Damage ratios for brick buildings in the 1942 Wairarapa earthquake

NZSEE 2001
Conference

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ABSTRACT: An analysis of damage costs to low-rise non-domestic brick buildings in the MM8 intensity zone of the M_w 7.1 Wairarapa earthquake of 24 June 1942 has evaluated the vulnerability of such buildings in New Zealand for the first time. The buildings studied were mostly of unreinforced brick of average workmanship and material quality, i.e. the second most vulnerable class of New Zealand buildings. Approximate vulnerabilities were also determined for partly reinforced and partly retrofitted buildings, and of one and two-storey buildings. The costs of damage were derived from insurance claims and local government records. The indicators of vulnerability that were determined were the statistical distributions and mean values of damage ratios, and the percentage of buildings damaged. Comparisons have also been made with results from studies of other earthquakes.

1 INTRODUCTION

In 1942, a series of damaging earthquakes occurred in the Wairarapa province of New Zealand. The locations and general effects of these earthquakes have recently been studied by Downes et al. (2001). The largest event in the sequence (24th June) was of magnitude M_s 7.2 (M_w 7.1) (Dowrick & Rhoades 1998) with a centroid depth of approximately 12 km (Doser & Webb, in prep.), while the second to largest event (1st August) was of magnitude M_s 7.0 (M_w 7.0) (Dowrick & Rhoades 1998) with a centroid depth of 40 km (Doser & Webb, in prep.).

The area inside the MM8 isoseismal, (i.e. the MM8 zone), was predominantly a farming area (population approximately 24,000), and so the total losses were quite low in national economic terms. However, in the six largest towns (Figure 1), there were numerous brick buildings, most of which suffered moderate to serious damage. About a quarter of these buildings had earthquake insurance. The costs of the repairs to the damaged buildings come from data compiled by the borough council engineers, lead by CR Mabson of Masterton.

The damage costs for a variety of classes of property have already been studied by the present authors for the 1931 Hawke's Bay, 1968 Inangahua and 1987 Edgecumbe earthquakes (e.g. Dowrick & Rhoades 1997; Dowrick et al. 2000). In the present case we have a representative and statistically reasonably robust set of data for studying the degree of damage to a class of buildings in terms of damage ratio, D_r, defined as

$$D_r = \frac{\text{Cost of Damage to a Building}}{\text{Replacement Value of that Building}} \qquad (1)$$

As in the previous studies, the damage ratios are studied here as a function of intensity of ground shaking, restricted this time to one intensity, MM8, as defined for New Zealand [Dowrick (1996)].

The present study offers us our first opportunity to evaluate the vulnerability of brick buildings at any level of hazard, providing nearly an upper bound estimate of the vulnerability of any class of New Zealand building, albeit for only one earthquake and only one intensity. A more detailed version of this paper has been submitted to the NZSEE Bulletin.

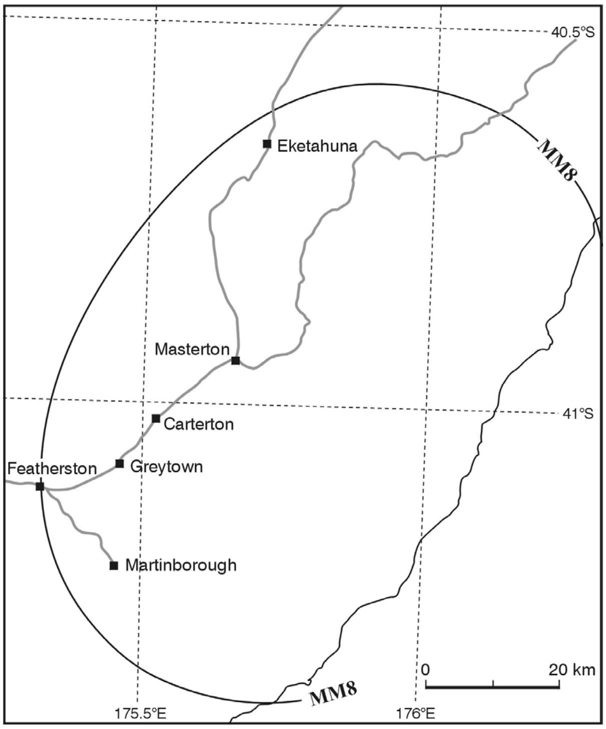

Figure 1. Map showing the innermost isoseismal MM8, state highways and key place names for the 24th June 1942 Wairarapa earthquake.

2 DESCRIPTION OF THE BUILDINGS STUDIED

All of the buildings studied were of non-domestic use, i.e. commercial, light industrial or institutional, and were built predominantly of brickwork. The geographical distribution of the buildings studied was as follows: Carterton (17), Eketahuna (17), Featherston (3), Greytown (3), Masterton (79) and Martinborough (10). The buildings were all low-rise, i.e. 79 were one-storey, 48 were two-storey and two were three-storey. Horizontal diaphragms, i.e. suspended floors and roofs, were of timber construction.

The buildings have been divided into three classes of vulnerability:

- Pure brick (With horizontal diaphragms of timber);
- Hybrid (Brick with some concrete or steel members as part of the original construction);
- Retrofitted (Originally pure brick, with some concrete or steel members added after the 1934 Pahiatua earthquake). The eight such buildings in our dataset were all considered at the time (Harris & Burns 1942) to be only partly retrofitted, and recommendations to complete the strengthening were made. These attempts at retrofitting are almost the earliest known to us in New Zealand.

The pure brick buildings, Item 1 above, were of ordinary workmanship and materials, without any extreme weaknesses. Thus they conform to the class of construction described in the MM intensity scale as “Buildings Type II” (Dowrick 1996), and are thus the second most vulnerable class of building in New Zealand. “Buildings Type I”, i.e. the most vulnerable class, where recognised, were excluded from our database.

3 THE DATA

As in our previous studies (Dowrick & Rhoades 1997; Dowrick et al. 2000), we attempted to account for all buildings of the class under consideration in order to avoid the problem of biased samples. In the present case we have accounted for nearly all such buildings in the MM8 intensity zone, excluding only a few for which the data was considered to be of inadequate quality. We consider that the data used is representative of the total population.

As mentioned earlier, local authority officials developed lists of most brick or part brick buildings for the six boroughs in the Wairarapa district. They included most private sector buildings and some owned by public utilities and local government, plus two of the Post Offices. The lists, while not complete in all details, included data on market value, insurance cover, insurance claims paid out, size of building, construction costs and costs of repairs to bylaw standards (which did not require compliance with the national earthquake standard). Costs of repairs were also obtained for a minority of the buildings from the files of the architect FC Daniell and the property owners known as Trust Lands Trust (who had earthquake insurance). The insurance sums paid out (for 32 buildings) were very similar to the amounts estimated by the borough officials. It is important to note that the damage costs were for repair only, and contained no element of retrofitting.

Much useful qualitative information held by the Wairarapa Archive in Masterton was also studied for verifying and amplifying the data used, including many photographs (especially from members of the Daniell family), design drawings, minutes of meetings and reports of the Reconstruction Committee, as well as the invaluable report by Harris & Burns (Dowrick 1996).

The replacement values of the buildings were based on their floor areas and unit building costs. Plan dimensions were given for almost all of the buildings in the tables of data prepared by the borough officials. These values were checked where possible, i.e. for most (66) of the Masterton buildings, and corrected where necessary. The unit costs of constructing a new building in 1942 were based on the typical costs of run-of-the-mill commercial buildings, industrial buildings and warehouses, which were \$1150, \$750 and \$500 per square metre respectively in 1998. As the Consumer Price Index was 43.5 in mid-1942 and 1101 in mid-1998, the unit building costs at the time of the earthquake are estimated as £2.1, £1.4 and £0.9 per square foot for the commercial, industrial and warehouse buildings respectively.

Finally, it is noted that while seven of the pure brick buildings were written off (i.e. $D_r = 1$), none collapsed (i.e. had volume losses > 50%). This is consistent with the New Zealand version of the MM intensity scale for Buildings Type II (Dowrick 1996).

4 DAMAGE RATIOS

4.1 *Statistical distributions of damage ratios*

The damage ratio (D_r) for each building was calculated as defined by equation (1) above. All of the authors' other studies (e.g. Dowrick & Rhoades 1997; Dowrick et al. 2000) of earthquake damage have shown the shape of the statistical distribution of non-zero damage ratios for various classes of property to be well approximated by a truncated lognormal distribution. The lognormal distribution has the density function:

$$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\log_e x - \mu)^2 / \sigma^2\right] \qquad x > 0. \tag{2}$$

In the truncated form of the distribution as fitted to damage ratios, there is a "spike" at 1, i.e.

$$P(D_r = 1) = \int_1^\infty f(x)dx .$$

Here the parameters μ and σ are estimated by the sample mean and standard deviation of the natural logarithm of the damage ratio of damaged items, with adjustments to compensate for properties having a damage ratio of 1.

The estimates of the parameters μ and σ found for the various datasets are given in Table 1. Also tabulated are the number of damaged items n, and the total population (damaged + undamaged) N.

4.2 *Mean damage ratios*

The mean damage ratio for all buildings in a given MM intensity zone is a useful parameter for various purposes, e.g. in comparing the earthquake resistance of different classes of property. Considering all N buildings (damaged and undamaged) in an MM intensity zone, we give here two principal ways of defining the Mean D_r. Firstly,

$$\overline{D}_r = \frac{\sum_{i=1}^{n}[\text{cost of damage to building } i]}{\sum_{i=1}^{N}[\text{value of building } i]} \tag{3}$$

where n is the number of damaged buildings. Secondly,

$$D_{rm} = \frac{\sum_{i=1}^{n}[D_{r_i}]}{N} \tag{4}$$

The values of $\overline{D}_r$ and D_{rm} for the three classes of non-domestic building considered in this study are presented in Table 1. As D_{rm} and its associated confidence limits are generally more reliable and useful than $\overline{D}_r$ (Harris & Burns 1942), the former are used throughout this paper.

Table 1. Basic statistics of the distribution of damage ratios by class of non-domestic brick building in the intensity MM8 zone of the Wairarapa earthquake of 24 June 1942.

Building Class	n	N	μ	σ	D_{rm}	$\overline{D}_r$
Pure brick						
All	107	111	-2.18	1.36	0.17	0.12
1 Storey	65	69	-2.32	1.13	0.14	0.11
2+ Storey	42	42	-1.95	1.70	0.22	0.12
Hybrid & part retrofit						
All	13	18	-3.14	1.38	0.041	0.043
All Hybrids	7	10	-3.05	0.67	0.036	0.030
All Part Retrofits	6	8	-3.25	2.02	0.047	0.060

4.3 *Effects of construction materials*

Plots of cumulative probability of damage ratios at intensity MM8 in the Wairarapa earthquake are shown in Figure 2(a) for two classes of building, i.e. pure brick, and hybrid plus partial retrofits. The shapes of the plots are broadly similar to the fitted lognormal curves, but the fits are not as close as we have obtained in studies of larger datasets (Dowrick & Rhoades 1997; Dowrick et al. 2000).

When considering mean damage ratios and percentages of buildings damaged, all three building classes are plotted (Fig. 2b, c). The beneficial effect of even small amounts of reinforcing steel is very apparent in all three plots of Figure 2. In particular, D_{rm} for the reinforced buildings at about 0.04 is only a quarter of the value for pure brick (0.17). The proportion of pure brick buildings damaged is 96% compared with 72% for the hybrids and partial retrofits.

4.4 *Number of storeys*

The vulnerabilities of pure brick buildings of one and two storeys at intensity MM8 are compared in Figure 3, where their D_{rm} and the associated 95% confidence limits are plotted. The vulnerability of two-storey buildings (D_{rm} = 0.22) is substantially greater than that for one-storey buildings (D_{rm} = 0.14). The difference in the above two values of D_{rm} was found not to be statistically significant, but only just, the p-value of the difference being 0.057.

The above findings are similar to those for one and two storey non-domestic buildings at MM7 and MM9 in the Edgecumbe earthquake (Dowrick & Rhoades 1997), and for houses at MM7 and MM8 in the 1968 Inangahua earthquake (Dowrick et al. 2000).

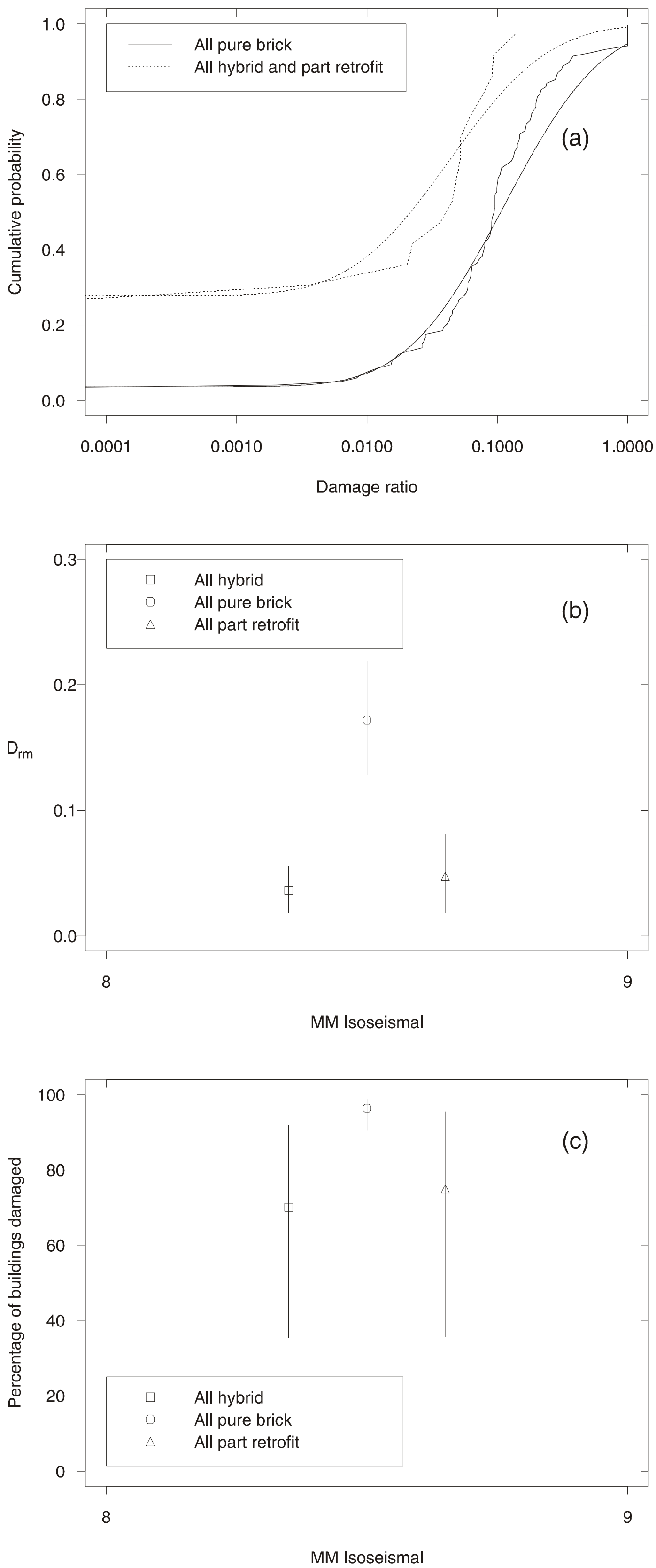

Figure 2. Three measures of vulnerability for three classes of non-domestic brick buildings in the MM8 intensity zone of the June 1942 Wairarapa earthquake: (a) Cumulative probability distributions of damage ratio, (b) D_{rm} and its 95% confidence limits, and (c) Percentage of buildings damaged with its 95% confidence limits.

Figure 3. D_{rm} and its 95% confidence limits for one and two-storey non-domestic pure brick buildings in the MM8 intensity zone of the June 1942 Wairarapa earthquake.

5 COMPARISONS WITH OTHER STUDIES

As mentioned earlier, the pure brick buildings studied here represent the second most vulnerable class of New Zealand buildings. It is therefore of particular interest to compare the vulnerabilities evaluated here with those obtained for other classes of New Zealand buildings. This is done in terms of mean damage ratio and percentage of buildings damaged, in Figures 4a and 4b respectively. All the results plotted are for one-storey buildings, because they comprise the largest subsets of data and hence have the most robust results. The results plotted from other studies are:

- Non - domestic concrete masonry (1935-1979), Edgecumbe earthquake, intensities MM7 and MM9 (Dowrick & Rhoades 1997).
- Timber framed houses with brittle chimneys, Inangahua earthquake, intensities MM7 - MM9 (Dowrick et al. 2000).
- Timber framed houses excluding chimney-related damage, Inangahua earthquake intensities MM7 - MM9 (Dowrick et al. 2000).

As seen in Figure 4a, D_{rm} for pure brick one storey buildings at MM8 is 2.9 times higher (at 0.14) than the next worst class of buildings, i.e. houses with brittle chimneys, for which D_{rm} = 0.048 at MM8 and 0.050 at MM9. In addition, the 95% confidence limits are widely separated. Also shown in Figure 4a, D_{rm} for pure brick is approximately seven times greater than that (~0.02) for 1935 - 1979 code-designed concrete masonry buildings (estimated by linear interpolation between the Edgecumbe earthquake MM7 and MM9 D_{rm} values).

Considering the percentage of buildings damaged (Fig. 4b), pure brick buildings are again worse (92%) than the next worst class of buildings, houses with brittle chimneys, for which n/N = 81% at both MM8 and MM9. Reinforced concrete masonry buildings from the Edgecumbe earthquake have n/N = 35%, estimated by linear interpolation between the MM7 and MM9 results.

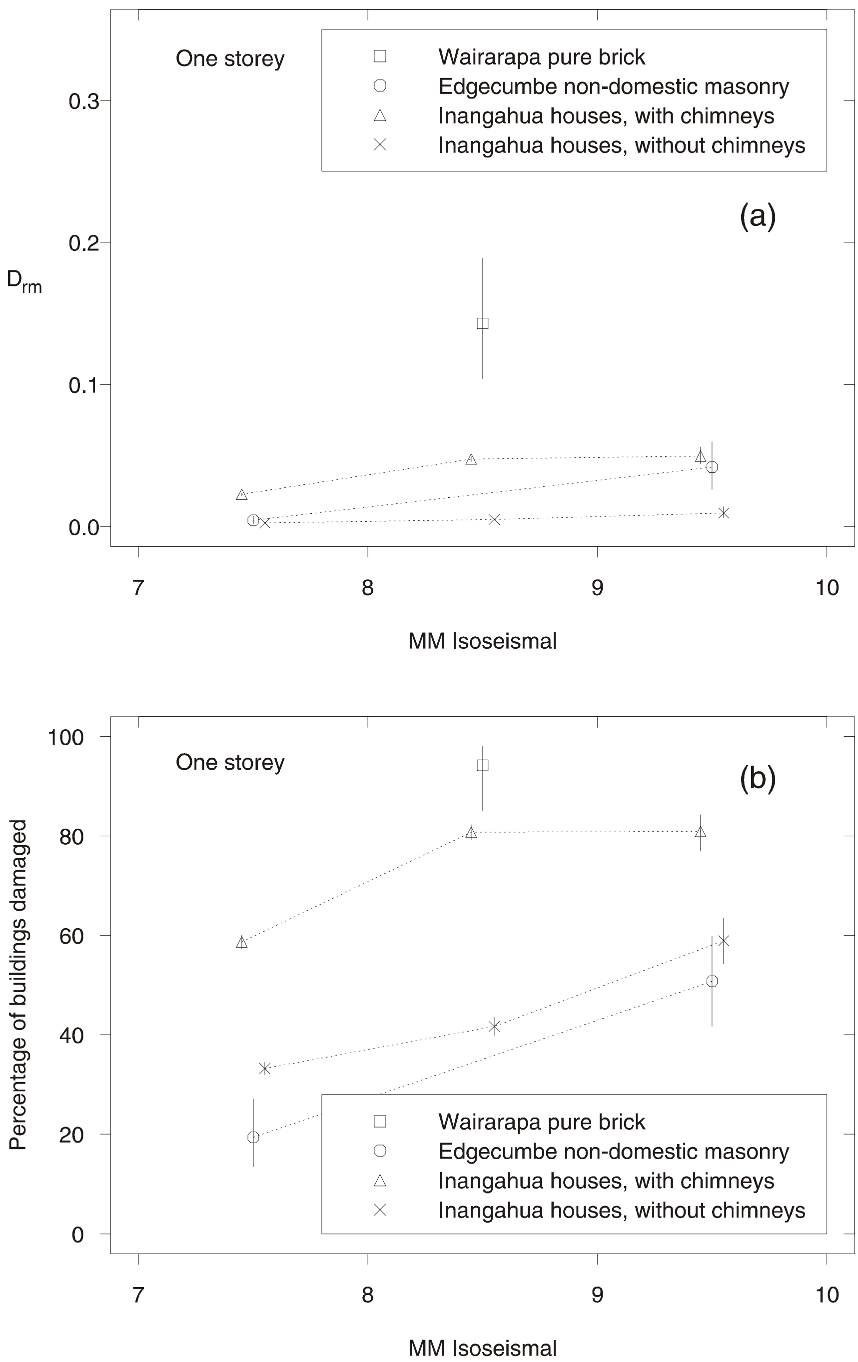

Figure 4. Two vulnerability measures for pure brick Wairarapa non-domestic buildings compared with those for three other building classes from the 1968 Inangahua and 1987 Edgecumbe earthquakes:

(a) D_{rm} with its 95% confidence limits, and

(b) Percentage of buildings damaged with its 95% confidence limits. The houses are timber framed.

6 CONCLUSIONS

Arising from this study the main conclusions are:

1. The vulnerability of non-domestic low-rise brick buildings has been determined in terms of probability distributions of damage ratio, mean damage ratio and percentage of buildings damaged at intensity MM8.

2. Brick buildings with quite primitive reinforcement (hybrids and partial retrofits) are much less vulnerable at intensity MM8 than pure brick buildings. The mean damage ratio, D_{rm}, for all the reinforced brick buildings was 24% of that for all the pure brick buildings, and the incidence of damage was also substantially reduced.
3. The mean damage ratio for two-storey pure brick buildings at 0.22 was 57% greater than that for one-storey buildings.
4. Comparing one-storey buildings at intensity MM8, the mean damage ratio for the pure brick Wairarapa buildings is (1) approximately three times that for timber framed houses with brittle chimneys in the Inangahua earthquake; (2) seven times that for 1935 - 1979 concrete masonry buildings in the Edgecumbe earthquake; and (3) 28 times that for timber framed houses excluding chimney damage in the Inangahua earthquake.

7 ACKNOWLEDGEMENTS

This study was funded by FRST under Contracts No's. C05804 and C05X0006. Much of the data used in this study was derived from material held by the Wairarapa Archive in Masterton and we are greatly indebted to the Wairarapa archivist, G. Winter. Thanks are due to J Cousins and N Perrin for their in-house reviews of the manuscript.

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