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As Safe as Houses

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NZS 3604

Most new houses in New Zealand are designed to the "Timber-framed Buildings" standard, NZS 3604. Sections 1-16 of this standard are invoked by the New Zealand Building Code (NZBC) as an "Approved Document" for clauses B1, B2 and E2, meaning that it is deemed to be an acceptable solution for the structural, durability and external moisture aspects of timber-framed buildings.

NZS 3604 is a "cook book" type of standard which enables builders to design timber-framed houses without having to use specific engineering design. The size of every timber member in the house – from rafters in the roof, purlins, ceiling joists, wall plates and studs, and lintels to floor joists bearers and piles – is selected from tables given in the standard as a function of member spacing, span, wind zone, roof and cladding weight (and perhaps snow loading, floor live load or whatever is relevant to the loading of the member). The standard also stipulates connection fixings, often as a function of these parameters.

The tables were prepared using spreadsheets using all the relevant load cases from NZS 4203 and the material strengths specified in NZS 3603, although account was sometimes taken of redundancies, additional strength and other favourable factors known to be present in these buildings, even though such factors cannot normally be taken into account in specific design. Territorial Authority inspectors check the construction. Timber must comply with strength, stiffness and durability requirements. All cladding must have a durability of 15 years and all structural material a durability of 50 years. Thus, provided the standards are complied with, failure under gravity or wind loading is expected to be rare. Houses generally have alternative load paths, and the total composite strength is greater than the sum of individual elements. Thus, life risk from structural failure is small.

HOUSE EARTHQUAKE RESISTANCE

NZS 3604 tabulates the earthquake and wind demand forces based on the loadings from NZS 4203, building weights, geometry and location. The earthquake forces assume the building has a ductility of 3. Manufacturers test their wall systems to the BRANZ P21 test method which assigns the walls a bracing rating, and then publish these strength results. Designers use this data to ensure the actual wind and earthquake strengths exceed the demand forces. A similar process is used for pile foundation systems.

NZS 3604 ensures all building elements are fixed together, which greatly enhances earthquake resistance. Well-constructed houses have tended to perform well in these extreme events. This is partially due to the box-like shape of houses with good horizontal diaphragms; elements adding strength, but usually ignored in the design process and the multitude of load paths and redundancies present in typical houses. However, the modern trend to larger, more open, houses of complex shapes and vertical and horizontal irregularities makes them susceptible to torsional forces and increases their vulnerability.

DAMAGE IN WINDSTORMS

New Zealand generally gets one or two major wind storms a year – although the wind speeds reached rarely exceed the design wind speed. Roofing iron and even tiles are often lifted (particularly on older buildings where the roof fixing strengths have deteriorated or were inadequate in the first place). Sometimes the entire roof is lifted if the roof to wall fixing is inadequate. This connection should be high on the Territorial Authority inspector's checklist.

Where windows or sliding doors blow in or are smashed by flying debris, the interior of the house will be pressurised which tends to lift the roof off. If the roof goes, lack of roof diaphragm can result in collapse of walls under face load pressures. Loss of wall cladding under wind suction may also occur. Racking failure of walls without roof failure, or failure of foundations or lintels in wind storms, has been rare. However, we should not forget the increased risk of wind storm severity associated with global warming.

Apparently some people in Fiji open leeward doors and windows of houses when experiencing cyclones. This reduces the air pressure in the interior of the house and thus decreases the tendency of roofs to blow off. Of course the reduced interior air pressure increases the differential pressure across the doors and windows of the windward side of the house which can lead to failure – and so there is a drawback.

LIFE RISK IN HOUSE FIRES

The majority of fire fatalities occur as a result of fires in the home. Annually there are approximately 5,000 domestic fires a year in New Zealand, and over the last five years there has been an average of 19 deaths per year. Worldwide the mortality rate is decreasing with the passage of time, which may be due to better fire services and rapid uptake in the use of smoke detectors. Most deaths in house fires are from smoke inhalation. BRANZ has been promoting the use of stand-alone battery powered smoke detectors which have been shown (Wade and Duncan) to be cost-effective. More than 50% of New Zealand homes have smoke detectors installed. Domestic water sprinklers are becoming more cost-effective.

THE INTERACTION OF RESIDENTIAL DAMAGE FROM NEW ZEALAND EARTHQUAKES AND THE BUILDING REGULATIONS

Since 1855, New Zealand houses have not been severely tested by earthquakes – particularly modern construction. However, it is only a matter of time. An exception was possibly the 1931 Napier earthquake, where the major damage was caused by fire rather than ground shaking, and to a lesser extent the 1987 Edgecumbe earthquake.

I will discuss the major earthquakes and their interaction with the New Zealand regulations. With his permission I have borrowed heavily from Russell Cooney's 1979 and 1987 papers which are still the authoritative documents on this subject.

- Most of the 4,800 inhabitants of the 1848 Wellington earthquake lived in masonry houses which were severely damaged. The timber-framed houses performed well. Consequently, the majority of houses were rebuilt in timber. The 1855 earthquake felled 80% of the chimneys and masonry houses were again severely hit. Damage to wooden houses was slight.

- A 1929 earthquake near Murchison severely damaged houses.

- New Zealand's greatest earthquake disaster occurred in 1931 at Napier. However, apart from falling chimneys, 90% of the wooden framed buildings were not damaged by the ground shaking in the earthquake. The two main causes of damage were inadequate anchorage of the superstructure to the foundations and lack of sub-floor bracing. Further, insufficient lower storey wall bracing resulted in damage and permanent distortion.

- The 1942 Wairarapa earthquake and subsequent aftershock resulted in more than 5,000 houses being damaged and 22,000 chimneys falling.

- Reports on the 1966 Seddon earthquake attributed damage to lack of bracing in heavy roofs, inadequate veneer ties and house shape irregularity including large openings ... and of course chimneys.

- Eighty houses experienced the heavy shaking of the 1968 Inangahua earthquake, most being timber-framed. It was concluded that performance was good, and the damage mainly occurred in buildings where diagonal wall and/or roof bracing was omitted and attachment to the foundations was inadequate. The few unreinforced masonry buildings in the area apparently disintegrated. Cooney notes buildings on piled foundations often have the superstructure protected by what is effectively base isolation. He observed that the only house which was founded on a slab-on-ground construction which experienced strong shaking in the 1968 earthquake appeared to have suffered greater superstructure seismic forces than those on timber piled foundations.

- Housner's report of the 1971 San Fernando earthquake (where the houses were similar to those in New Zealand) came to similar conclusions – namely the damage was due to (a) inadequate sub-floor bracing, (b) inadequate lower storey wall bracing particularly where there was a large garage opening, and (c) inadequate roof bracing … and of course chimneys! After this earthquake, Yanev (1974) stated … "the same type of buildings that failed in the 1906 San Francisco earthquake failed in the 1933 Long Beach, the 1952 Bakersfield, the 1964 Alaska and the 1971 San Fernando earthquake. The same types of building will continue to fail until the building codes pay some heed to history and the principles of physics.

Before the 1931 earthquake there were few New Zealand regulations for residential building construction and it was based on "experience and trade practice". The lessons from previous earthquakes had apparently not been heeded. A model bylaw (NZSS 95) was published in 1935, but was still largely inadequate – except perhaps for bracing of walls between storeys. Houses were permitted to be built on free-standing piles up to 760 mm long. Some parts were vague – such as the requirement that roof framing must be effectively braced without specifying criteria. The far-sighted recommendations by Dixon (1929) on subfloor, wall and roof bracing were largely ignored. Adoption of the bylaws by local government was voluntary.

Later, the 1936 State house specification required continuous reinforced concrete foundation walls. Twenty-eight years later (1964), NZSS 1900 replaced NZSS 95, but the provisions added little seismic strength enhancement to houses.

The introduction of NZS 3604 in 1978 was a major step forward, as it did not rely on good trade practice and tradition, but was instead based on sound engineering principles and calculations. Bracing demand depended on construction weights. A number of wall and foundation bracing systems were offered. The standard placed particular emphasis on piled foundations, as these had such a poor history of seismic performance.

NZS 3604:1978 aimed at minimising damage to houses in major earthquakes to ensure they were habitable after the design earthquake event.

Cooney 1981, predicted large damage to “a significant number” of pre-1978 houses in a major earthquake, with many houses being required to be evacuated while being repaired. Cooney’s predictions of the type of earthquake damage were largely borne out by the outcome of the 1987 Edgecumbe earthquake. He predicts far less damage to houses built to NZS 3604:1978 except for masonry veneer and chimneys. He highlights the importance of building inspections during construction to ensure compliance with NZS 3604. He emphasises that careful study of earthquake damage is the best way to learn how to refine future codes.

1987 EDGECUMBE EARTHQUAKE, ML 6.3, MM IX OR PGA 0.33G

Two-thirds of the Edgecumbe area houses were built in the 1950-1979 era when awareness of earthquake resistant construction was not high. Several hundred houses experienced minor structural damage, but less than 50 buildings were substantially structurally damaged. None of those which complied with the 1978 NZS 3604 standard were damaged by the shaking, with the exception of those on concrete slabs discussed later.

Permanent ground deformation through rupture or subsidence caused much of the damage to houses, especially to concrete and masonry foundations and walls and masonry veneers. Modern houses are still expected to be vulnerable to such differential movement, although probably not to the same degree. The highly variable soil conditions resulted in many examples of almost identical buildings in close proximity having widely different levels of damage.

Most damage involved the foundations – mainly in houses with unbraced piles and jack studs. Approximately 20 foundations collapsed (damaging their superstructure as well) and 100 were laterally displaced at foundation level. Much of the resistance of these houses was due to cast-in porches/chimneys etc. Those on continuous or corner foundation walls performed very well. The construction on slab-on-ground also performed well, except where the slab sat on a perimeter foundation wall and there was no connection between the two. In this instance, the slabs moved up to 300 mm relative to the walls and caused significant damage. Such construction is not permitted in the current NZS 3604.

Although no collapse of timber-framed walls occurred, and none had significant permanent racking deformations, plasterboard cracking was often severe, particularly where external walls had large openings. Houses designed to the current revision of NZS 3604 are expected to have significantly less damage for the same shaking.

Torsion-induced damage in houses with vertical and horizontal irregularity was noted. Damage occurred at junctions of wings of a house, particularly where the different wings had different foundation types.

Inadequate bracing of houses under construction resulted in severe damage.

The largest monetary loss was to house contents such as whiteware overturned, electrical appliances such as TVs falling, and shelves emptied. A number of solid fuel stoves moved on their hearths and became disconnected from their flues creating a fire danger.

This is unlikely to change for contents in the lower ground floor of modern construction. Better wall bracing may reduce the shaking in the upper floors, but the more open modern construction will exacerbate it.

Most concrete or masonry chimneys in areas of high shaking were extensively damaged – mainly due to non-compliance with the bylaw requiring them to be tied to the house. If the chimneys had had an open fire this failure would have posed a fire risk. Few modern houses have concrete or masonry chimneys, and these must now be constructed according to the NZBC Acceptable Solutions and are expected to perform better. Existing chimneys in older houses will remain vulnerable, although many have been strengthened or “topped” on the owner’s initiative.

Over 100 of the 600 houses with brick veneer in Kawerau had damage to the veneer other than slight cracking. Most of this was attributed to the type of tie used, the manner in which the tie was fixed to the wall framing and the spacing of the ties. Damage included portions of the veneer being shed, diagonal cracks originating at openings and re-entrant corners and mortar cracks. Movement between the flexible timber frame behind and the brick veneer sometimes resulted in glass breakage at windows.

Summary of damage from the Edgecumbe earthquake. The damage in this moderate (less than design level earthquake) was largely attributable to inadequate bylaws for earthquake resistance in past decades, non-compliance, and poor construction practices.

BRACING WALLS

Prior to the 1930’s most houses were lined with horizontal boarding with 150 x 25 mm checked in braces. Fibrous plaster sheets and paper faced gypsum boards then started to be introduced and the brace size reduced to 100 x 25 mm. The sheet bracing is far more effective as a bracing element than the diagonal braces. This was not recognised or provided for in the provisions up to and including NZSS 1900 (1964). However, the concept of bracing walls of tested strength to meet design bracing demand used in NZS 3604 has rationalised the problem and a more reliable wall bracing performance is now expected.

FOUNDATIONS

Early foundations consisted solely of timber piles or stone blocks without any form of lateral support or embedment in the ground.

Slab-on-ground and continuous concrete wall foundations have performed well in earthquakes. Apart from chimneys, no other single element of construction has resulted in so many failures in earthquakes as piled foundations. However, the piles may have provided some base isolation protection to the superstructure. Many of the older style free-standing piled foundations were woefully inadequate.

NZS 3604 now permits specifically detailed braced piles, cantilevered piles with substantial footings and driven timber piles - each with assigned strength based on tests. Proprietary or bolted connections between pile to bearer and bearer to joists must have an even greater proven strength and 50 year durability. Thus better seismic performance is expected. NZS 3604:1979 only allowed single storey buildings to be founded on piles, but subsequent revisions extended this to two storeys.

MASONRY VENEERS

Masonry veneers have had poor performance in past earthquakes. This is largely due to the incompatibility of fixing the stiff veneers to the more flexible timber framed walls. Veneer ties are intended to allow the timber framed walls to move vertically as the timber dries, to rack by ±20 mm relative to the stiff veneer and then to prevent large portions of veneer from falling out under seismic face load.

Shelton (1995) found that many brick ties were inadequately held in the mortar. This was caused by nailing of the tie to the stud during construction, causing the stud to vibrate and thereby loosen the tie fixings in the still soft mortar of the layers below. The NZS 4210:2001 requirement for ties to be screwed to studs and the test method (AS/NZS 2699.1:2000) for brick ties is expected to give a much improved seismic performance as evidenced by BRANZ shake table tests. Cracking in the veneer in modern construction is still likely, particularly at veneer corners and window openings (Beattie 2005), although this is expected to be repairable if the brick ties are in sound condition. Inadequate tie fixing was noted as being a major factor in the 1989 Newcastle earthquake.

RECENT CODE/STANDARD CHANGES

Based on the lessons learnt from the Newcastle earthquake and testing by Shelton (1995), an amendment to the NZBC required brick ties in house veneers to be fixed by screwing or other non-impact means. The spacing, tie embedment and tie testing method and criteria has been upgraded. The durability requirements for ties have increased. Better seismic performance of veneers built since the 1990s is now expected. The NZBC also specifies seismic restraint of chimneys and hot water cylinders.

Major revisions to NZS 3604 occurred in 1990 and 1999. These resulted in a significant increase in bracing demand based on NZS 4203:1992. There were changes in piled foundation design and greater emphasis was placed on the connections between the foundations and the superstructure. Large decks must be braced and wings of a house must be separately braced. Roofs must be braced both within the roof plane and in the roof space depending on roof shape, area and weight. However, on the negative side, many modern houses have complex shapes, large rooms, large window and garage/sliding door openings and few load-bearing internal walls (as trussed-roof construction is now prevalent).

CONCLUSION

Houses compliant with NZS 3604, especially the more recent revisions, are expected to have greater earthquake resilience than they have shown in the past. Use of sheet wall bracing (rather than let-in timber braces), strong superstructure to foundation connections, strong sub-floor bracing will each improve the performance. Heavy chimneys are rarer and where used are better reinforced and well tied back to the house. Heavy roofs are also less common. Plasterboard ceilings with fully taped and stopped joints and particle board floors will provide better horizontal diaphragms than historic construction. The modern fixing method for masonry veneers is a major advance and will result in better performance, but veneer cracking near openings and corners is still likely, stepped diagonal cracks may occur and in some instances portions of the veneer will fall. Few roof tiles in modern houses are expected to dislodge as they are now fixed to the framing. Roof bracing provisions are expected to result in few examples of major roof damage.

Non-compliant houses, those with reduced strength from material degradation such as from leaks or floods, corroded tile ties, and those with bracing systems removed as part of renovations, will not fare as well.

Damage to house contents in a seismic event will still be high as there has been generally little effort to brace these items, despite efforts by the EQC to encourage home owners to secure the contents. Significant cracking of plasterboard wall linings can be expected in regions of high shaking, particularly in lower storeys of houses which have few internal walls and large exterior wall openings, such as garages and sliding doors. These walls may be left out-of-plumb. Damage near the junctions of wings of heavy buildings is expected. Large, complex shaped houses, especially those with large openings, are expected to have proportionally more damage. However, life risk due to shaking will be low. Houses built on/by steep slopes may be at risk from landslides. Where houses are sited in ground experiencing distortion and rupture there will still be severe structural damage. Modern water/sewerage and electrical/communication services are relatively flexible and are not expected to be damaged above the ground, but services below the ground may be vulnerable to large ground differential movements.

Houses built to pre-1978 standards will suffer the same damage as noted in past earthquakes. Chimneys will fall, heavy roofs of gable ended houses will be damaged, roof tiles with corroded wire fixings and broken mortar bond at ridge and hip capping tiles will dislodge often falling into roof spaces and perhaps penetrating these, lower storey walls will rack, masonry veneers will crack and fall and piles foundations collapse. Older style brittle clay pipe services, with fully cemented joints, are likely to be ruptured. Hot water cylinders, if not secured, will be dislodged and their valuable post earthquake water supply lost.

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