THE SERVICEABILITY OF NORMAL-USE, NON-DOMESTIC BUILDINGS IN EARTHQUAKES - ARE SERVICEABILITY DESIGN CHECKS NECESSARY?

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SUMMARY

This paper reports on an empirical study of whether it is necessary to carry out design checks on the serviceability of normal-use non-domestic buildings in earthquakes in New Zealand. It is found that at the relevant hazard level, i.e. at a return period of 25 years, the highest intensity anywhere in New Zealand is Modified Mercalli VII (MM7). At that intensity, no loss of function (predictable by a serviceability design check) has been reported in any structures classified as Buildings Type III (brittle) or better, since the introduction of reinforced concrete construction. For normal-use non-domestic structures designed for the ultimate limit state earthquake loading, the author contends (with one interim proviso affecting 10 percent of the country) that serviceability can be deemed to be satisfactory for new buildings anywhere in the New Zealand.

INTRODUCTION

In common with other countries, the New Zealand loadings standard has a serviceability requirement for earthquakes. The 2004 revision (NZS 1170.5) requirement for normal-use structures (i.e. with Importance Levels 2 and 3), is that for earthquake shaking that may be expected to occur at an average return period of 25 years, *the structure and its non-structural components will avoid damage " that would prevent the structure from being used as originally intended without repair"[ie. there would be no loss of function]* (Clauses 2.1.4(b)(i) and 2.5.2). This return period (25 years) is so low that three questions arise, i.e. (1) what levels of damage are being protected against? (2) what formal design checks need to be made for serviceability? and (3) where in New Zealand are such checks required? These questions are investigated below.

THRESHOLDS FOR DAMAGE AND LOSS OF FUNCTION

In a recent paper, Dowrick and Cousins (2003) studied the historical incidence (from 1840-1997) of Modified Mercalli (MM) intensity at 47 locations throughout New Zealand. Shown here in Figure 1 are their maps (adapted to show the 25 year hazard) showing the geographical distribution of the return periods for intensities (a) MMI ≥ 6 and (b) MMI ≥ 7. From Figure 1(a) it is seen that a return period of 25 years results in intensities I ≥ MM6 for about half of New Zealand south of a bent line approximately through Whakatane, Turangi and New Plymouth. From Figure 1(b) it is seen that for a return period of 25 years, the highest hazard (of I ≥ MM7) is in two small areas (hatched on Figure 1(b)) in the vicinities of (1) Otira, and (2) Masterton, Palmerston North, Porangahau and Napier, which together comprise 10 percent of the land area of New Zealand.

It is clear from the definitions of the various levels of intensity in the MM scale (Dowrick, 1996), given here in Appendix 1, that loss of function will not occur at MM6, as this is the threshold of structural damage, with only slight damage occurring to very brittle structure at this intensity. Nor is loss of function likely at intensity MM7 for Buildings Type III (defined in Appendix I) or better. Although more structural damage obviously occurs, as seen in Appendix 1 it again occurs only in structures or components thereof which may be classified as "brittle" or those of inferior workmanship. At worst, unreinforced chimneys or parapets (long since not permitted in New Zealand) could fall through roofs.

Thus, for *post-code* structures, we find that the threshold of loss of function, due to building damage from earthquake shaking, must be at an intensity >MM7 (ie. at least MM8). However, by extrapolation of the plots on Figures 1 and 2, it is seen that the intensity for a return period of 25 years does not reach MM8 anywhere in New Zealand.

However, in addition to the above inferences made from the definitions of MM intensities, we need to check what has actually happened in the intensity zones of interest in past New Zealand earthquakes. The above statements regarding pre-code and post-code structures have been verified in studies carried out by the author of damage in over 70 New Zealand earthquakes, with magnitudes in the range $5 \leq M_w \leq 8.2$ (eg. regarding reinforce concrete buildings: Dowrick and Rhoades, 2000). These studies included those of damage and its consequences as experienced in three major earthquakes of the post-code era, namely Wairarapa 1942 (M_w 7.1), Inangahua 1968 (M_w 7.2) and Edgecumbe 1987 (M_w 6.5). In Table 1 are given statistics on damage levels in

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these events in three intensity zones, MM6, MM7 and MM8 (where zone MM6 is the area between the MM6 and MM7 isoseismals). The information given includes: the total number (N) of items of a given class in the given zone; the proportion (n/N) of items damaged; the mean damage ratio D_{rm}, where damage ratio is defined as

$$D_r = \frac{\text{Cost of damage to an item}}{\text{Replacement Value of that Item}} \quad (1)$$

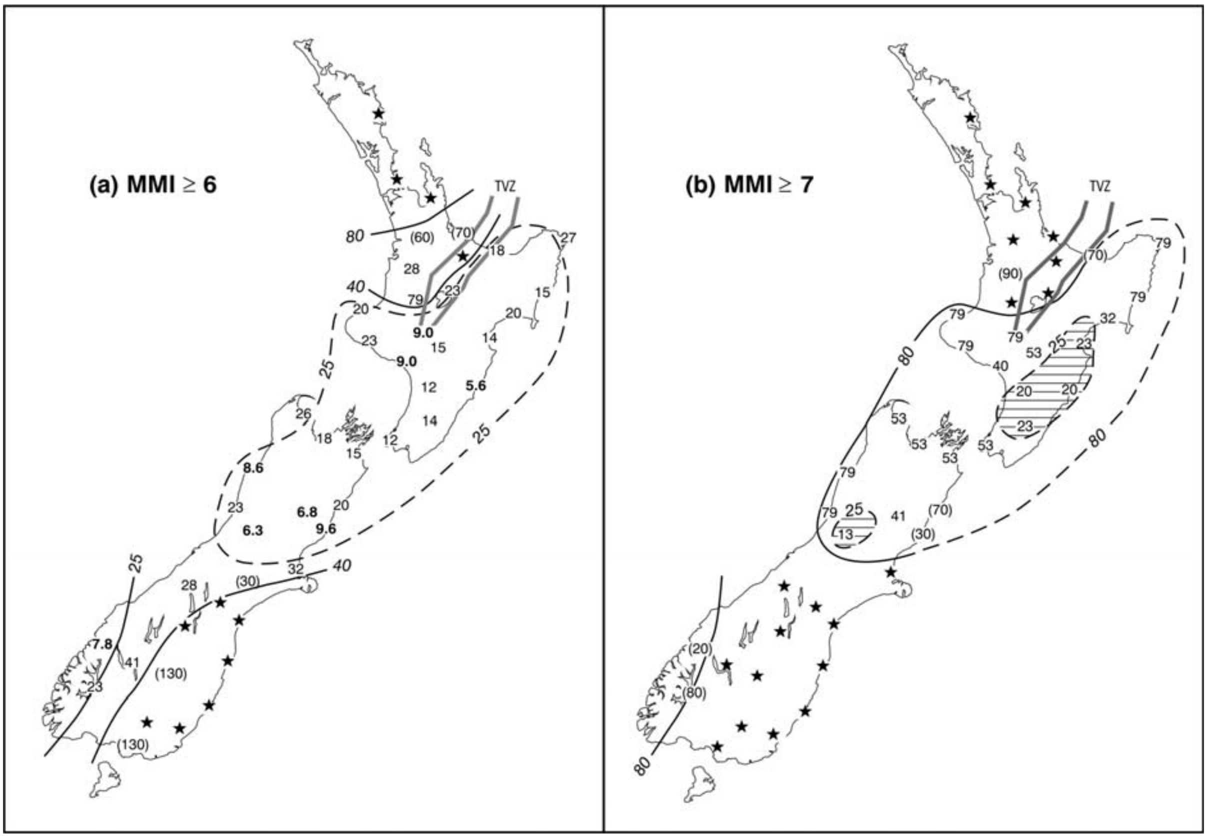

Figure 1: ***Map showing average return periods for historical isoseismal intensities (a) for MMI ≥ 6, and (b) for MMI ≥ 7. Values in brackets are those derived by extrapolation as replacements for the inherently unreliable "158-year" and "55-year" values, and ★ indicates that there were no observations (adapted from Dowrick and Cousins, 2003). However it is seen that the bracketed values are generally consistent with the rest of the map.***

Also given in Table 1 is the percentage of buildings which required repairs before the building could again be used as originally intended, ie. those losing function. (Statistics for fragile equipment are also given for comparison).

In Table 1 it is seen that no loss of function was experienced at intensity MM6.

As seen in Table 1, the threshold of loss of function has been experienced (as has been inferred above from the MM scale) at intensity MM7. This occurred to brittle pre-code unreinforced masonry (URM) buildings (Type II) in Dannevirke in the 1990 M_w6.4 Weber II earthquake. The damage statistics of these buildings have not been assembled, but descriptions of the damage are given by Johnstone and Potangaroa (1993). The data on D_{rm} and loss of function given in Table 1 are plotted for graphical examination on Figure 3.

The only other case of loss of function at intensity MM7 known to the author is that of a 1970's warehouse in Whakatane in 1987, when the ground subsided differentially causing damage to the ground floor slab, which had to be replaced. This case, marked ** in Table 1, is irrelevant in the sense that the damage would not be predicted by a structural design check. This case also highlights the difficulty of predicting loss of function using structural analysis.

As seen in Table 1, at intensity MM7, no loss of function (predictable by a serviceability design check) has occurred in *post-code* buildings, despite the fact that moderate proportions of these buildings have been damaged at this intensity of ground shaking. But as would be expected for buildings in which no loss of function occurred, the damage levels were low, i.e. D_{rm} was ≤ 0.01 in all cases.

Also for intensity MM7, in Table 1 the damage statistics for fragile equipment and plant in the Edgecumbe earthquake are given for the purposes of comparison. It is seen that this property class, although not designed to earthquakes, performed as well as the buildings.

It is noted that only one of the classes of property subjected to intensity MM8 listed in Table 1 was not URM, i.e. Item 10 (which was specifically designed for earthquake resistance). Therefore this data on URM buildings is supplemented by that found by considering all concrete buildings designed before 1976, i.e. with ductility factor $\mu \leq 3$, that have been in intensity MM8 zones. As listed in Table 2 this has involved 233 low-rise buildings in 10 major earthquakes. It is seen that in none of these cases has the building suffered loss of function, the worst damage which occurred having been modest cracking (Dowrick and Rhoades, 2000). Thus historical New Zealand field experience is consistent with the implication of the definition of intensity MM8 that loss of function occurs only in URM buildings.

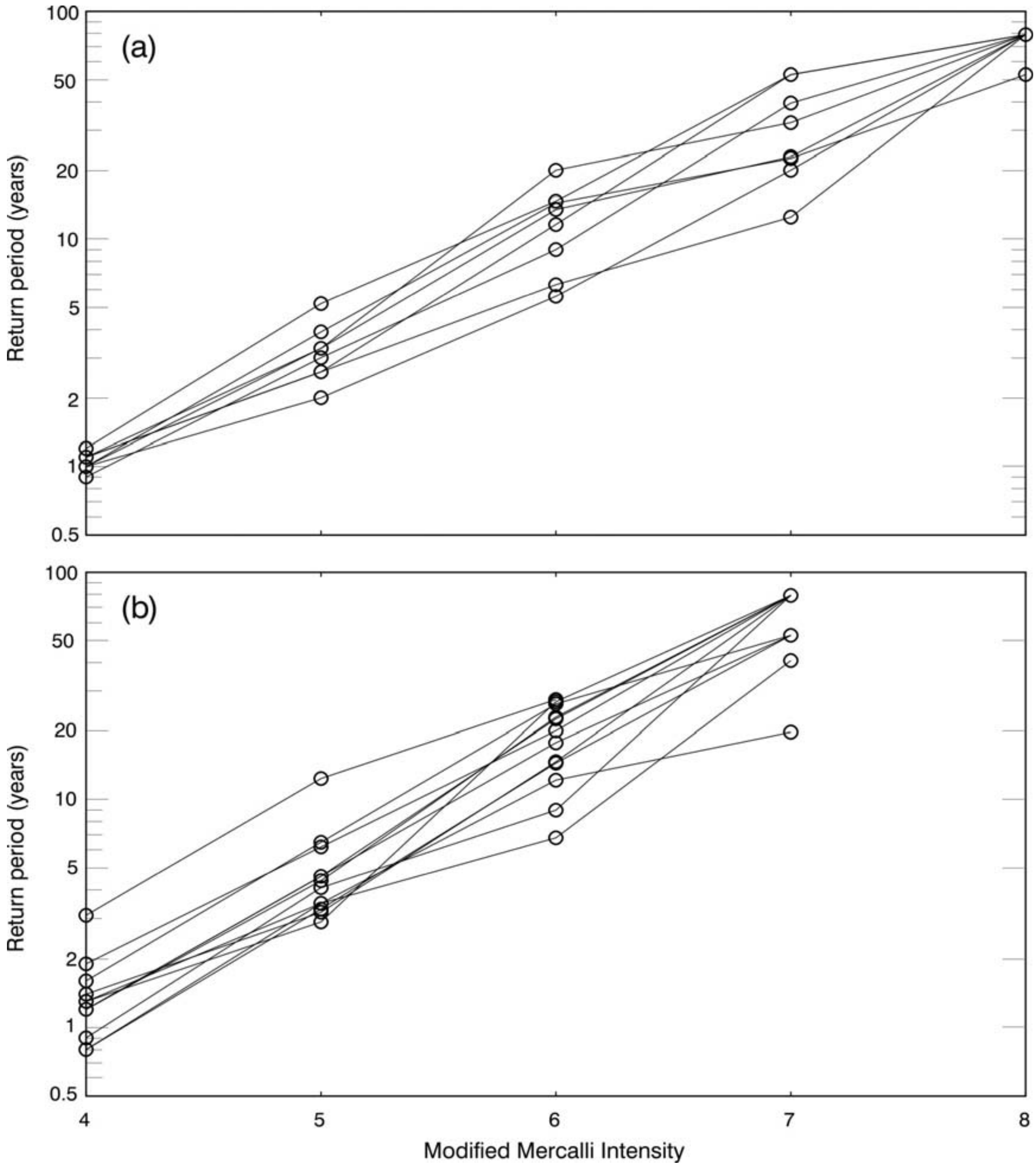

Figure 2: Return period as a function of MM Intensity for selected sites, (a) locations with 5 different return period values, and (b) locations with 4 different return period values. The logarithm of the return period appears to be a linear function of MMI for most of the observation sites (from Dowrick and Cousins, 2003).

FULLY DUCTILE STRUCTURES

Because they have been designed for lower loads than have less ductile structures, *fully ductile* structures ($\mu \geq 4$) are a different proposition for serviceability thresholds from those discussed above. Unfortunately we have no field experience of the performance of fully ductile structures at the serviceability intensity of MM7. The nearest such experience is the possibility that there were some buildings with $\mu = 3$ in the MM7 zone of the 1987 Edgecumbe earthquake. The 27 reinforced masonry buildings referred to in Item 6 of Table 1 may include a few buildings with $\mu = 3$. Also there were a few concrete and steel buildings in Whakatane (MM7) which may have had a ductility factor of $\mu = 4$. None of these buildings suffered loss of function.

A class of fully ductile structures which is most unlikely to suffer loss of function at intensity MM7 comprises concrete buildings gaining their lateral resistance from structural walls. Thus we are left with fully ductile *flexible* buildings (i.e. without substantial structural walls or diagonal bracing), which may be shown by structural analysis to be

Table 1 : Statistics of damage levels to non-domestic property at three intensities in three large New Zealand earthquakes (1942, 1968, 1987). (The data for buildings includes their non-structural components).

Intensity and Property Class	N	n/N	D_{rm}	Percent of N losing function	Reference
Buildings in the MM6 Zone					
1. 1 and 2 storey C & M[(1)] bldgs (1968)	c.650	c.0.02	<0.0001	0	This study
2. 1 storey bldgs mostly post-1935[(2)] (1987)	c.1000	c.0.007	<0.0001	0	3
Buildings in the MM7 Zone					
3. URM bldgs (1990)*	NA	NA	NA	>0*	9
4. 1 storey 1935-75 bldgs [(2)] (1987)	426	0.11	0.0022	0**	5
5. 2 storey 1935-75 bldgs [(2)] (1987)	51	0.33	0.0072	0	5
6. 1 storey 1980-86 RM bldgs[(2)] (1987)	83	0.10	0.0013	0	5
Equipment in the MM7 Zone					
7. Fragile equipment and plant (1987)	24	0.17	0.0019	0	4
Buildings in the MM8 Zone					
8. 1 storey URM bldgs (1942)	69	0.94	0.17	25%	7
9. 2,3 storey URM bldgs (1942)	42	1.0	0.22	40%	7
10. 1 storey 1976-86 bldgs[(2)] (1987)	21		0.006[(3)]	0	

Notes: [(1)] C & M = Bldgs of reinforced concrete or masonry respectively;

[(2)] All building materials;

[(3)] Interpolated between MM7 and MM9 values in reference 5;

* See text;

** One irrelevant case, see text;

NA = statistics not available.

likely to experience onset of damage (e.g. modest cracks in concrete) to structure or non-structural elements at serviceability loadings. However, modest cracking or similar damage at intensity MM7 in less flexible structures has not caused loss of function in any New Zealand earthquakes to date (see Tables 1 and 2). It is unlikely that damage at intensity MM7 in fully ductile, flexible normal-use buildings would be sufficiently worse so as to cause loss of function.

This leaves open the likelihood that the threshold for damage requiring repair to restore function to fully ductile flexible buildings is at intensity MM8, which is the threshold for damage to structures designed for earthquakes (Appendix 1). However, as discussed above, intensity MM8 does not occur in New Zealand at return periods as low as that for serviceability design checks of normal-use structures, i.e. 25 years.

PARTS OF BUILDINGS

It is noted in NZS 1170.5 (2004) that those parts of buildings (i.e. Part P.6) for which the consequential damage caused by its failure are disproportionately great, should be designed for twice the standard serviceability load for a part, i.e. for loadings with a 100 year return period. Therefore such parts in new buildings should have thresholds of damage and loss of function at an intensity > MM7, ie at least MM8, as discussed above for post-code structures (buildings and their parts). It would thus be appropriate (on the safe side) to check for the serviceability of Parts P.6 in areas where the hazard is intensity ≥ MM8 with a return period of 100 years. By extrapolation from Figures 1(a) and 1(b), these areas are seen to be similar to (but smaller than) the 25 year MM7 zones on Figure 1(b).

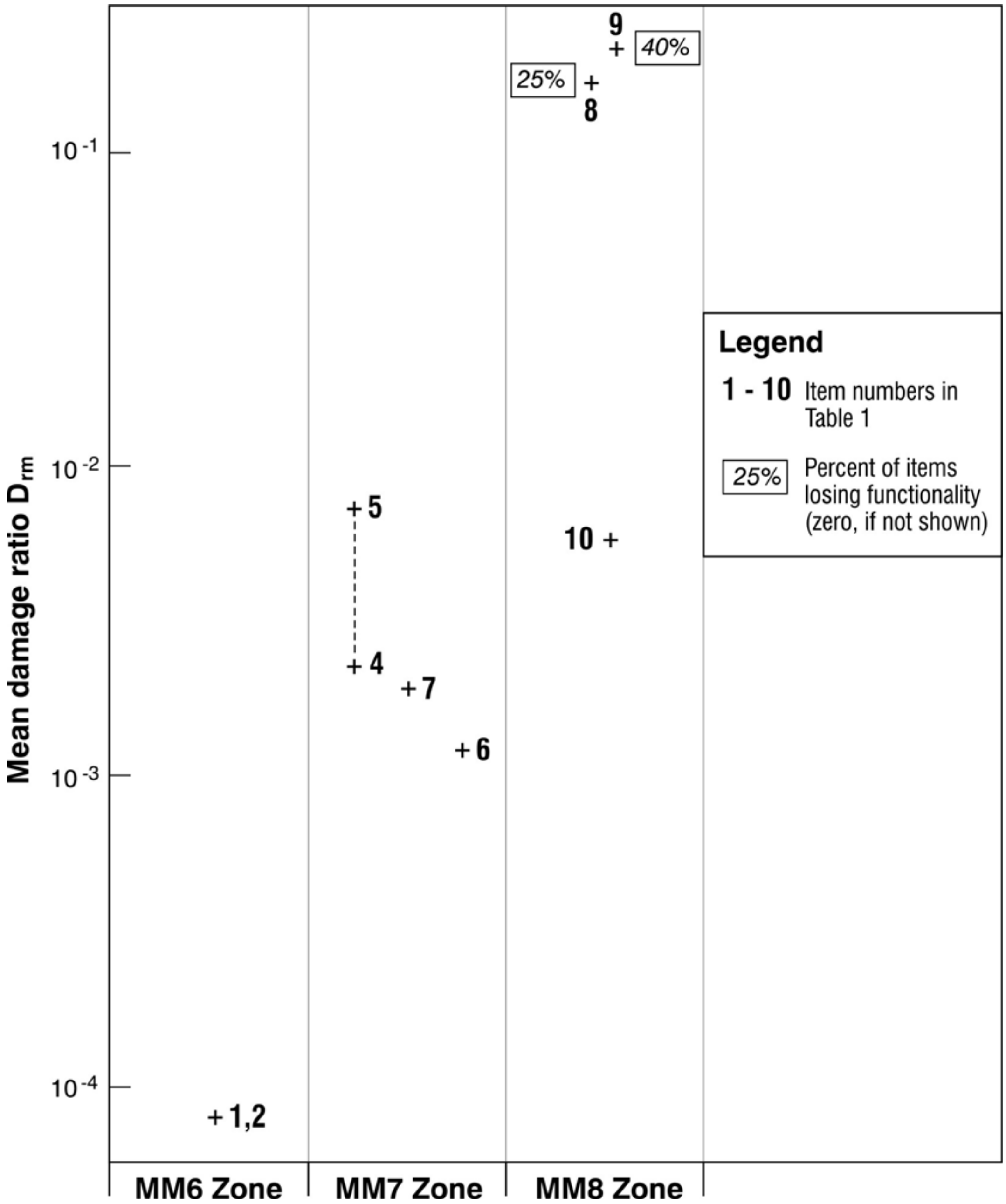

Figure 3: ***Plot of mean damage ratios vs. MM intensity for various classes of structure as listed in Table 1.***

CONCLUSIONS

The earthquake hazard level for serviceability of normal-use structures in New Zealand is set at a return period of 25 years. This is equivalent to intensities ≤ MM7 throughout the country, with the MM7 hazard zones covering small fractions of the areas of the North and South Islands. According to both the intensity definition and historical experience, intensity MM7 causes no loss of function in any structures with ductility factors $\mu \leq 3$, including those not designed for earthquake resistance, such as unreinforced masonry and fragile equipment and plant.

Like the pre-1990 buildings involved in the above findings, some future fully ductile flexible buildings designed to the 2004 loadings standard are expected to exhibit the onset of damage at intensity MM7. Theoretically this damage may be worse in fully ductile flexible structures than the damage of the earlier cases, but it is argued that such damage is unlikely to result in loss of function.

As a consequence it appears to be unnecessary to carry out design checks for serviceability of any normal-use non-domestic buildings throughout New Zealand. At most, until appropriate further New Zealand field experience has been obtained, a precautionary measure would be to check for possible loss of function to fully ductile flexible buildings in the two zones where the 25 year intensity is ≥ MM7. These zones are the hatched areas on Figure 1(b), which together comprise 10 percent of the land area of New Zealand.

Parts of buildings Type P.6 in NZS 1170.5 (2004) may need separate consideration with 100 year return period loading rather than that for 25 years.

Table 2 : Statistics of damage states of all pre-1976 concrete buildings subject to intensity MM8 (PGA 0.15-0.5g) in New Zealand earthquakes (extracted from Dowrick and Rhoades (2000)).

		Damage States								
Event Date	**M_W**	**OK**			**Cracks**			**Loss of Function**		
		No. of Bldgs per No. of Storeys								
		1	**2**	**3+**	**1**	**2**	**3+**	**1**	**2**	**3+**
1922 Dec 25	6.4	1								
1929 Jun 16	7.7	12	11	1	2	3	1			
1931 Feb 2	7.8	13	8	3	2	1				
1932 Sep 15	6.8	9	3	3	2	2				
1934 Mar 5	7.4			1						
1942 Jun 24	7.1	56	16	2	5	8	2			
1948 May 22	6.4	1	2							
1968 May 23	7.2	26	2		20					
1987 Mar 2	6.5	6	6	2						
1994 Jun 18	6.7		1							
Totals		**124**	**49**	**12**	**31**	**14**	**3**	**0**	**0**	**0**

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Appendix 1: Extracts from the Modified Mercalli Scale for New Zealand (Dowrick, 1996)

MM6 Structures

Slight damage to Buildings Type I*.

Some stucco or cement plaster falls.

Windows Type I* broken.

Damage to a few weak domestic chimneys, some may fall.

MM7 Structures

Unreinforced stone and brick walls cracked.

Buildings Type I cracked, some with minor masonry falls.

A few instances of damage to Buildings Type II.

Unbraced parapets, unbraced brick gables, and architectural ornaments fall.

Roofing tiles, especially ridge tiles may be dislodged.

Many unreinforced domestic chimneys damaged, often falling from roof line.

Water tanks Type I burst.

A few instances of damage to brick veneers and plaster or cement-based linings.

Unrestrained water cylinders (Water Tanks Type II) may move and leak.

Some Windows Type II cracked.

Suspended ceilings damaged.

MM8 Structures

Buildings Type I heavily damaged, some collapse.

Buildings Type II damaged, some partial collapse.

Buildings Type III damaged in some cases.

A few instances of damage to Structures Type IV.

Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down.

Some pre-1965 infill masonry panels damaged.

A few post-1980 brick veneers damaged.

Decayed timber piles of houses damaged.

Houses not secured to foundations may move.

Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Categories of Construction

Buildings Type I:

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I-III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II:

Buildings of ordinary workmanship, with mortar of average quality. No extreme weaknesses, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III:

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV:

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c. 1980 other materials).