Performance of irregular seismic bracing in light timber-framed buildings

BRANZ research has found that the current requirements for the distribution of seismic bracing elements in NZS 3604:2011 *Timber-framed buildings* are too lenient. Full-scale experiments and three-dimensional modelling suggest that some parts of irregular light timber-framed (LTF) buildings could be unacceptably flexible during earthquakes, with lateral deflections up to five times greater than for regular LTF buildings. This would result in Code-compliant buildings experiencing damage during earthquakes that is uneconomical to repair.

New Zealand is unique internationally in considering plasterboard wall and ceiling linings to be structural elements of timber-framed buildings. These elements are also relied on as bracing to provide resistance against movement during seismic events.

During the 2010/11 Christchurch earthquakes, the damage to LTF buildings varied considerably. Overall, regular houses performed well. Conversely, irregular houses often had significant damage that was uneconomical to repair.

Structural irregularities are irregular arrangements of bracing systems and/or irregular geometric shapes. Irregularities in building structures cannot be avoided and occur for various reasons. A few examples are:

- irregular shapes of floor plans due to functional requirements or restrictions of available sites
- non-symmetrical arrangements of lateral load-resisting systems in a building structure within a floor plan or along the elevation

The distribution of seismic bracing built into residential LTF buildings in New Zealand should meet the standard prescribed in NZS 3604:2011. However, the requirements for arranging the bracing systems in this standard are specified by engineering rules of thumb rather than scientific evidence. BRANZ set out to investigate the performance of irregular bracing in single-storey buildings during earthquakes under the limits prescribed by the standard.

International literature review on the seismic behaviour of irregular buildings

BRANZ undertook a literature review of research into seismic responses of building structures with structural irregularities. This showed that structural irregularities in buildings cause them to respond in a much more sophisticated manner than regular buildings.

When a building structure has in-plan structural irregularities, its translational responses will be coupled with its torsional responses during earthquakes. This means seismic actions will be transmitted by the

New Zealand standard for seismic bracing in LTF buildings

NZS 3604:2011 provides methods and details for designing timber-framed houses and small buildings up to 3 storeys where only part of the top floor could be used as a floor space.

To ensure the adequate performance of buildings during earthquakes, NZS 3604:2011 includes recommendations on seismic bracing provisions to meet a specified seismic demand and irregularity limits of bracing arrangements within a floor plan. A force-based approach is used to derive requirements for building designs to meet the seismic demand. The seismic demand itself is determined from a predefined table based on:

- soil classification
- seismic hazard zone
- house foundation type - concrete slab on ground or suspended timber floor
- building envelope weight.

Bracing lines within a floor plan are required to be spaced at no more than 6 metres in each direction.

Bracing arrangements can be irregular but should be within certain limits:

- 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 per metre of external wall length for external walls.

NZS 3604:2011 also specifies that the BRANZ P21 test and evaluation procedure should be used to evaluate the seismic bracing capacity of proprietary LTF wall elements.

floor/ceiling diaphragms into the lateral load-resisting systems in both directions across the entire building. The rigidity of roof/ceiling diaphragms is crucial for an LTF building with in-plan irregularity. This rigidity mobilises the lateral load-resisting systems in both directions in resolving the torsional response.

In the case of a perfectly regular building, a two-dimensional seismic analysis would be adequate. For irregular LTF buildings, three-dimensional analyses with adequate modelling of the interaction between wall bracing elements and ceiling diaphragms would be essential. This sort of analysis would require an understanding and incorporation of the racking behaviour of primary lateral load-resisting systems and the in-plane rigidities of floor/ceiling diaphragms to adequately capture the seismic performance of buildings with structural irregularities.

Modelling plasterboard wall performance

The results of many racking tests of LTF walls that are typical of New Zealand residential construction were collected and studied. These allowed the development of a model capable of capturing the racking performance of LTF walls typically built in New Zealand.

A literature search was also conducted on the seismic performance and modelling of the bracing performance of LTF walls in general, but this revealed that most of these research efforts were based on overseas practices, which are different from New Zealand practice.

The racking tests on plasterboard walls show that plasterboard sheathing behaves like a rigid plate. Deformation observed was mainly due to slips between plasterboard sheets and fasteners, which are universally screws.

These are the key elements of the resulting model:

- The calculations are constrained by BRANZ in-house test results on plasterboard bracing walls.
- Plasterboard walls are represented in the model using solid-shell elements.
- Two mechanical engineering properties - modulus of elasticity and shear modulus - of the assigned materials to the solid-shell elements are determined by conducting calibration against test results of plasterboard walls.
- The degrading behaviour of plasterboard walls is simulated through a degrading shear modulus.

Rigidity study of ceiling diaphragms

For LTF buildings constructed to NZS 3604:2011, there is no requirement for bracing elements at one level to be aligned vertically with bracing elements at the level below or above. This means a diaphragm is essential to transfer the concentrated lateral loads from bracing elements above to bracing elements below. The strength and stiffness of the ceiling diaphragms of an LTF building will directly affect the effectiveness of the load transfer from the bracing elements at the level above to the bracing elements at the level below in earthquakes.

The diaphragms in LTF buildings are timber diaphragms, and they are neither rigid nor flexible. Their semi-rigid nature complicates the analysis and the assessment of the actions resisted by lateral bracing elements. It is essential to understand and quantify the in-plane rigidity of the diaphragms to be able to adequately study the seismic performance of LTF buildings with structural irregularities.

A literature review of in-plane structural performance of ceiling diaphragms showed that the majority of research conducted was based on overseas practice and bore little relevance to New Zealand applications.

Current roof diaphragm construction practice in New Zealand was therefore surveyed, and a test programme on suitable ceiling diaphragms was designed. A series of tests informed and allowed the development of an in-plane stiffness model of ceiling diaphragms that was more typical of New Zealand residential construction.

Findings from this phase of the research:

- Plasterboard linings behave like one monolithic plate over the entire diaphragm under consideration when the plasterboard ceiling diaphragm is subjected to in-plane loading.
- About 80% of total in-plane deformation of plasterboard ceiling diaphragms, when subjected to in-plane loading, is from slips of screws from plasterboard linings to the frames.
- The beam-analogy method in predicting in-plane deflection of floor diaphragms (as in NZS 3603:1993 *Timber structures standard*) can be used in estimating the rigidity of plasterboard ceiling diaphragms if the screw slip model is adequate.
- Stiffness degradation of the plasterboard ceiling diaphragm is significant as the loading progresses and the non-linear deformation mechanism is limited to screw slips.

A mathematical model simulating the in-plane rigidity of plasterboard ceiling diaphragms was developed based on these test results. The degrading characteristics of the plasterboard ceiling diaphragms is represented by a degrading shear modulus. The developed model is straightforward to use when diaphragms are modelled as shell elements of a solid section.

Design of test buildings for three-dimensional seismic analyses

Six case study LTF buildings were designed according to NZS 3604:2011. It was assumed that all were constructed on a site with the same seismic hazard factor (0.46) and subsoil (class D, according to NZS 1170.5:2004 *Structural design actions - Part 5: Earthquake actions - New Zealand*). All building designs had a roof pitch of less than 25°, a storey height of 2.4 metres and concrete slab foundations.

Of these six buildings, three were rectangular in plan - one had no bracing irregularities, and the structural irregularity in the other two was caused by irregular arrangements of bracing elements within the floor plan in the Y-direction only (Figure 1 and Table 1). The other three buildings were L-shaped in plan and had some degree of irregular bracing arrangement within each wing of the floor plan, also in the Y-direction only (Figure 1 and Table 2).

These building designs were selected to:

- evaluate the seismic effects of permissible irregular distribution of bracing resistance within the scope of NZS 3604:2011
- determine the appropriate irregularity limits required for controlling earthquake damage.

Table 1. Summary of seismic bracing designs of the rectangular case study buildings (RR, RIR1 and RIR2).

		X-DIRECTION			Y-DIRECTION			
Bracing line #		A	B	C	1	2	3	4
Minimum bracing requirement in NZS 3604:2011 (BUs)		270	270	270	202	202	202	202
RR	Bracing provision at each bracing line (BUs)	531	587	531	423	408	408	423
	Total bracing provision (BUs)		1,650			1,662		
RIR1	Bracing provision at each bracing line (BUs)	531	587	531	720	527	212	204
	Total bracing provision (BUs)		1,650			1,665		
RIR2	Bracing provision at each bracing line (BUs)	531	587	531	720	305	305	300
	Total bracing provision (BUs)		1,650			1,630		

Table 2. Summary of seismic bracing designs of the L-shaped case study buildings (LR, LIR1 and LIR2).

		X-DIRECTION			Y-DIRECTION			
Bracing line #		A	B	C	1	2	3	4
Minimum bracing requirement in NZS 3604:2011 (BUs)		90*	174	240	165	130	130	75*
LR	Bracing provision at each bracing line (BUs)	168	520	360	300	447	153	150
	Total bracing provision (BUs)		1,048			1,050		
LIR1	Bracing provision at each bracing line (BUs)	168	520	360	450	358	170	75
	Total bracing provision (BUs)		1,064			1,053		
LIR2	Bracing provision at each bracing line (BUs)	90	596	378	450	358	170	75
	Total bracing provision (BUs)		1,064			1,053		

* Minimum bracing requirement if bracing demand is derived based on each building wing.

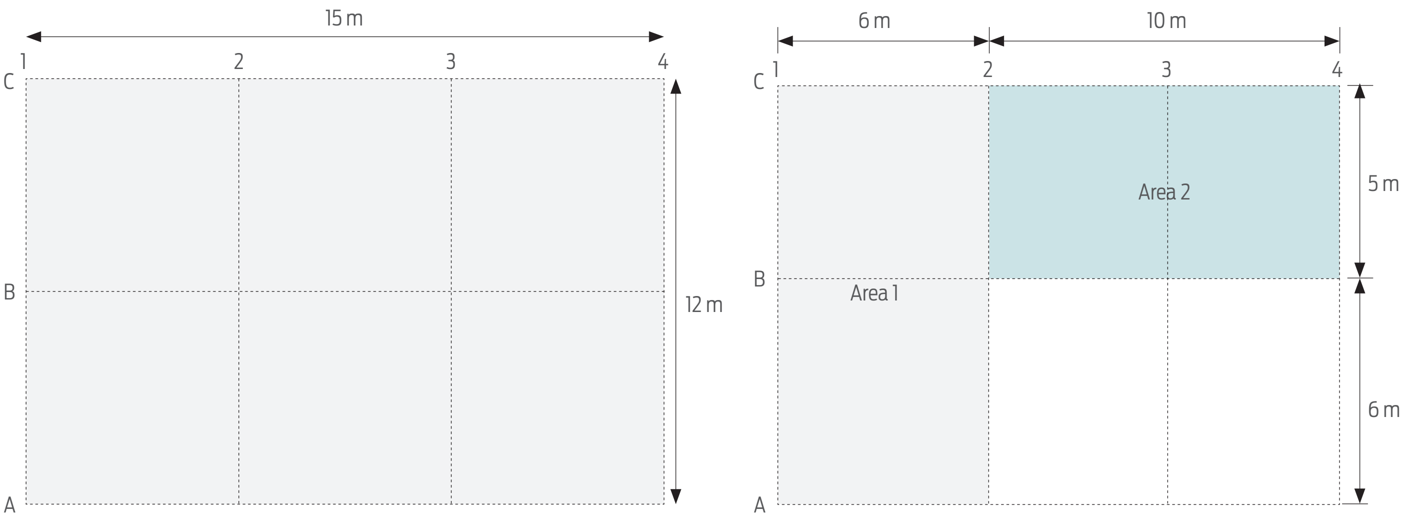
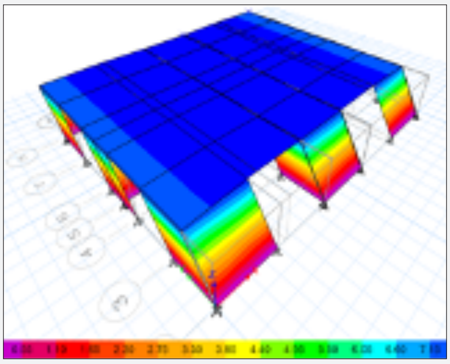


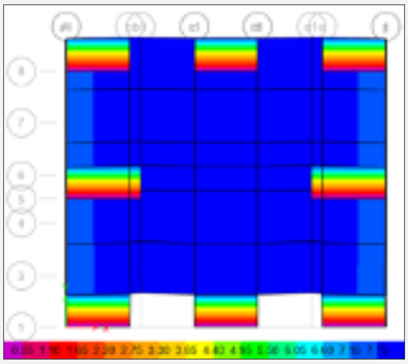
Figure 1. Dimensions of the rectangular and L-shaped floor plans used in the six case study buildings. Y-direction is parallel to the vertical axis.

Structural modelling and seismic analyses

To evaluate the seismic performance of the six case study building designs, a three-dimensional model for each was created using ETABS modelling software, and non-linear equivalent static push-over analyses were completed. The analyses were undertaken in the Y-direction only because the seismic irregularities were only in the Y-direction of the floor plans. The seismic action inputs to this modelling were derived from NZS 3604:2011. The fundamental periods were shorter than 0.45 seconds for the rectangular buildings and about 0.45–0.55 seconds for the L-shaped buildings. The modelled lateral deflection occurring in response to the seismic action in the case study buildings is shown in Figures 2 and 3, with corresponding values at defined points listed in Tables 3 and 4.

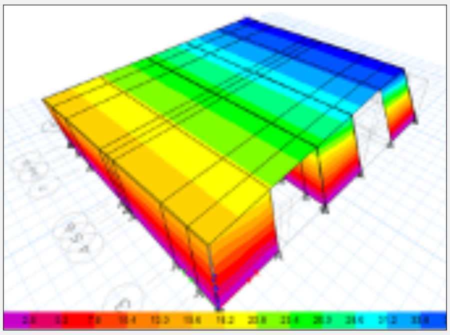


(i) 3D view

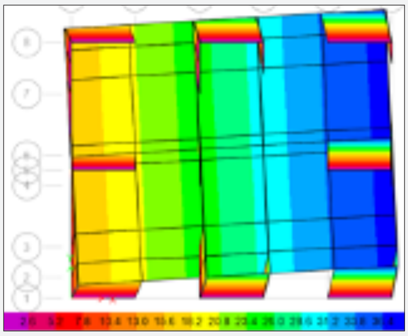


(ii) Plan view

Case study building RR (regular)

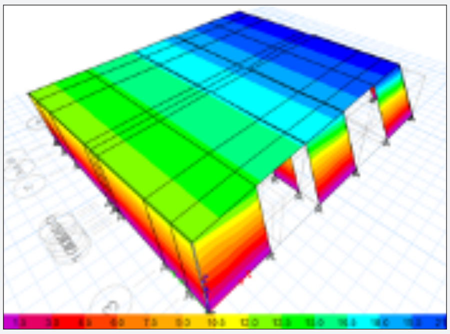


(i) 3D view

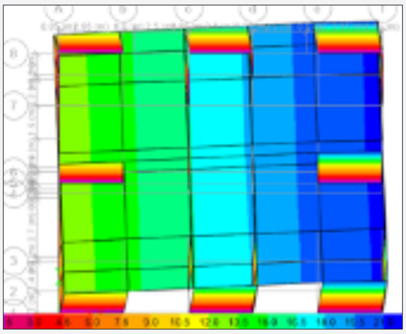


(ii) Plan view

Case study building RIR1 (irregular)



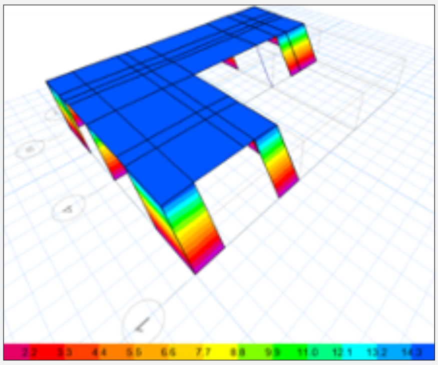
(i) 3D view



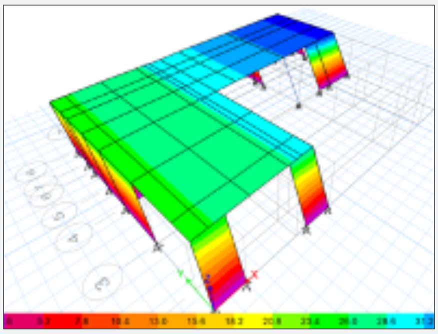
(ii) Plan view

Case study building RIR2 (moderately irregular)

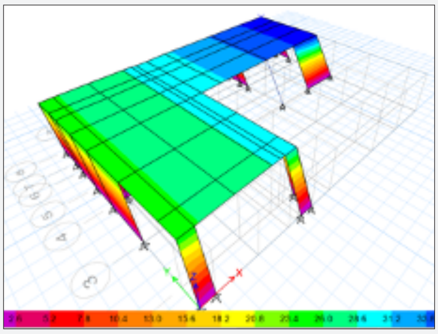
Figure 2. Lateral deflection modelled for the rectangular case study building. The colour scale from red to blue indicates larger to smaller deflection respectively.



Case study building LR (regular)



Case study building LIR1 (irregular)



Case study building LIR2 (moderately irregular)

Figure 3. Lateral deflection modelled for the L-shaped case study building. Colour scale as in figure 2.

Table 3. Lateral deflections in mm along different grid lines for the rectangular case study buildings. Values in red indicate the displacement at which a plasterboard-sheathed wall of reasonable length is expected to experience significant strength degradation and softening over a 2.4 m storey height.

CASE STUDY BUILDING	GRID LINE ID			
	1	2	3	4
RR	7.5	7.5	7.5	7.5
RIR1	16.0	25.0	29.7	37.8
RIR2	12.5	16.6	18.5	21.6

Table 4. Lateral deflections in mm along different grid lines for the L-shaped case study buildings. Values in red indicate the displacement at which a plasterboard-sheathed wall of reasonable length is expected to experience significant strength degradation and softening over a 2.4 m storey height.

CASE STUDY BUILDING	GRID LINE ID			
	1	2	3	4
LR	14.1	14.1	14.1	13.6
LIR1	25.0	29.4	34.0	38.3
LIR2	25.1	29.2	33.6	38.6

Key findings

In this study, the performance characteristics of wall bracing elements and ceiling diaphragms were determined experimentally. These characteristics were then used in three-dimensional analytical models of various regular and irregular plan configurations to determine the expected seismic performance of permissible irregular bracing arrangements by NZS 3604:2011.

The research found that the current rules for distribution of bracing elements in NZS 3604:2011 are too lenient. The lateral deflections in some parts of irregular buildings could be up to five times greater than for regular buildings. This would result in LTF buildings with Code-minimum bracing provisions experiencing earthquake damage well beyond economic repair.

The in-plane rigidity of plasterboard ceiling diaphragms varies greatly, depending on the adopted construction practice. In general, plasterboard ceiling diaphragms are relatively rigid in comparison with plasterboard bracing walls. The higher the in-plane rigidity of the ceiling diaphragm, the better the overall performance of an irregular building.

Recommendations

Tightening 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 in a design earthquake event.

The seismic effect of geometrical irregularity in an irregular-shaped LTF building is similar to that of irregular bracing arrangements in regular buildings. To mitigate the adverse effects of irregularities in buildings, it is suggested that bracing designs provided to each part of a building be based on a tributary area theory.

Future work

Further study is needed to examine the seismic actions used to ensure they are appropriate. The expected seismic actions induced in LTF buildings could be significantly higher than the demand prescribed currently by NZS 3604:2011. The in-plane rigidity of suspended timber floors plays an important role in distributing seismic actions especially for irregular buildings. As these floors are typically used in New Zealand residential construction, their rigidity should also be studied further - this would fill a knowledge gap in understanding the seismic performance of structures built to NZS 3604:2011.

Study into other contributors (floors and others) to overall damping levels was beyond the scope of this project but will be required to appropriately evaluate the adequacy of the seismic actions recommended in NZS 3604:2011.

More information

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