BRANZ

ISSUE 635 BULLETIN

BRACING DISTRIBUTION

February 2019

- The Christchurch earthquake events highlighted a number of potential issues with the way we brace light timber-framed (LTF) buildings.
- While simple regular LTF houses performed well, unevenly braced or irregular houses often had significant damage that was uneconomical to repair.
- This bulletin outlines BRANZ LTF structural research and provides guidance on bracing design to minimise the impact of uneven bracing distribution and building irregularity in an earthquake.

1 HOW WE BUILD NOW

1.0.1 The majority of residential buildings in New Zealand are traditionally low-rise light timber-framed (LTF) buildings, and their gravity load and lateral load-resisting systems are typically plasterboard-lined walls.

1.0.2 Construction of residential LTF buildings in New Zealand largely follows NZS 3604:2011 *Timber-framed buildings* (a prescriptive standard cited as a means of compliance for Building Code clause B1 *Structure*).

1.0.3 This bulletin outlines recent BRANZ structural research and provides guidance on bracing design to minimise the impact of uneven bracing distribution and building irregularity in an earthquake event.

2 STRUCTURAL IRREGULARITIES AND THEIR IMPACTS

2.0.1 In a bracing context, irregularities in building structures occur when one part of a structure is much less stiff or strong than another part. This can arise in steel and concrete-framed structures as well as LTF buildings and is usually a result of functional or aesthetic requirements or a restriction arising from the building site.

2.0.2 Irregularities in building structures can be broadly classified into two categories – vertical and horizontal (plan) irregularities.

2.0.3 Vertical irregularity arises from the change of the stiffness and/or strength of the lateral load-resisting systems or offsets of the bracing systems up the building height. Frequently, it is a result of differing building footprints at different levels to accommodate sloping sites.

2.0.4 Horizontal (plan) irregularity arises when the distance between the centre of rigidity and the centre of the applied storey shear force at any level of the building becomes significant. This is usually a result of asymmetrical floor plans or uneven bracing arrangements within a floor area.

2.0.5 LTF buildings under NZS 3604:2011 typically use the platform framing technique. There are no requirements for bracing elements at one level to be aligned with bracing elements at the level below or above. As such, LTF residential buildings are characterised by frequent offsets of wall bracing elements from level to level. This is one of the most significant vertical irregularity issues considered in classifying buildings as irregular buildings in the seismic loading standard NZS 1170.5:2004 *Structural design actions – Part 5: Earthquake actions – New Zealand* (Amendment 1).

2.0.6 When a building structure has **vertical irregularities**, deformation/damage of the building in earthquakes could concentrate in one level, leading to the increased possibility of a soft storey collapse.

2.0.7 When a building structure has **plan irregularities**, the building will have torsional responses as well as translational responses (Figures 1 and 2) in earthquakes. This sort of behaviour leads to significantly unpredictable seismic behaviour.

2.0.8 For a perfectly regular building, a simple two-dimensional seismic analysis could adequately predict its seismic performance. In contrast, an irregular building will have torsional responses in earthquakes, which will be coupled with translational responses. This type of structure requires three dimensional (3D) modelling to predict its behaviour.

2.0.9 In this latter case, seismic actions will be transmitted by the floor diaphragms into the lateral load-resisting systems in both directions across the entire building. The seismic performance of an irregular building thus depends not only on the racking behaviour of the bracing walls but also on the in-plane rigidities of floor/roof diaphragms.

2.0.10 The rule of thumb is that the greater the irregularity of a structure, the harder it is to predict its seismic performance. Research on the seismic behaviour of irregular building structures is ongoing, and there are no definitive recommendations for building designers.

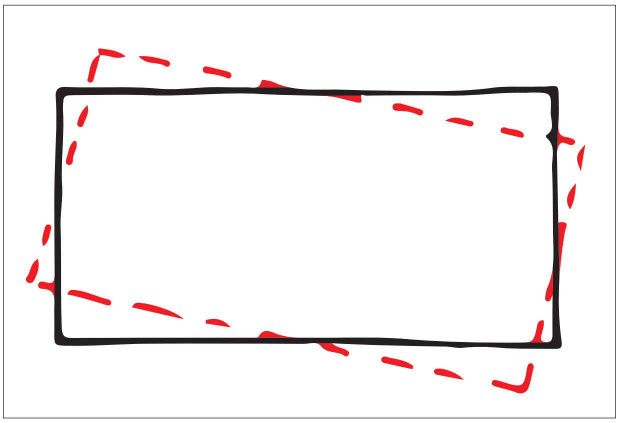

Figure 1. Torsional response.

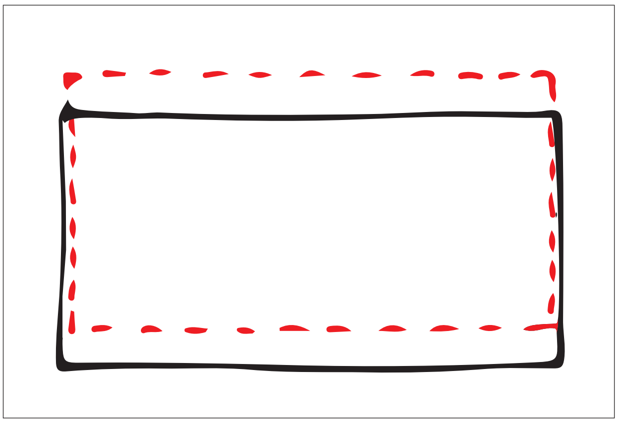

Figure 2. Translational response.

3 WHAT THE CHRISTCHURCH EARTHQUAKE EVENTS SHOWED US

3.0.1 LTF residential buildings in the Canterbury region all achieved life-safety "safeguarding people from injury caused by structural failure". This is a Building Code requirement, but there were a number of LTF buildings with unacceptable earthquake damage.

3.0.2 In essence, the earthquake events highlighted a number of issues with the way we design and construct LTF buildings. Houses with a simple plan shape such as a rectangle and modest window openings (Figure 3) performed well. However, those with a more extravagant plan shape (Figure 4) or large windows often had significant damage that was uneconomical to repair.

3.0.3 Uneven distribution of wall bracing elements within a floor plan was also found to have exacerbated the seismic damage significantly. This frequently occurred where the floor layout was arranged to take advantage of a view. Large windows in one wall and a concentration of closely spaced walls at the other end (Figure 5) were common in some parts of Christchurch.

3.0.4 When the bracing elements are arranged in an irregular manner, the building tends to have torsional responses in an earthquake (Figure 6). The consequence of the torsional responses is a significant amplification of the lateral deflections in some parts of the buildings. Because damage sustained by a building in an earthquake is a result of lateral deflections, such irregular bracing arrangements in a building are likely to cause more significant earthquake damage.

3.0.5 The adverse effect of irregular bracing distribution within a floor plan is more significant when the integrity of the roof/floor diaphragms between the heavily braced part and the lightly braced part of the building is not maintained. This occurs because of the lack of load sharing between bracing elements within a building. NZS 3604:2011 is not well suited to deal with such plan or bracing irregularities.

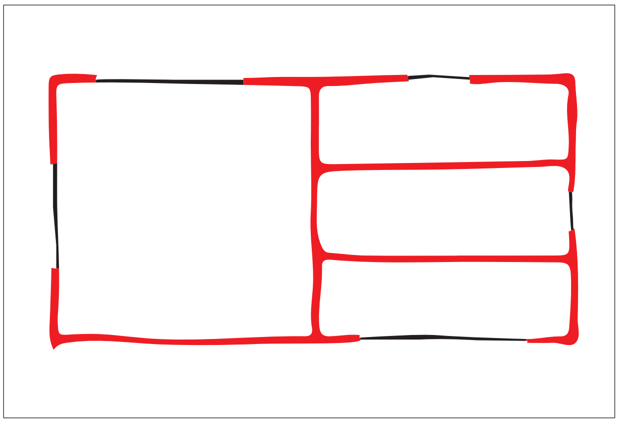

Figure 3. Simple rectangular building with simple regular bracing distribution.

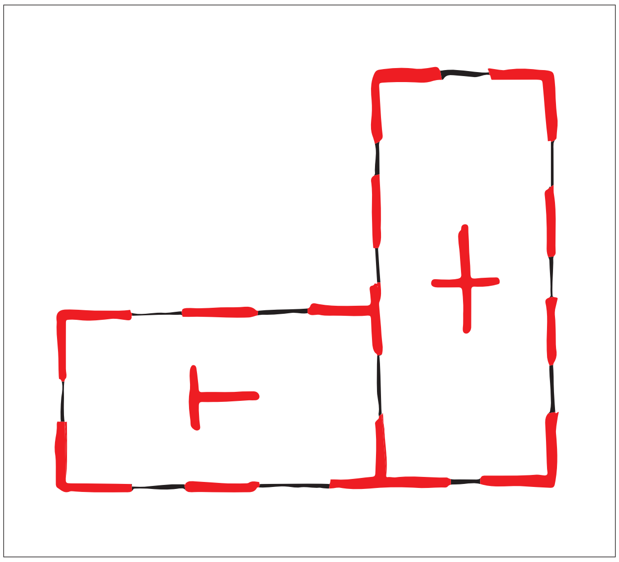

Figure 4. L-shaped building with irregular bracing distribution.

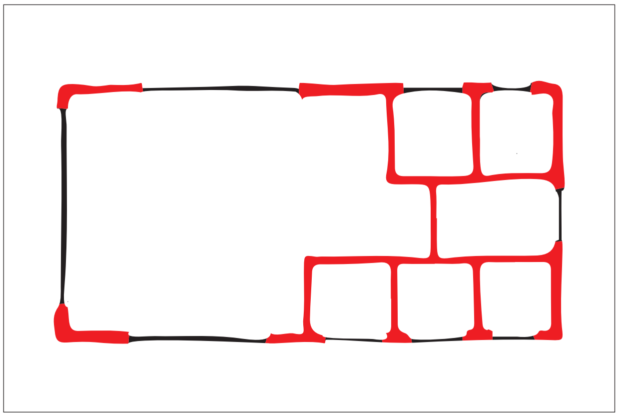

Figure 5. Simple building with irregular bracing distribution between left-hand (low-capacity) and right-hand (high-capacity) ends of the building.

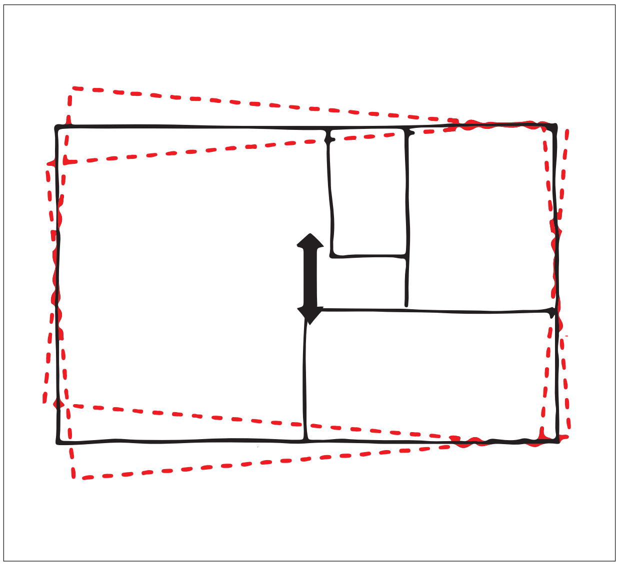

Figure 6. Torsional effect of loading with bracing at one extremity of a building.

4 WHAT NZS 3604:2011 REQUIRES

4.0.1 Although a prescriptive standard, the development of NZS 3604:2011 has an engineering basis that used a force-based approach in deriving the seismic design actions (demand). The resistance (or capacity) is based on standardised tests of wall bracing elements.

4.0.2 NZS 3604:2011 specifies not only seismic demand but also seismic bracing provisions. Designers need to ensure the total seismic bracing capacity provided is greater than the total seismic bracing demand at each floor level.

4.0.3 NZS 3604:2011 also specifies the distribution of bracing elements within a floor plan. Bracing lines are required to be spaced at no more than 6 metres in each direction. The bracing arrangements can be irregular but must be within certain limits. The bracing distribution rules specified by NZS 3604:2011 are:

- the minimum bracing provision in each bracing line should be greater than 100 bracing units (BUs) or 50% of the total bracing demand divided by the number of bracing lines in the direction being considered
- the minimum bracing provision in each bracing line should be not less than 15 BUs/m of external wall length for external walls.

4.0.4 The bracing distribution rules of NZS 3604:2011 are based on a compromise between engineering rules of thumb and architectural planning freedom. There has been no scientific research to quantify the adverse seismic effects of bracing irregularity for designs following NZS 3604:2011 nor any work to justify the appropriateness of the rules in the standard.

5 BRANZ RESEARCH PROJECT

5.0.1 Damage observed in the 2010/11 Canterbury earthquake sequence demonstrated that simple regular LTF buildings performed well while irregular buildings often had significant damage that was uneconomical to repair. As a result, BRANZ put in place a research project to:

- study quantitatively the seismic effects of permissible plan irregularities within the scope of NZS 3604:2011 on the seismic performance of LTF buildings
- provide a scientific basis for adjusting the current irregularity limits in NZS 3604:2011 if necessary.

5.0.2 The research included these phases:

- A literature review of research efforts on the seismic behaviour of irregular LTF buildings and in-plane structural performance of timber diaphragms. A research review of seismic effects of structural irregularities in concrete buildings.
- Analyses of past bracing test results of plasterboard walls and observation of the photographic records of the damage that occurred.
- The development of a racking model of plasterboard bracing wall elements, based on the racking test results.
- Experimental studies of plasterboard ceiling diaphragms as typical of New Zealand residential construction practice in different applications.
- The development of an in-plane stiffness model for roof/ceiling diaphragms typical of New Zealand residential construction, based on the test results.
- A study of the seismic effects of permissible plan irregularities from NZS 3604:2011 on six case study LTF buildings using three-dimensional non-linear push-over analyses (Figures 7, 8 and 9 show three examples). LTF braced walls and ceiling diaphragms were modelled using the models developed in this project.

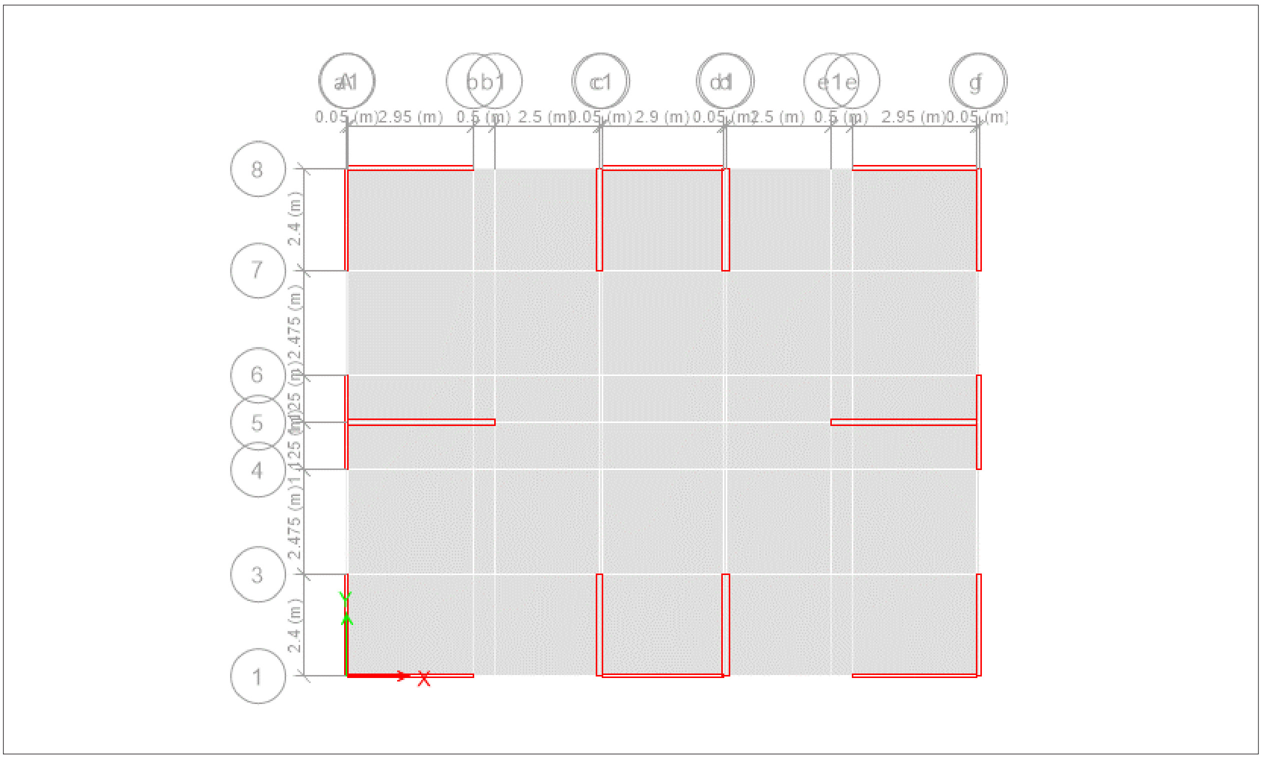

Figure 7. Floor plan of single-level rectangular benchmark case study building with regular bracing distribution.

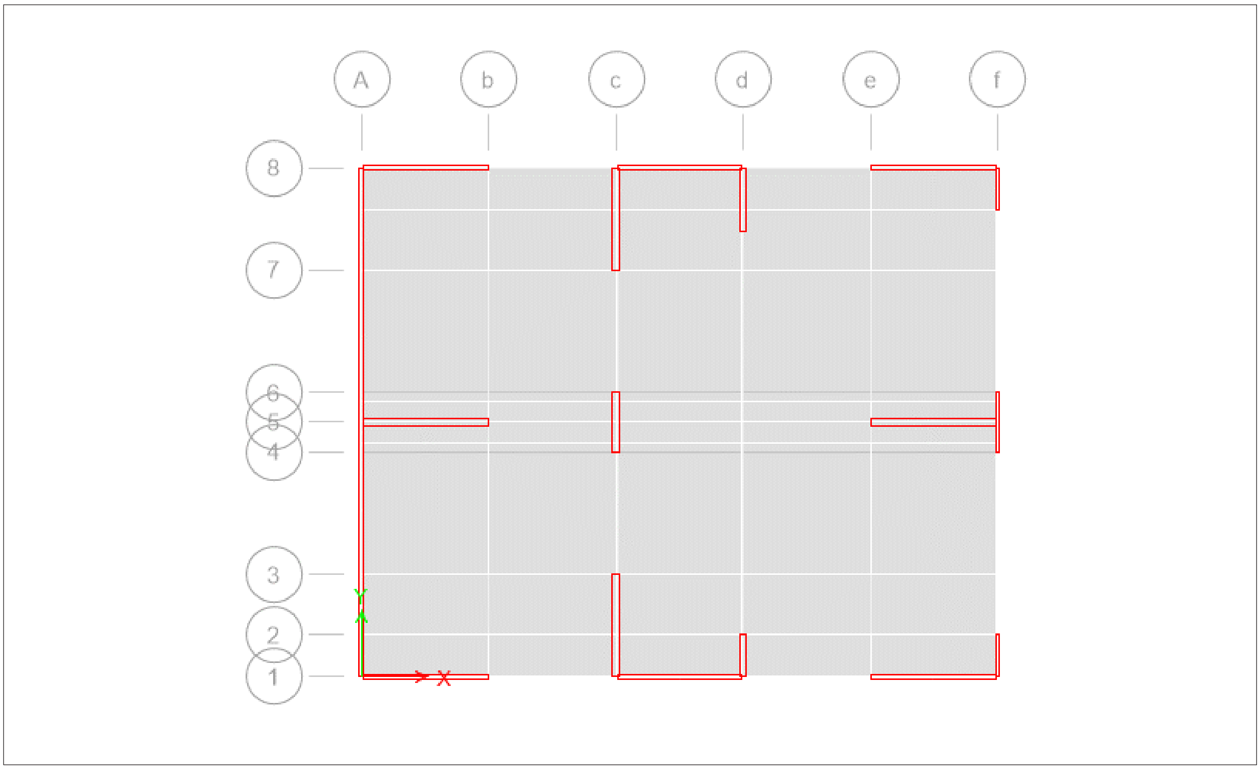

Figure 8. Bracing arrangement of case study building RIR1, with bracing towards the extreme end of allowable irregularity under NZS 3604:2011.

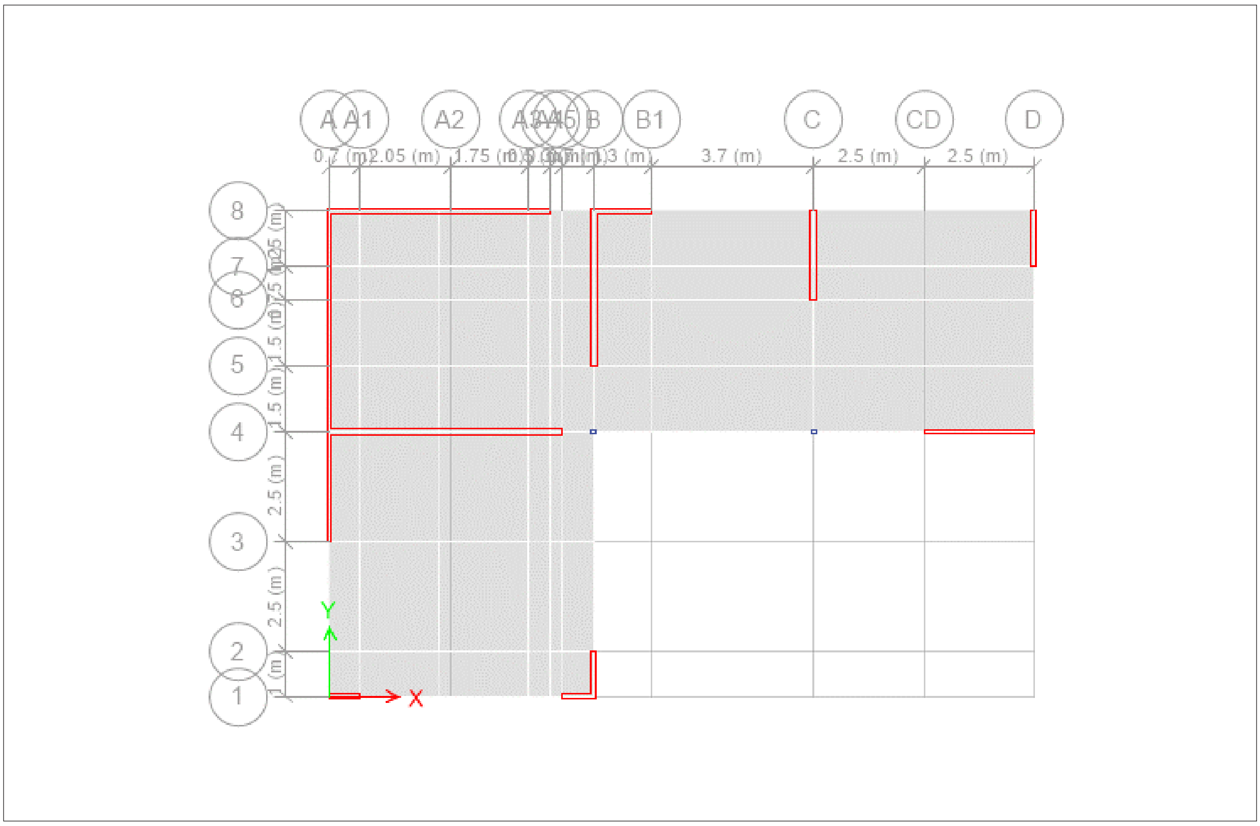

Figure 9. Bracing distribution of case study building LIR2 – an L-shaped building with irregular bracing within the allowable limits of NZS 3604:2011.

5.0.3 While this bulletin does not cover all of the research in detail, it summarises the key points that can be applied to the bracing design of LTF buildings. (For more detail, see BRANZ Study Report SR404 *Seismic effects of structural irregularity of light timber-framed buildings*.)

5.1 PLASTERBOARD BRACING PERFORMANCE UNDER TEST

5.1.1 Studies of many past wall bracing tests carried out at BRANZ using the P21 test method show that the primary deformation source of an LTF plasterboard-lined wall of reasonable length is the slip in the screws (or nails) fixing the plasterboard to the framing. For slender walls or walls of shorter length, there is also a significant contribution from uplift at each end especially where there may be insufficient hold-down capacity.

5.1.2 Timber-framed plasterboard-lined walls have different cyclic responses from timber-framed plywood-lined walls. Typically, during a racking test, the sheathing of a plasterboard wall behaves like a plate element and rotates as one unit relative to the timber frames. This is different from plywood or other wood-based sheathing sheets where significant movements would occur between sheets during the racking. So, walls lined with plasterboard are stiffer than walls lined with plywood or other wood-based sheets. Clearly, a mathematical model developed on the basis of timber framing with wood-based sheathing is not suitable for timber-framed walls with plasterboard.

5.1.3 A rich database of P21 test results available at BRANZ was used to develop a racking model of timber-framed plasterboard-lined bracing walls. The developed model was used in the three-dimensional analyses discussed in this study.

5.1.4 Based on these historical tests of plasterboard walls and the tests on plasterboard ceiling diaphragms during this study (and previous studies), it is concluded that plasterboard ceiling diaphragms are significantly stiffer than plasterboard walls, and diaphragms are strong enough to transfer the seismic actions induced in lightly braced areas to heavily braced areas.

5.1.5 Racking behaviour of plasterboard-lined walls has many similarities to the in-plane performance of plasterboard ceiling diaphragms. Both are strongly dependent on the fixing details from plasterboard sheets to the framing.

5.2 SEISMIC GLOBAL PERFORMANCE OF LTF BUILDINGS

5.2.1 LTF building structures potentially have more significant structural irregularities that cannot be avoided and occur for various reasons such as:
- irregular shapes of floor plans because of the functional requirements or restrictions of available sites or something else
- non-symmetrical arrangements of lateral load-resisting systems in a building structure within a floor plan or along the elevation
- significant mass variation within a floor plan or from floor to floor
- discontinued bracing systems from floor to floor due to the platform construction technique.

5.2.2 The BRANZ research has shown that current permissible bracing distribution allowed for in NZS 3604:2011 (when taken to its extreme) could amplify the lateral deflections in some parts of a building. This can be by up to 500% in comparison with a building that has evenly distributed bracing.

5.2.3 LTF buildings with minimum bracing provision at one end of the building as allowed by NZS 3604:2011 are likely to sustain earthquake damage well beyond economical repair. This occurs because a building with an irregular bracing arrangement will develop coupled translational and torsional responses in earthquakes, as explained above. Consequently, the areas light in bracing capacity will deflect significantly more than the remaining areas heavily braced, leading to more severe damage.

6 SIMPLIFYING BRACING

6.0.1 There are ways to make the bracing of LTF buildings more regular. These may not always be palatable to building designers, so compromise may often be necessary. They include:
- keeping the layout compact with smaller rather than larger spaces
- keeping to regular shapes
- spacing openings regularly around the perimeter
- making openings smaller
- aiming for an even distribution and capacity of bracing elements particularly around the building's perimeter
- locating bracing at each building external corner to resist torsion
- increasing diaphragm in-plane rigidity through better construction detailing – the greater the in-plane rigidity, the better the overall performance of an irregular building.

6.0.2 Where an evenly distributed bracing solution is difficult to achieve using NZS 3604:2011, adopting a specific engineering design for the bracing is considered prudent rather than trying to make the bracing design fit to NZS 3604:2011.

6.1 ADOPTING CODE-PLUS BRACING DESIGN

6.1.1 As a result of the research, suggested changes to adopt a Code-plus approach to bracing design should include the following:
- Significantly increasing the minimum bracing provision along the perimeter bracing lines. Increasing the minimum bracing provisions in NZS 3604:2011 by 50% along the perimeter bracing lines could reduce the induced lateral deflection by 43% and keep the deflection within a tolerable damage control limit.
- When a building has a sophisticated plan geometry/wings (such as the plan shown in Figure 10), bracing elements should be provided to each part of a building that are based on a tributary area theory.
- LTF houses with the minimum seismic bracing required by NZS 3604:2011 are likely to be flexible. They can deflect beyond the Building Code-specified deflection limit of 2.5% storey drift in an ultimate limit state earthquake event.

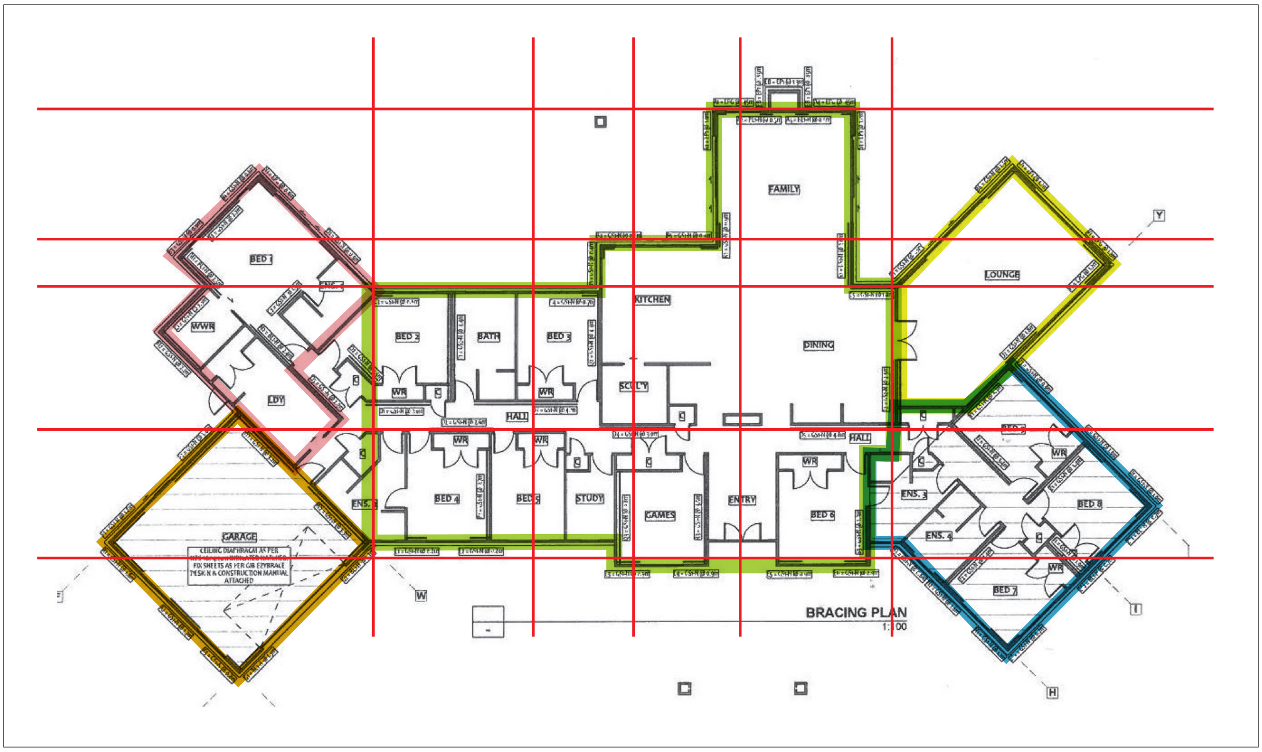

Figure 10. A building with a plan consisting of wings/blocks – bracing lines for the green block shown. Bracing capacity of walls common to both a wing and a block must be the sum of the requirements for the wing and the block.

- Where specifically designed bracing elements (such as steel portals) are required in a mainly LTF building, they often have little significant stiffening potential unless of a large sectional size. So, the performance criteria for designing such bracing elements needs to include damage control (a deflection check for compatibility with sheathed bracing elements).

7 FURTHER READING

BRANZ

A wall bracing test and evaluation procedure (BRANZ Technical Paper P21)

Engineering Basis of NZS 3604

Study Report SR337 *Design guidance of specifically designed bracing systems in light timber-framed residential buildings*

Study Report SR404 *Seismic effects of structural irregularity of light timber-framed buildings*

Standards

NZS 1170.5:2004 *Structural design actions – Part 5: Earthquake actions – New Zealand*

NZS 3604:2011 *Timber-framed buildings*

INSPIRING THE INDUSTRY TO PROVIDE BETTER BUILDINGS FOR NEW ZEALANDERS

BRANZ ADVISORY HELP LINES

FOR THE BUILDING INDUSTRY

0800 80 80 85

FOR THE HOME OWNER AND PUBLIC ENQUIRIES

0900 5 90 90

Calls cost $1.99 per minute plus GST. Children please ask your parents first.

BRANZ Find www.branzfind.co.nz

HEAD OFFICE AND RESEARCH STATION
1222 Moonshine Road, Judgeford, Porirua, New Zealand
Private Bag 50 908, Porirua 5240, New Zealand
Telephone 04 237 1170 - Fax 04 237 1171
www.branz.nz

Standards referred to in this publication can be purchased from Standards New Zealand by phone 0800 782 632 or by visiting the website: www.standards.co.nz.

Please note, BRANZ books or bulletins mentioned in this publication may be withdrawn at any time. For more information and an up-to-date list, visit BRANZ Shop online: www.branz.nz or phone BRANZ 0800 80 80 85, press 2.

ISSN 1178-4725 (Print) 2537-7310 (Online)