Changes to the Seismic Design of Houses in New Zealand

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ABSTRACT: Since the settlement of New Zealand there have been significant advances in the seismic design of houses. The influences of the country’s English heritage led to the construction of unreinforced masonry houses by the early settlers until it was discovered that earthquakes could demolish such structures with little effort. Subsequent to the 1848 Wellington earthquake, it was realised that timber framed construction had a better resilience than the traditional unreinforced masonry construction. Significant but incremental changes have subsequently been made to timber framed construction. The advent of NZS 3604 in 1978 introduced an engineering approach to ensure gravity, wind and earthquake loads could be appropriately resisted.

This paper traces the development of the house construction standards for earthquake resistance over the years to the present day and also comments on the types of damage that have occurred in significant earthquakes over that time and how these deficiencies have been addressed in the standards. A prediction is made of the expected performance of the current building stock in the event of a major earthquake.

1 INTRODUCTION

This paper seeks to trace the development of the New Zealand domestic dwelling through the ages from early settlement to the present day in terms of its earthquake resistance. Historic developments do not change and therefore the paper draws heavily on several existing publications that have traced the history of the development of design and construction standards and the changes that have occurred in house construction [Cooney, 1979 & NZNSEE, 1987].

2 HISTORY

Since early times in the settlement of New Zealand, New Zealanders have lived in dwellings with varying degrees of earthquake resistance. At the onset, earthquake resistance was not considered by the early settlers because many of them had come from countries where large earthquakes were not known to occur.

The first major test of houses constructed by European settlers occurred in 1848. Most of the houses of the 4800 residents of Wellington had been constructed of masonry although some were similar to the timber framed European houses of that time. As we would expect from our experience, the masonry houses fared badly. Much of the reconstruction was with timber framing.

Again, in 1855, Wellington was hit again by a severe earthquake. Unreinforced masonry houses were severely damaged but the timber framed ones sustained only light damage. It was reported that 80% of the chimneys were felled, because they were still constructed of unreinforced masonry.

It was another 75 odd years before the next significant earthquake, which hit the Buller region in 1929. It was reported [Grayland, 1957] that houses sustained severe damage, although the type of damage was not recorded.
New Zealand’s greatest earthquake disaster to date occurred on 3 February 1931 at Napier. While the devastation in Napier was enormous, it was reported that wooden structures fared remarkably well with next to no loss of life. Dixon [Dixon, 1931] noted that more than 90% had no damage other than from falling chimneys. When other failures did occur, they were due to:

- A lack of anchorage of the superstructure to the foundation, or
- Lack of bracing in either the subfloor framing or the lower storey walls in two or more storey buildings.

In 1942, the Wairarapa region was hit by two successive severe earthquakes, which caused significant damage in Wellington. The major issue was again falling chimneys (several thousand) but it was reported [Grayland, 1957] that houses were damaged over the lower part of the North Island.

A number of smaller earthquakes were reported to have caused damage in the next 20 or so years. It is interesting to note the comments of Adams et al [Adams et al, 1966], relating to the Seddon earthquake of April 1966. The report blamed the lack of bracing of heavy roofs, lack of adequate support for veneer walls, inadequately braced foundations, large window and other openings and irregular plan shape for the observed damage.

The Inangahua earthquake in 1968 tested both old and new houses. The older houses were of substandard construction in terms of the NZ Standard Building Bylaws, although the Government owned houses were of a better quality. Lack of attachment between the superstructure and the foundations was again a major cause of damage.

The most recent earthquake to cause widespread damage was the 1987 Edgecumbe event, which was a moderate earthquake (less than the design level earthquake). Being more recent, the observations made after this earthquake were more extensive [NZNSEE, 1987].

Two-thirds of the Edgecumbe area houses were built in the 1950-1979 era when awareness of earthquake resistant construction was not high and appropriate codes of practice were not completely adequate. Several hundred houses experienced minor structural damage, but less than 50 buildings were substantially structurally damaged in a total of approximately 8000 houses.

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 with no connection between the two except friction. In these instances, the slabs moved up to 300 mm relative to the foundation walls and caused significant damage. Such construction is not permitted by the current NZS 3604 (see later discussion).

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.

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

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.

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.

To summarise, the major damage types that had persistently reoccurred over the history of NZ house construction prior to 1978 were:

- Inadequate lateral load resistance between the ground and the ground floor, particularly where piles or timber stud framing were used.
- Inadequate bracing in lower storey walls, particularly when heavy roof materials were used.
- Inadequate roof bracing when clay or concrete tiles were used, and inadequate fixing of the tiles.
- Inadequate strength of chimneys.

3 REGULATIONS

3.1 The Beginning

Before 1900, it appeared that timber framed house construction essentially developed based on experience and good trade practice. While some local bodies had some building bylaws for houses in the early 1900’s, these did not relate to structural issues.

The first generally adopted “regulations” came out of a conference of representatives of local bodies, architects, engineers, builders, timber merchants and sawmillers that was held in 1924. The outcome of the conference was the document titled “Recommended Minimum Requirements for Safe and Economical Construction of Small Wooden Frame Buildings” (Government Print, 1924), although “small” extended to 3 storeys in height. There was general adoption of these recommendations.

However, it seemed that the memory of the 1855 earthquake was distant because there was little consideration given to the bracing of piled foundations. This may have been because the buildings hit by the 1855 event were mainly on flat ground and therefore supported on relatively low stubby blocks.

With respect to walls, there were prescriptive recommendations for timber diagonal braces at exterior corners unless the cladding was laid diagonally. “Other measures taken to secure rigidity as may be necessary” were also recommended.

Interestingly, in the conference conclusions, it was recommended that all roof tiles be individually secured so that they could not slip in an earthquake.

Dixon [Dixon, 1931] prepared a very comprehensive article containing recommendations for the design and construction of light wooden buildings for resisting earthquakes, fire and tornadoes after the earthquake in the Buller region in 1929. The article was first published shortly after the 1931 Napier earthquake but so thorough was it that little amendment was required as a result of the 1931 earthquake. Cooney [Cooney, 1979] notes the document was the most comprehensive produced in New Zealand on design for earthquake resistance and laments that many were either omitted from building bylaws or not adhered to. He notes that the first NZS 3604 [SANZ, 1978] provided for most of Dixon’s recommendations, 47 years later.

3.2 The First Code (NZS 95)

As a result of the Napier earthquake, the Government set up a building regulations committee “to investigate the whole question of earthquake resistant design and construction”. A model building bylaw was drafted and this was completed by the newly formed Standards Institution. The original model bylaw was published in December, 1935 as NZS 95 [NZSI, 1935]. However, the preface to the bylaw stated that “Sections I-X now presented, do not cover welded structures nor timber buildings”. Indeed it took until 1944 before Part IX Light Timber Construction was published.

Part IX had significant omissions around the bracing of timber piles, although its treatment of wall
bracing appeared to be quite adequate. Requirements for roof bracing were more qualitative than quantitative and there was no recognition of the effect of the added mass of concrete of clay roof tiles over a metal or fabric roof on the bracing requirements in the structure below.

In the meantime, the 1942 Wairarapa earthquake had occurred, with significant chimney damage. The original 1935 document called for reinforcement in the chimney flues of not less than four 5/8” reinforcing bars at the corners of the flue and No 8 wire horizontal ties and it also required 1” boarding around all chimneys, over a radius equal to the height of the chimney above the roof as roof protection in the event of an earthquake. In 1951 a new Part XII (Chimneys) of NZS 95 was published which superseded the 1935 provisions. New requirements were included for the tying of chimneys to the timber structure at discrete points or otherwise be designed as self-supporting. An amendment was issued in 1959 that deleted the need to include the surrounding boarding. Presumably this was because it was thought that the chimneys would no longer be expected to collapse since they were tied and reinforced.

In parallel to some extent with the development of NZS 95, the State Housing specification was developed and amended. At its first issue in 1936, it required continuous reinforced concrete perimeter foundation walls. The reasons were not for earthquake resistance, but rather to prevent termite infestation and to cater for the expansive clays in Auckland. However, the practice was accidentally good for earthquake resistance. The 1939 issue appeared to be the best prepared at the time as far as earthquake resisting provisions were concerned. Its biggest drawback was the lack of specific detail, meaning that the construction only had to be of good trade practice. The 1946 issue probably presented the biggest backward step in the earthquake resistant design of timber houses. Since termites were no longer seen as an issue, the continuous perimeter foundation requirement was removed in favour of piles. One further backward step was a relaxation in the requirement for securing roof tiles to every alternate tile.

In 1964 NZS 95 was replaced with NZSS 1900 [SANZ, 1964], although the requirements were essentially no different. Two notable changes were the deletion of the bracing requirements for roof framing and trusses and the accidental removal of the need for all walings on outer pile rows, which would have provided a degree of bracing to the piles, because of the accidental omission of “outer” from one clause.

3.3 NZS 3604, Light Timber Framed Buildings not requiring specific design

The first publication of NZS 3604, Code of practice for Light Timber framed Buildings not requiring specific design, occurred in 1978 [SANZ, 1978], in recognition of the fact that it was no longer possible to rely on good trade practice and experience gained from previous earthquakes alone to formulate house construction standards.

The introduction of NZS 3604 in 1978 was a major step forward as it was based on sound engineering principles and calculations. For the first time, the standard for light timber framed construction was based on the loadings standard, NZS 4203, first published in 1976 [SANZ, 1976], but with account taken of redundancies, additional strength and other favourable factors known to be present in such structures. The standard aimed at minimising damage to houses in major earthquakes to ensure they were habitable after the design earthquake event. Wall claddings were divided into three weight categories and the roof covering was divided into two categories covering metal and fabric roofing or concrete and clay tiles. Bracing demand depended on construction weights. The country was split into three seismic zones, in recognition of the geographic variability of seismic risk.

Most significantly, large quantities of “acceptable” construction details were included. 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. Specifically detailed braced piles, cantilevered piles with substantial footings and driven timber piles, each with assigned strength based on tests, were provided. Proprietary or bolted connections between pile and bearer and from bearers to joists were required to have an even greater proven strength. Thus better seismic performance was expected. NZS 3604:1978 only allowed single storey buildings to be founded on piles, but subsequent revisions extended this to two storeys.
This standard has continued to be the “bible” for light timber framed construction till the present day, having been reviewed and revised in 1984, 1990 and 1999. Both the 1990 and sections 1 to 16 of the 1999 versions have been cited in the New Zealand Building Code (NZBC) as an “Acceptable Solution” to the NZBC.

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. At each re-issue, efforts have been made to incorporate suggestions for ease of use of the document and provisions have been added to accommodate more modern construction systems.

Bracing provisions were collected together in one section in the 1999 edition of the standard and, with one or two minor exceptions, the generic bracing systems were removed in favour of the use of published bracing ratings for proprietary systems provided by the manufacturers. A greater recognition of the importance of a continuous load path to the foundation has been included in the form of appropriate minimum connection details between elements from the roof to the foundation.

3.4 NZS 4229, Concrete Masonry Buildings not requiring specific design

The first New Zealand standard for non-specific design of masonry houses was published in 1986 (NZS 4229 [SANZ, 1986]). This standard replaced NZS 1900:Chapter 6.2:1964, which contained provisions for the design of small reinforced concrete masonry houses. In the earlier standard, the maximum gross floor area was limited to 3000 sq ft; houses could have a maximum of two storeys; maximum floor or roof spans were limited to 20 feet; and floors and roofs had to be constructed of light timber. There was no specific mention of design for earthquake resistance, but by following the standard, a degree of seismic resistance could be expected.

Like NZS 3604, NZS 4229 took account of the seismic zoning of New Zealand with design tables reflecting the differences. A range of non-specific design options was presented in the standard and there were similar limits placed on floor plan sizes, number of storeys, etc, to the predecessor standard. The user was provided with a wide selection of details for construction. Diaphragms were only able to be provided in light timber framing with sheet claddings. Tables of minimum bracing requirements were given for the various building configurations, within the above-mentioned limits, and bracing ratings were tabulated for the various wall thicknesses and grout fill condition. It was a relatively simple matter to determine the minimum bracing required and then work out the required length of walls to resist this. Although only contained in a commentary clause, partially filled walls were not allowed to be used for lateral load resistance in seismic zone A.

In 1999, NZS 4229 was revised and several changes were included in the revision, mainly as a result of the publication of the Loadings Standard, NZS 4203:1992 [SNZ, 1992]. The revision also drew on the results of recent research on reinforced masonry construction. The outcome of the changes was a simpler document than its predecessor, more aligned with the format of NZS 3604, with increased spans for bond beams, the use of concrete floor diaphragms (although these had to be the subject of specific design) and a relaxation allowing walls in earthquake zone A to be partially filled.

3.5 Performance of NZS 3604 Structures in the 1987 Edgecumbe earthquake

The 1987 Edgecumbe earthquake is the largest earthquake to strike New Zealand since the first introduction of NZS 3604. An NZNSEE reconnaissance team visited the Edgecumbe area shortly after the event and their findings are reported in the NZNSEE Bulletin [NZNSEE, 1987]. The performance of light timber framed structures built in accordance with NZS 3604 was very encouraging. None of those which complied with the 1978 NZS 3604 standard were damaged by the shaking, with the exception of those on concrete slabs. In these cases, a weakness in the NZS 3604 provisions was the allowance of a slab of a single storey structure to be cast over the foundation wall with no mechanical connection. This was remedied in the 1990 issue of the standard.
Masonry veneers did not perform well in the Edgecumbe earthquake. Many of these veneers were on older structures and the failures were due to corroded ties, widely spaced ties or ties not properly attached to the wall framing. However, there were some veneer failures on the more modern houses as well.

In the 1990’s BRANZ investigated the performance of brick veneer walls under face loading and in this process determined that the nailing of the ties to the timber framing was causing the ties placed earlier in the wet mortar mix to de-bond from the mortar. Thus, there was no connection present and when excited by significant lateral force as in an earthquake, the veneer was free to fall away from the framing. As a consequence of this finding, the current version of NZS 3604 requires that the ties be placed in accordance with NZS 4210 [SNZ, 2001] and this in turn refers to AS/NZS 2699.1:2000 [SNZ, 2000], which requires the ties to be screwed or fixed in a manner that does not cause the studs to vibrate as the tie is fixed. Interestingly, the 2001 issue of NZS 4210 is not yet cited in the NZBC.

Chimneys faired poorly in the Edgecumbe earthquake, although many had been incorrectly constructed (there was a failure to meet the bylaw requirement that the chimney be tied to the house). Few modern houses have concrete or masonry chimneys, and these must now be constructed according to the NZBC Acceptable Solutions [BIA, 1992] and are expected to perform better. The 1992 Amendment to the 1990 edition of NZS 3604 referred the user to the NZBC for extra house bracing requirements when a heavy chimney was present. The 1999 version of the standard also referred to the NZBC Acceptable Solution, which was further amended in 2001. Existing chimneys in older houses will remain vulnerable, although many have been strengthened or “topped” on the owner’s initiative.

Only one concrete block masonry wall was observed to have significant structural damage in the Edgecumbe earthquake [NZNSEE, 1987] and it was reported that the walls were either unreinforced or poorly reinforced. There have been no significant earthquakes to test the adequacy of houses designed in accordance with NZS 4229.

4 MODERN DEVELOPMENTS IN TIMBER FRAMED CONSTRUCTION

While NZS 3604 has developed in its detail and application over the years since it was first introduced, so have the styles of houses. It is common for houses to be built in the present construction climate that stretch the requirements of NZS 3604 to the limit. Such changes include:

- Large open plan rooms, limiting the available walls for bracing
- Large window and door openings reducing the stiffness and strength of exterior walls
- Complicated plan shapes with variable earthquake responses from adjacent wings of the structure likely to cause damage at intersections, and
- Split level floors with an intermediate level in one part of the house attached midway between the two floors in the remainder of the house.

While few if any modern houses are expected to collapse in future major earthquakes due to ground shaking alone, there is still likely to be a significant amount of non-structural damage that will require repair.

5 CONCLUSIONS

Whilst houses perhaps appear to the uninformed viewer to be not significantly different from those built by our forebears, except for changes in house size, omission of chimneys, introduction of different window and cladding styles, within the structural system there have been significant advancements made.

It must be remembered that none of the New Zealand housing stock has been subjected to the design level earthquake. Nevertheless, 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 and 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. 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, are not likely to 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 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.

Many 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 unbraced pile foundations will collapse.

REFERENCES:


Grayland E C 1957. New Zealand Disasters. Published by Reed, Wellington.


