Retrofitting House Foundations to Resist Earthquakes; Justification, Benefits and Costs

G.C. Thomas[1] and J.D. Irvine[2]

[1] *Senior Lecturer, School of Architecture, Victoria University of Wellington, Wellington, New Zealand*
[2] *M.Arch Graduate, School of Architecture, Victoria University of Wellington, Wellington, New Zealand*
Email:geoff.thomas@vuw.ac.nz

ABSTRACT :

Most houses in New Zealand are constructed of light timber framing, with good earthquake resistance. Damage during past earthquakes was due to a lack of foundation bracing and inadequate connections within and to the foundations. This study showed that 39%, of a sample of houses in Wellington had inadequate sub-floor bracing, and 76% had some form of fixing deficiency, ranging from minor degradation to incorrect or non-existent fixings. The cost of remedies to upgrade foundation bracing, including labour, ranged between about NZ$15 per m² and NZ$50 per m² of dwelling floor area (US$10-40/$m^2$). The total cost to upgrade all house foundations in Wellington City is over NZ$290 million (US$175 million). The estimated cost of damage to residential dwellings was calculated for a maximum credible earthquake. Damage without foundation retrofitting was estimated at NZ$3.8 billion and $1.8 billion after retrofitting (US$2.8 and $1.3 billion respectively). The overall benefit: cost ratio for retro-fitting foundation is therefore about 4. Apart from reducing the direct cost of repair and replacement following an earthquake, limiting damage will reduce casualties, reduce the demand for emergency accommodation and other services and hasten disaster recovery. When including the costs of casualties, emergency accommodation and other indirect costs, the benefit: cost ratio increased to about 13.

KEYWORDS: houses, light timber frame, foundations, upgrading, cost: benefit

1. INTRODUCTION

New Zealand's housing stock consists mainly of light timber frame dwellings. These perform well in earthquakes with wall linings and claddings providing a high degree of bracing. On average in New Zealand we experience a large earthquake (greater than Magnitude 7) every ten years. The two first recorded earthquakes occurred in 1848 and 1855 in the Wairarapa region (Slade, 1979). At the time residential dwellings were influenced in design and construction by European building practices, for example using unreinforced stone masonry. Consequently, dwellings suffered major damage, forcing colonialists to consider alternative building practices and materials. The destruction witnessed after the 1931 Napier earthquake (Dixon, 1931), suggested that building practices had not evolved uniformly due to the lack of enforceable construction by-laws prompting changes to building legislation. Damage from later earthquakes such as Seddon, Murchison and Inangahua in the mid 1960's, highlighted significant gaps in foundation building practices (Adams et al., 1970). These events did little to enforce better bracing standards in formal legislation. The 1987 Edgecumbe earthquake proved that modern construction methods had generally improved since 1931, with many dwellings receiving negligible damage to the superstructure and many dwellings avoiding collapse, but foundation bracing and connections were a weak point (BRANZ, 2003). Overseas experience is similar, with destruction in the 1971 San Fernando (Jennings & Housner, 1971) and 1995 Kobe earthquakes (Park, 1995) further reinforced that adherence to modern building standards greatly increased the chances of a dwelling surviving a large earthquake. (BRANZ, 2003).

1.1 History of sub-floor construction Standards

In 1924, Circular 14, on light timber construction, was developed and listed recommendations relating to the sizing of foundation piers and concrete walls and the sizing of timber members in relation to dwelling height and floor loading (NZSFS, 1924). Following the 1931 Napier earthquake, in an attempt to improve the standard of dwelling construction N.Z.S.95 (SANZ, 1944) was released. N.Z.S.95 was limited to prescribing reinforcement requirements for concrete piles and walls and included new foundation systems such as jack-studding. Foundation bracing and construction was enhanced with the introduction of the State House Specifications in 1936 (ten Broeke, 1979). However further amendments to the Specification reverted to requiring piled foundations under exterior walls in order to reduce termite infestation, reducing the bracing capacity of dwellings significantly. A new Standard was developed in 1964 (SANZ, 1964) superseding N.Z.S.95, however, it was uncertain whether sub-floor bracing was actually required or not. In 1978, the Light Timber Frame design standard NZS3604 (SANZ, 1978), based more on engineering principles, rather than "good trade practice" was introduced. The 1978 standard specifies a high standard of foundations and associated connections suitable for expected earthquake loads.

1.2 The past strength of dwellings

In the 1929 Murchison earthquake, timber dwellings fell easily from their piled foundations, whereas dwellings built on concrete foundations resisted lateral loading and maintained the structural integrity with negligible damage (Henderson, 1937). Following, the Gisbourne earthquake in 1966, the movement of repiled dwellings from their foundations showed a lack of bracing and fixings to the sub-floor (Hamilton et al., 1969). Dwellings affected in the Seddon earthquake reacted badly due to poor soil conditions and the asymmetry of bracing systems (Adams et al., 1970). In the Inangahua earthquake, piles overturned and jack studding collapsed due to the lack of bracing, particularly on sloping sites (Shepherd et al., 1970). Plan irregularity resulted in torsional racking at the extremities of dwellings in the Edgecumbe earthquake (Pender & Robertson, 1987). The connection of R6 steel reinforcing bars between slab-on-ground and foundation wall failed to prevent the slab moving relative to the foundations. In overseas earthquakes, such as the 1971 San Fernando earthquake many split level dwellings and other asymmetric configurations, collapsed due to differential movement of the superstructure (Jennings & Housner, 1971).

2 ASSESSING FOUNDATION ADEQUACY

The New Zealand Standard, NZS3604:1999 (SNZ, 1999) sets out the minimum requirements for foundations, including the seismic bracing potential, the connections between the sub-floor framing members and the overall general condition and durability requirements of a foundation. This standard is used in this study to determine whether a foundation is seismically adequate. Bracing requirements depend on the seismicity of the area, other geographical, architectural and topographical factors.

The sub-floor must be able to transfer the induced lateral forces in an earthquake from the superstructure to the ground. Although, not specifically included in NZS3604, lateral bracing from anchors such as chimney bases, additional concrete slabs and concrete porches was assessed for this study. Similarly the lateral resistance of ordinary (shallow) piles is included although this is also ignored by NZS3604.

The overall adequacy of connections to transfer induced loads through a foundation rely on the integration of material interfaces, quality of material, the configuration of the fixings and the construction methods used to connect the different framing members. Connections must be durable otherwise they physically degrade and hence lose strength. The effectiveness of a connection depends on the material used and the friction coefficient between different material members. During earthquake shaking, friction maybe reduced or non-existent during momentary periods of vertical accelerations.

The sub-floor requires sufficient ventilation. The ventilation requirements in the current Standard have not significantly changed since the requirements in the first recommendations in 1924. A minimum of 150mm ground clearance is required to maintain ventilation and to limit moisture movement from the ground to the structure and connections. A regular bracing layout is also required to maximise its ability to resist seismic loading.

3 STUDY AND ASSESSMENT OF EXISTING HOUSE FOUNDATIONS

A selected random sample of 80 dwellings was chosen. The selection was biased according to the age of the dwellings as shown in Figure 1. Hence a larger proportion of the sample is from decades when more dwellings were built and vice versa. A site visit was conducted for each dwelling with permission from the owner. In each case, the bracing, connections and general condition of the foundation was assessed against the requirements of NZS3604:1999 in light of the site, age and weight of the dwelling. The study is described in more detail in Irvine and Thomas (2008) and Irvine (2007).

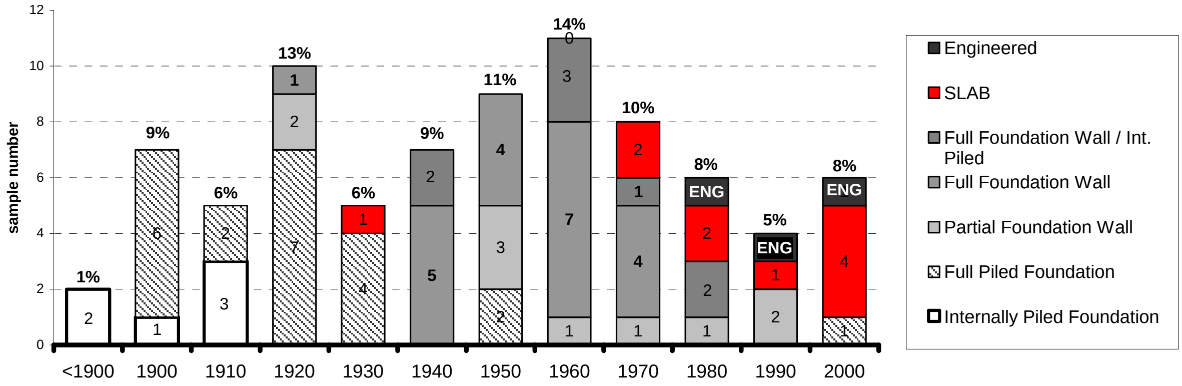

Figure 1. Foundation type for age of dwelling, percentages of the total sample.

3.1 *Were the dwellings Adequate?*

Overall, an average of 49% of foundations, were below acceptable requirements for all key elements of foundation adequacy. As shown in Figure 2, 16% of sample dwellings had little or no bracing and a further 33% used non-prescribed methods such as chimney bases and concrete porches, to provide bracing potential. The majority of houses that failed to meet the required standards had full piled foundations that were commonly found in houses prior to the 1940's. The connections providing the load paths to the bracing members from the floor were inadequate in at least one location in 32% of dwellings. Weak connections in repiled dwellings accounted for a large proportion of the sample built prior to 1940, usually occurring between the ordinary pile to bearer connections.

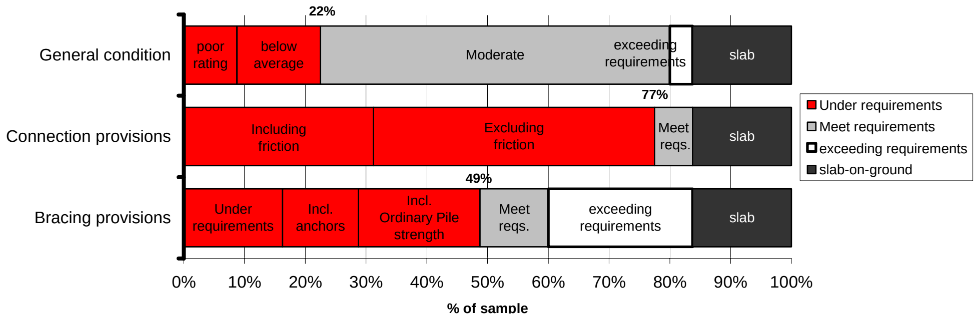

Figure 2 Overall failure for key foundation elements

The poorest connection observed in all dwellings was bearer to bearer end connections over piles. Most of the sample (69%) failed to meet the minimum bearing distance and the nail plate connection requirement, which could result in bearer ends separating and falling off the piles. The overall general condition of foundations surveyed was moderate and most consistent in dwellings constructed between 1940 and 1960. However, some newer dwellings from the 1970's and 1990's showed signs of premature degradation. Serious ventilation issues were seen in 45% of dwellings and 54% of connections in dwellings showed rust or oxidization compromising their strength.

Although 49% of dwellings failed to meet the prescribed bracing requirements, some of those dwellings relied (unintentionally) on non-prescribed bracing anchors such as concrete porches and chimney bases. Twenty percent of the total sample relied entirely on ordinary piles fort heir lateral load resistance, usually in pre 1940's piled dwellings.

Overall, an average of 13% of connections providing load paths to the bracing members was inadequate. Excluding the effects of friction, the number of connections failing increases by 24% for the Joist to Bearer connections and 65% for connections from Bearers or Plates to the concrete Foundation wall. The Ordinary pile to Bearer connection was inadequate in 56% of the sample, so about half of connections were inadequate. Older dwellings had connections that are weaker than those prescribed by modern Standards.

3.2 Configuration issues

The general conditions observed onsite correlated well with the 2005 BRANZ House Condition Survey (Clark et al., 2005), however more deficiencies such as excessive levelling wedges in repiled and re-levelled dwellings were observed in the sample. Figure 3 shows the percentage of the sample with general condition deficiencies. A number of dwellings, particularly older dwellings had a combination of these deficiencies. Dwellings that had been renovated often had full or half split-level additions usually made to the lower floor by excavating the foundations, and almost half of these dwellings had differing foundations likely to cause serious configuration issues under lateral loading.

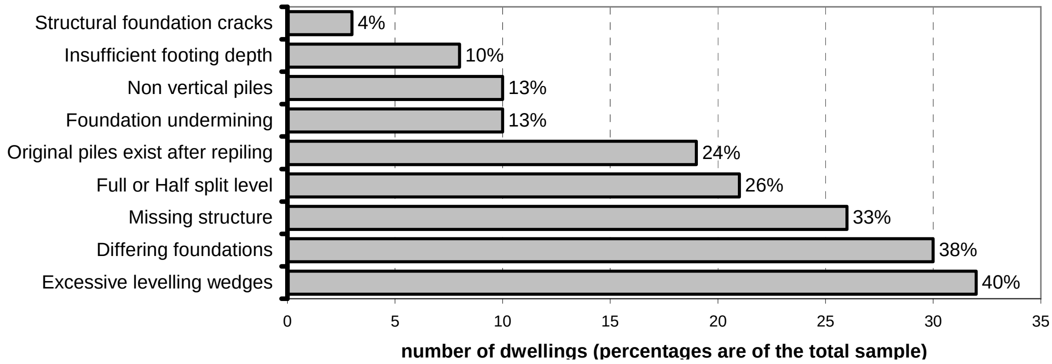

Figure 3. General conditions pertaining to foundation durability

3.3 Discussion

Overall 39% of dwellings were shown to be inadequate to resist the expected earthquake loads. Slab-on-ground construction or engineered foundations that were assumed adequate was 16% of the sample. Slabs built prior to 1990 may have non-visible reinforcing deficiencies or inadequate connections to the framing. A significant number of fixings failed to comply with NZS3604:1999, however, they would still adequately transfer loads through to the bracing and other connections. Just over 25% of the sample showed adequate fixing capacity under conditions where friction cannot be expected. 18% of the sample had excellent overall general condition, usually seen in newer dwellings and 58% had only moderate condition issues.

As expected, older dwellings had a lower bracing capacity and were more likely to have deficient connections compared with NZS3604 requirements. However, foundations in some modern dwellings around the 1970's, 1980's and 1990's were in extremely poor general condition and had limited connection capacity as a result of fixing degradation. Dwellings with heavier claddings are more likely to fail due to higher lateral loads. These heavier dwellings were the most evident around the 1940's and peaked around the 1980's. To understand the impact of remedying these dwellings, we must first understand the overall cost and benefit of the remedial action and the potential risk, and then we can estimate the economic cost of remedial action to the individual and the direct economic savings for society.

4 DESCRIPTION OF THE "LOSS MODELLER"

The economic costs of an earthquake hitting Wellington, was calculated using the Geological and Nuclear Sciences "Earthquake Loss Modeller" (Cousins, 2005). The loss modeller output displays the number of casualties, total economic loss to residential dwellings and commercial properties for any given city. For the purposes of this study, the results were limited to the Wellington City suburban limits, as described in Wellington City Council District plan maps. The damage costs described do not include Porirua or the Hutt Valley or any of the wider affected area in New Zealand. The modeller uses Damage Ratios and values are assumed "reasonable probabilistic fits to Earthquake Commission (EQC) losses for period 1990 to 2003". Remedial measures are applied to the foundation to ensure that the dwelling may remain habitable following an earthquake. The foundation behaviour should remain predictable and failure mechanisms should be capable of dissipating energy through ductile yielding (SANZ, 1992). Without remedial measures and assuming a predicted earthquake of Magnitude 7.2 at a depth of 8km, the Wellington earthquake is likely to result in the total collapse of over 440 timber dwellings and cause serious damage to over 18,220. This is expected to result in the direct economic loss of NZ$3.8B dollars in the timber residential sector claiming 930 lives and injuring 1290 people if it occurs during the daytime.

5 REMEDIAL MEASURES

The study identified key areas where foundations were inadequate and to which remedial measures could be applied to increase the likelihood of a dwelling remaining habitable following an earthquake. Applied remedial measures were sourced from NZS3604:1999 (the Braced pile and Anchor pile systems) and the concrete Infill Wall solution and Sheet Bracing Applications, both set out in the BRANZ publication, “Strengthening Houses against Earthquake: a Handbook of Remedial Measures” (Cooney, 1982). The application of bracing methods was initially applied on the basis that new systems should complement existing systems. Also, site factors such as height of dwelling from cleared ground level and the materiality of existing sub-floor structures were considered for the purposes of achieving the most cost-effective solution. Remedial measure costing included remedying connections and existing general conditions that could affect the future strength of the foundation.

The cost of upgrading dwellings was based on values obtained by quantity surveying methods for different remedial bracing applications. Table 1 provides a break down of the applied remedial measures for the foundation, stating the average costs per square metre for all remedial applications. For an average Wellington dwelling (139m^2) a Piled foundation will cost $974 to apply remedial sheet bracing. Other foundation systems rate higher at around $2800 to remedy the bracing in a Partial foundation wall.

Table 1. The remedial measures and costs applied to each foundation type (NZ$).

Foundation type	Existing bracing system	% Sample requiring bracing	Remedial solution	Average remedy per dwelling	Average cost of improvement per square metre of dwelling			TOTAL
					fixings	durability/ condition	bracing	
Internal Piled	Pile	83%	Anchor pile	10 piles	$4.17	$147.00	$21.42	**$172.59**
Full Piled	Pile	63%	Sheet	7m sheeting	$5.10	$96.70	$7.01	**$108.81**
	Pile / sheet	17%	Anchor pile	10 piles	~	~	$13.80	**$115.60**
Partial Wall	Pile / Conc. Wall	50%	Sheet	5m sheeting	$5.30	$52.50	$20.16	**$77.96**
Full Wall	Conc. Wall	10%	Infill wall	4m infill	$6.54	$26.30	$41.40	**$74.24**
Full Wall / Internal piles	Conc. Wall	0%	n/a	~	$5.35	$26.50	~	**$31.85**
SLAB	n/a	0%	n/a	~	$0	$0	~	**$0.00**
ENG	varies	0%	n/a	~	$0	$0	~	**$0.00**

6 INDIRECT COSTS AND BENEFITS

Based on the Loss Modeller estimate of the number of dwellings collapsed with and without remedial measures for the scenario earthquake, Table 2 forecasts lower casualty rates and fewer evacuees requiring emergency accommodation after their dwellings have collapsed or been seriously damaged. The calculation and assumptions inherent in assessing indirect costs are described in more detail elsewhere (Thomas and Irvine 2008).

Table 2 Number of Casualties and Evacuees Before and after Applying Remedial Measures for a Night time Earthquake Scenario, from Loss Modeller estimates (NZ$)

	Fatalities	**Serious Injuries**	**Moderate Injuries**	**Evacuees**
Before remedial measures	120	85	450	21500
After remedial measures	24	64	339	8000

With foundation remedies, from Table 2, the number of immediate evacuees requiring temporary accommodation re-housing reduces from about 21,500 to 8,000. This is made up of the number of homeless waiting an average of 2 year for re-housing after their homes have been destroyed, which reduces from about 3700 to 900 and the number waiting an average of 3 months for repairs to homes damaged so badly as to be uninhabitable dropping from 17,700 to 7100. The costs of emergency accommodation drops NZ$91M compared to the damage to dwellings cost of NZ$1659M. The increase in costs is not therefore significant; however it is likely that providing such a level of emergency accommodation would prove impossible. Another benefit of upgrading foundations is a reduction in the number of casualties, particularly for a night-time earthquake when occupants are at home. Indirect costs of casualties such as loss of working hours have not been included. It should be noted that the cost per life saved is NZ$3.4M, the supposed average economic value of a life. Please note that this value is the net average economic benefit of one life and is not intended to “value” a life. Such a dollar value can in no way take into account the societal and other implications of a premature death.

The estimates of repair and replacement costs for dwellings exclude damage to contents. Estimates suggest that the contents damage will cost around 50% (Hopkins, 1995), and up to around 2/3 of the dwelling damage costs (Birss 1985). Post disaster inflation is the norm due to shortages of material and labour and has been assumed to be 30% for this study (Wellington Earthquake Lifelines Group 1995; Davey and Shephard 1995). This 30% inflation is based on conservative past estimates, however for short periods following a disaster, inflation has been known to be as high as 75% (Walker 1995).

7 OVERALL COSTS AND BENEFITS

The affect on both direct and indirect costs of remedying foundations is summarised in Table 3.

Table 3. The total costs, including indirect and other costs

	Cost saving ($M)	**Remedial Costs ($M)**	**Benefit /cost ratio**
Dwelling Only	1659	291	5.7
Dwelling and indirect	1994	291	6.9
Dwelling, indirect costs and contents	3884	291	13
Dwelling, 30% inflation, indirect and contents	**5018**	**291**	**17**

Including contents and building cost inflation more than trebles the savings with a corresponding improvement in the benefit/cost ratio. The results above suggest that dwellings require, on average, reasonable expenditure to achieve the current standards requirements. The very high benefit: cost ratio suggests that it is economically justifiable to remedy foundation defects in dwellings, even if more conservative assumptions on the reduction in damage had been made. Assuming the likelihood of piled dwelling collapse (over 70% probability), and applying information contained in the House Condition Survey, the cost of upgrading certain foundation types may be less than the total average annual expenditure currently spent on maintaining dwellings (Clark et al., 2005).

Although a number of studies has been carried out on the probability of the maximum credible earthquake on the Wellington fault, the precise level of risk is uncertain. It is also very difficult to predict what the life of a domestic dwelling may be. If a 50 year dwelling life is assumed, and the annual risk of an earthquake is about 1%. Table 4 shows the benefit/cost ratios for a 0.5%, 1.0% and 2.0% annual probability of such an earthquake.

Table 4. Benefit / Cost ration for varying earthquake risk.

Annual probability of an earthquake.	**0.5%**	**1.0%**	**2.0%**
Dwelling Only	1.4	2.9	5.7
Dwelling and indirect	1.7	3.5	6.9
Dwelling, indirect costs and contents	3.3	6.5	13
Dwelling, 30% inflation, indirect and contents	**4.25**	**8.5**	**17**

8 CONCLUSIONS

Successful implementation and moderately good compliance with foundation construction standards significantly reduces the likelihood of collapse and serious damage to timber framed dwellings. Piled dwellings assumed “at risk”, cost less than 5% of the average dwelling reconstruction bill, not including inflated labour and material costs. Remedying dwellings with piled foundations only could potentially save over NZ$1B in post earthquake repairs. A crude analysis of other costs results in much higher benefit / cost with other savings being more than twice that of direct repair and replacement costs. Of perhaps more significance is the likely difficulty or impossibility of providing sufficient emergency accommodation.

Unfortunately this value of upgrading may not be seen as cost-effective by the homeowner, as the EQC and personal insurance cover dwelling reinstatement. At present, no real incentive exists for upgrading residential foundations. Although the exact figures could be debated the significant reduction in fatalities for a night time earthquake if foundations were upgraded is a benefit that significantly outweighs any economic saving.

ACKNOWLEDGEMENTS:

The Earthquake Commission and New Zealand Fire Service Commission for funding this project.
Building Research Association of New Zealand (Graeme Beattie and Stuart Thurston) for technical advice.
GNS Science (Jim Cousins) for technical advice and use of the earthquake loss modeller.
My colleague Assoc. Prof. Andrew Charleson for reviewing this paper.

REFERENCES

Adams, R. D., Lensen, G. J., Strachan. C. M. & Laws, H. R. (1970). Seddon Earthquake, New Zealand, April 1966. *DSIR, Wellington*, Bulletin 199.

Birss, G. R. (1985). Methodology for the Assessment of the Damage Cost resulting from a Large Earthquake in the Vicinity of Wellington, *Bulletin of the New Zealand National Society for Earthquake Engineering* **18(3)**: pp. 214-223.

BRANZ (2003). Lessons from the 1987 Edgecumbe earthquake. *BRANZ Bulletin 444*.

Clark, S., Jones, M. & Page, I. C. (2005). BRANZ Study Report 2005 House Condition Survey. *BRANZ Study Report 142*. Wellington, BRANZ.

Cooney, R. C. (1982). Strengthening houses against earthquake: a handbook of remedial measures. *BRANZ Technical Paper 37*.

Cousins, J. (2005). Earthquake Loss Modeller. 14 Sep 2005 ed. Wellington, Institute of Geological and Nuclear Sciences Limited.

Davey, R. A. & Shephard, R. B. (1995). *Earthquake risk assessment study : study area 1, Wellington City,* Works Consultancy Services, Wellington.

Dixon, C. E. (1931). Earthquake proves superiority of wooden buildings, *New Zealand National Review***,** p.45-48.

Hamilton, R. M., Lensen, G. J., Skinner, R. I., Hall, O. J., Andrews, A. L., Strachan, C. M. & Glogau, O. A. (1969) Gisbourne earthquake, New Zealand, March 1966, *DSIR, Wellington,* Bulletin 194.

Henderson, J. (1937). The West Nelson earthquakes of 1929 : with notes on the geological structure of West Nelson Government Printer, Wellington.

Hopkins, D. C. (1995). Assessment of Resources for Reinstatement Proceedings of *Wellington after the 'Quake: The Challenge of Rebuilding Cities*, Wellington.

Irvine, J. D. (2007), Foundation and Sub-floor Bracing Analysis: the Cost-Benefit of Upgrading. M.Arch Thesis, Victoria University of Wellington, Wellington.

Irvine, J. D and Thomas, G.C. (2008), Adequacy of existing House Foundations to resist earthquakes: the Cost-befit of Upgrading, *Bulletin of the New Zealand Society for Earthquake Engineering,* **41(1)**.

Jennings, P. C. & Housner, G. W. (1971). Engineering features of the San Fernando Earthquake, February 9, 1971. Pasadena, California. *California Institute of Technology, Earthquake Engineering Research,* Laboratory Report 71-02.

New Zealand State Forest Service, (NZSFS). (1924). Building conference relating to the use of Timber in building construction. IN NZSFS (Ed.), Government Printer, Wellington.

Park, R. (1995) The Great Hanshin earthquake, *Wellington after the 'Quake : The Challenge of Rebuilding Cities.* Earthquake Commission and Centre for Advanced Engineering, Wellington.

Pender, M. J. & Robertson, T. W. (1987) Edgecumbe Earthquake: Reconnaissance Report. *Bulletin of the National Society for Earthquake Engineering,* **20(3)**.

Shepherd, R., Bryant, A. H. & Carr, A. J. (1970). The 1968 Inangahua earthquake, *Canterbury Engineering Journal* **No.1,** pp. 2-86.

Slade, G. P. (1979) Domestic Detailing for earthquakes - past and present practice, *School of Architecture.* Victoria University of Wellington,. Wellington.

Standards Association of New Zealand, (SANZ), (1944). **N.Z.S.95** New Zealand Standard Code of Building Bylaws. Government Printer, Wellington.

Standards Association of New Zealand, (SANZ), (1964). **NZSS 1900 : Chapter 6.1**: Residential buildings, SANZ, Wellington.

Standards Association of New Zealand, (SANZ), (1978). *Code of Practice for light timber frame buildings not requiring specific design*, **NZS 3604:1978**. SANZ, Wellington

Standards Association of New Zealand, (SANZ), (1992). Code of Practice for general structural design and design loadings for buildings **NZS 4203:1992**, SANZ,. Wellington.

Standards New Zealand, (SNZ), (1999). Code of Practice for light timber frame buildings not requiring specific design **NZS 3604:1999**, SNZ. Wellington.

ten Broeke, J. M. (1979). Diploma in building, Case study, Architecture, Wellington, Victoria University of Wellington.

Thomas, G.C. and Irvine, J. D, (2007). Post-Disaster Benefits of Upgrading Residential Dwellings Foundations, New Zealand Society for Earthquake Engineering Annual Conference, Wairakei. April, 2008.

Walker, G. (1995). Physical Reconstruction, Proceedings of *Wellington after the 'Quake: The Challenge of Rebuilding Cities,* Wellington.

Wellington Earthquake Lifelines Group. 1995. Wellington Earthquake Lifelines Group: 1995 Report, Wellington Regional Council. Wellington.