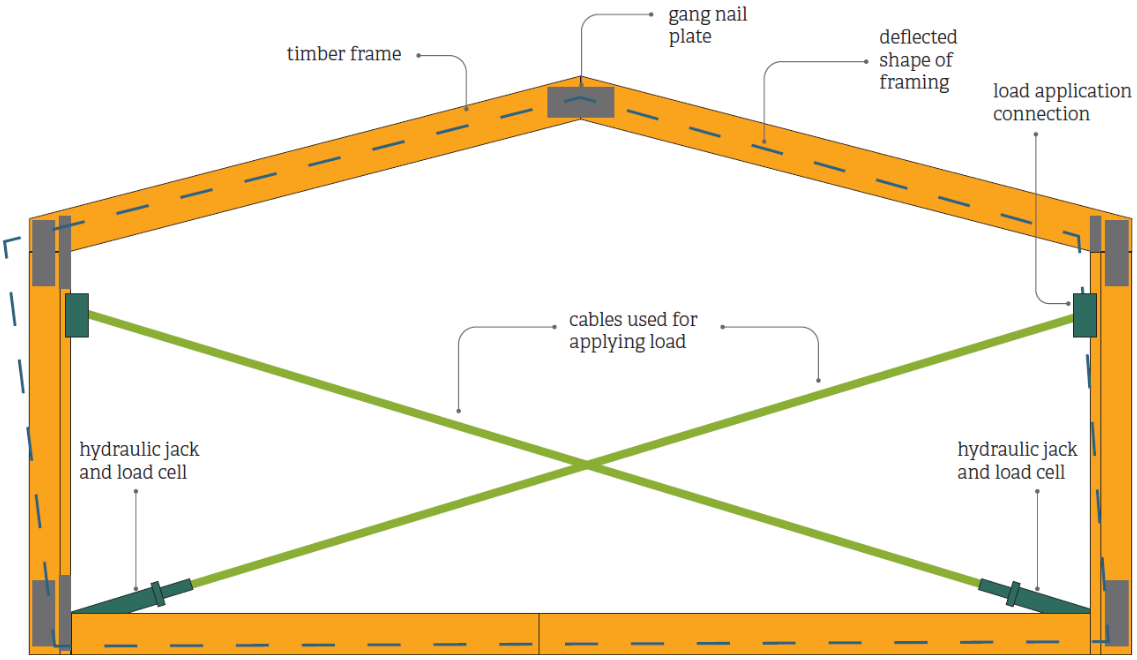

Figure 6 – Schematic loading of portal frame

In the in-situ test, the central frame of Block A was horizontally loaded up to 19kN (1.9 tonnes) in each direction, and while creaking of the building could be heard there was no recorded damage or permanent deformation. The average deflection at the tops of columns was 11.3mm when applied loads reached 19kN. The corresponding central frame of Block R was horizontally loaded in both directions up to 12.5kN (1.25 tonnes), and testing was stopped just beyond these load levels due to visible damage to the gang nail plates and observable permanent deformation between the timber members, although the overall average lateral displacement was only 14mm. While neither test was considered to have been taken to the ultimate capacity of the frames, both frames sustained loads greater than their calculated ultimate capacities.

4.2 Testing of Bare Frames

Following on-site testing, the tested frames were carefully removed from the buildings and transported to the BRANZ Structures Laboratory. It was necessary to cut the columns at mid-height to transport them. Prior to laboratory testing the columns were spliced back together using LVL and screws, which did not compromise the behaviour of the frames during testing. The same loading equipment and attachment locations from the on-site testing were used and both frames were mounted on timber blocks on the laboratory strong floor to simulate the in-situ foundations and also avoid uplift during testing. Rollers were placed on either side of the rafters to model the roof purlins and avoid transverse movements as loads were applied. Displacement measurements were recorded throughout testing and located to allow for comparisons with the on-site testing. The set up of the frame in the laboratory immediately prior to the test is shown in Figure 7.

The objective of the testing was to load the frame, in plane, in each direction up to 20kN, while observing the lateral displacement and signs of distress to the test frame. More information on the dimensions of the frames and the loading directions can be found in the BRANZ test report (BRANZ 2022).

Figure 7 – BRANZ Structures Lab set up to test CEBUS portal frames

The testing of the Block A frame included single cycles in both directions of 1kN load levels that were increased up to horizontal loads of approximately 15kN, at which point the frame was racking significantly and considered to have reached its ultimate capacity. Some buckling and detachment of the gang nail plates at the tops and bottoms of columns were observed at a loading of around 10kN. Eave displacements for the Block A frame were approximately 10 times those observed in in-situ tests at the same load levels.

Testing of the Block R frame started with 1kN cycles, but after reaching 2kN in both directions the increment was cut back to 0.5kN due to the greater flexibility of the frame. Horizontal loads of only 5kN were reached before testing was stopped due to large movements, and the frame was considered to have failed. Longitudinal timber splitting of the rafter just beyond the plate connection occurred first at the end of one rafter (Figure 8), followed by buckling and fracture of the gang nail plates at the top of the other column which ended the test. Eave displacements for the Block R frame were approximately 7.5 times those observed in in-situ tests, but at only one-third the load.

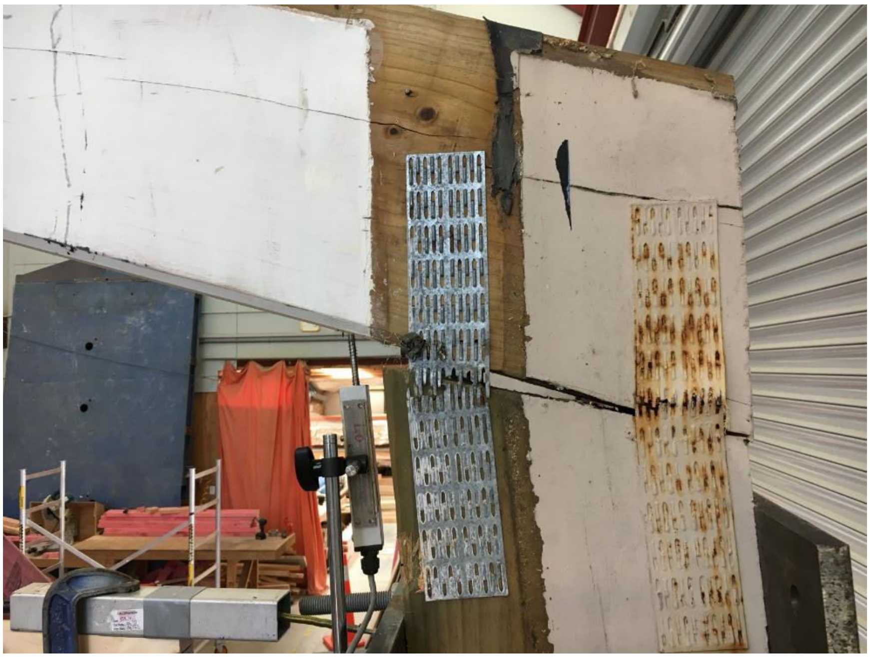

Figure 8 – Failure of the knee joint of the Block R frame (noting the inadequate anchorage length of the gangnail plates)

5. DISCUSSION

The eaves displacement ratio (between the bare frame and the clad frame) of 10 for the Block A frame clearly demonstrates the stiffness and strength that roof sheeting in combination with flexible diaphragm bracing elements provides, and highlights the significant difference in structural performance between bare frames and fully clad buildings. The much greater stiffness of the clad frame over the bare frame also suggests that the steel roof sheeting provided a significant contribution over and above that from the let-in diagonal timber roof braces.

The corresponding displacement ratio from the testing of the Block R frame of 7.5 represented comparable findings, but the context was slightly different. This frame had a pinned base joint and smaller underfloor tie member, which resulted in a much more flexible bare frame than the standard CEBUS designs. Joint strength was also lacking in comparison, as the single larger timber section had only half the number of gangnail plates as the 'sandwich' composite section of the standard CEBUS portal frames. However these issues associated with the bare frames became of little consequence once the frames and building were fully clad, as shown by the relatively good performance of this frame in the in-situ test.

In-situ testing on full buildings followed by laboratory testing of the Block A frame has provided valuable information on the performance of CEBUS school blocks. The tests have confirmed calculations and actual event experience that the buildings are inherently resilient and that the frames can resist design-level earthquake and wind loads.

6. SUMMARY AND RECOMMENDATIONS

This series of testing of the central portal frame in two modular timber-framed classroom buildings constructed at Tauhara College in Taupo in 1975 and 2000 has provided valuable information on the performance of these buildings, and confirmed the inherent resilience of the widely used CEBUS block designs. This testing has added further to the knowledge about the general resilience of single storey timber-framed buildings obtained from the previous destructive tests undertaken by the Ministry of Education and BRANZ.

The testing of the 1975 CEBUS block has shown that the timber portal frames can resist levels of force greater than those calculated for the ultimate seismic and wind loads applicable for the building in a high seismic area and wind exposure location. The second more significant finding is that the fully clad structure has a transverse stiffness of an order of magnitude greater than the individual portal frame elements.

The in-situ testing on elements of complete buildings prior to demolition represented a reasonable proxy of whole-of-building testing, which was reinforced by the subsequent laboratory testing of the same frames. Based on observations following the Canterbury earthquakes, and the inherent robustness inherent within typical timber framed buildings, it was expected that these school blocks would have sufficient strength and stiffness to be able to avoid significant damage during cyclic loading up to and beyond design levels.

Currently available tools and information for the assessment of buildings like these do not allow for the inclusion of resistance provided by other parts of the building and often result in conservatives estimates of lateral load performance. Therefore, it was further expected that in-situ testing would provide data on the performance of these school blocks that was less conservative and more reflective of in-service load carrying capacity. The contrasting results between the two phases of the tests clearly convey the inherent conservatism in the design and assessment of smaller lightweight timber structures when the significant strength and stiffness provided by the cladding elements and secondary timber framing are not able to be taken into account.

It is hoped that the findings of this research prompt a further review and refinement of how lighter weight structures are assessed for life safety purposes, and how the typical benefits of cladding and secondary framing can be taken into account when appropriate.

ACKNOWLEDGEMENTS

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