Potential benefits of strengthening earthquake-prone buildings

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2013 NZSEE Conference

ABSTRACT: The New Zealand Department of Building and Housing was considering the implications of possible changes to policies concerning earthquake-prone buildings. As one of the inputs to that process I estimated damage and casualties for portfolios of buildings that simulated first the original states of the buildings and then progressive upgrading of the weakest buildings to 33%, 67% and 100% of new building standard. Six portfolios were modelled, representing small, medium and large population centres, and two zones of seismic hazard, high (e.g. Wellington) and low (e.g. Auckland). Only buildings covered by the earthquake-prone policies were included in the portfolios. Each portfolio was exposed to a variety of scenario earthquakes, and outputs from the simulations included estimates of the repair costs and the numbers of casualties.

The paper describes the computation path (models for the assets, the strengthening, and the earthquakes), the main results and trends, and a simple way of visualising relative earthquake risks in various types of building in various parts of New Zealand. While the modelling demonstrated that strengthening could give large reductions in casualty rates, the reductions in losses were only modest. The risk of death in deficient old buildings in Auckland appeared to be much less than in sound modern buildings in Wellington.

1 INTRODUCTION

The Department of Building and Housing (DBH) wished to assess the implications of possible changes to policies concerning earthquake-prone buildings in New Zealand. One of the inputs to that assessment was to be a cost-benefit model that relied on estimates of damage to buildings, and of casualties within them, under different assumptions about building strength and level of seismic shaking. GNS Science was contracted to the Department to provide estimates of damage and casualties (Cousins, 2012).

Detailed models of workplace buildings were created to represent the proportions of construction types expected in three sizes of locality (workplace populations of about 200,000, 35,000 and 2500, i.e. city, small city and town) and two levels of seismic hazard (low, e.g. Auckland, and high, e.g. Wellington). Three additional models were then created from each of the above basic models to simulate strengthening of substandard buildings to (a) 33%, (b) 67% and (c) 100% of new building standard (NBS), giving a total of twenty-four models.

Each building model was exposed to four scenario earthquakes, designed to give dominant levels of shaking over the central business districts of MM8, MM9, MM10 and MM11 (MM is Modified Mercalli Intensity). The outputs for each simulation were the repair cost, the number of collapsed buildings, the number of fatalities and the number of injuries, with the numbers of deaths and injuries being estimated for both workday and night-time occupancy rates. “Injured” meant needed medical attention, ranging from first-aid to intensive care. It was intended that the loss and casualty results would be scaled by DBH to other localities throughout New Zealand.

2 ASSETS AND OCCUPANCY

2.1 Characteristics of the basic models for buildings and occupants

The starting point in the modelling was a set of three buildings models for representative large, medium and small-sized localities in areas of high-seismic hazard. Existing models were chosen because they were judged to be the best available for the modelling, there was insufficient time to develop completely new models, and being on a building-by-building basis they were sufficiently detailed.

The existing models, for Wellington, Hastings and Greytown, had been developed for use in the RiskScape risk modelling tool. RiskScape is a multi-hazard risk modelling package being developed jointly by GNS and NIWA (National Institute of Water and Atmospheric Research) (King & Bell, 2009). Buildings in the assets models were classified according to the many criteria needed for loss modelling under several hazards of importance to New Zealand, including earthquakes, volcanoes, tsunami, flooding and windstorm. Attributes of relevance to the present modelling included the use category (e.g. commercial business, education), the construction type (e.g. reinforced-concrete shear-wall, tilt-up panel, timber), the construction era (e.g. pre-1980, representing buildings constructed before major upgrades were made to building codes from about 1976 to 1980) and the seismic quality (sound or deficient). Other attributes were the floor area, the replacement value, the numbers of occupants during a typical workday, and the numbers at night.

The quality term "sound" was assigned to a building that was well-proportioned and constructed in accordance with the code of the era, whereas "deficient" indicated that the building suffered from two or more of deficiencies like irregular plan or elevation, soft storey, torsional instability or general poor condition. An exception was that URM (unreinforced masonry) buildings "as built" were classified as deficient, and those which had been strengthened were classified as sound.

The original models contained both residential and non-residential buildings. Because the targets of the work were buildings that might be covered by the earthquake-prone buildings legislation all low-rise residential buildings that were smaller than 1000 m^2, and had fewer than 10 occupants at night, were removed from the models.

Table 1 provides key statistics on the final Wellington model. The main subdivisions were by construction date and quality, with the boundaries between classes being chosen to match the fragility functions available in RiskScape. Year 1940 was used to distinguish structural brick construction (URM) from brick veneer over timber frame. Year 1980 was used as a marker for major changes made to codes for concrete and steel construction in the late 1970s. Timber buildings were treated separately because they are much safer than most other types of construction, and few are expected to be rated as earthquake-prone. Finally, sound and deficient are as defined above.

Table 1. Statistics on the final buildings model for Wellington.

Building Subdivision	Value ($million)	Value ($million)	Occupants Day	Occupants Day	Occupants Night	Occupants Night
	Sound	Deficient	Sound	Deficient	Sound	Deficient
pre-1940	780	435	11,210	4,085	355	679
1940 to 1979	3,560	1,525	46,194	12,758	1,147	5,435
1980-on	4,277	2,419	56,247	25,077	1,411	5,296
Timber	738	1,663	7,986	41,035	415	4,650
Totals	9,354	6,041	121,637	82,955	3,328	16,060

2.2 Adaptation to places of low seismic hazard

Seismic design in New Zealand follows a uniform hazard approach such that, for instance, a normaluse building in any part of the country would be designed to withstand the level of shaking expected to occur not more than once in any 500 years. This automatically means that the design requirements are less stringent in places where the seismic hazard is low than where it is high. As an example, the 500-year shaking intensity for Auckland is MM6.6, compared with MM9.2 for Wellington, noting however that a minimum level of MMI applies in many areas of low to very low seismic hazard.

A second point of difference is that Territorial Authorities in places of high seismic hazard have actively encouraged the removal or upgrading of risky buildings.

All three of the starting models were in zones of high seismic hazard. Because RiskScape did not contain similar models for regions of low seismic hazard, the approach was to derive downgraded versions of the starting three to represent similar-sized towns and cities in zones of low seismic hazard. Downgrading steps, which mostly involved increasing the proportions of buildings rated as deficient in the model, were as follows:

- Sufficient pre-1940 non-URM buildings were converted to URM to house twice as many people in URM as in the starting models.
- Seven out of the eight base-isolated buildings in the Wellington model were assigned to reinforced-concrete shear-wall (which reflects the situation in Auckland and Christchurch). There were no buildings of this type in the smaller models.
- The percentage of buildings rated as deficient was increased from the original 20-40% (the percentage varied with age-group) up to 50%.
- For buildings constructed from 1990 to 2004, an era when site-specific hazard modelling could be used to lower standards below the specified minimum levels for areas of low seismic hazard, all reinforced concrete buildings of more than three stories were rated as deficient, as were all tilt-up and light industrial buildings of more than two storeys.

2.3 **Simulation of upgrading**

The main purpose of the work was to estimate the potential benefits of upgrading substandard buildings. Three levels of upgrading were specified, first to 33% of NBS, then 67% and finally to 100%. Given the large scale of the models it was not possible to base the upgrading on formal engineering calculations, hence it simulated by making suitable changes to the attributes of the buildings in the models. This was a process governed entirely by judgement, and constrained by the class structure of the assets model and the available fragility/casualty functions.

2.3.1 *Upgrade to 33% of NBS*

All pre-1980 buildings that were rated as “deficient” in the assets model were changed to “sound”, except for timber buildings, which were of low risk to people and assumed not likely to be subject to upgrading. The prime assumption here was that deficient pre-1980 buildings would be below 33% NBS, and that sound ones would be at least 33%.

2.3.2 *Upgrade to 67% of NBS*

All pre-1980 buildings were converted to post-1980 status, and URM buildings were converted to reinforced-concrete shear-wall construction.

2.3.3 *Upgrade to 100% of NBS*

Models for high and low-seismicity places were treated differently, as follows:

- High-seismicity models: All remaining "deficient" buildings were converted to "sound".
- Low-seismicity models: 50% of remaining "deficient" buildings were converted to "sound". The residual deficient buildings were judged to adequately account for the lower design standards prevailing in the low-seismicity areas.

3 EARTHQUAKE MODELS

The hazard specification was for scenario earthquakes giving shaking levels of MM8 to MM11 in the areas of interest. Because some of the buildings models were large, ranging from about 3 km^2 for a town (Greytown size) to more than 100 km^2 for a city (Wellington size), the strength of shaking would be expected vary over the models in any real earthquake. An event giving MM10 in the CBD of Wellington for example could give as little as MM9 at the distant suburbs of Tawa and Makara. The variation would be greater over large cities than over small ones, greater for small earthquakes than for large ones, and greater for high shaking intensities than for low. Hence relatively large, but realistic, model earthquakes were used, as follows:

- for MM11, a magnitude 8.0 earthquake at 10 km depth, with epicentre 4 km from a reference site in the CBD (parliament buildings in the case of Wellington),
- for MM10, magnitude 7.2, depth 10 km, epicentre 4 km from reference site,
- for MM9, magnitude 7.2, depth 10 km, epicentre 21 km, and
- for MM8, magnitude 7.2, depth 10 km, epicentre 50 km.

For the two largest earthquakes affecting Wellington the epicentre was placed east of the reference location so that the innermost intensity isoseismal, MM11 or MM10, passed approximately through the centre of the CBD.

4 DAMAGE AND CASUALTIES

The modelling sequence, for each combination of assets model and target intensity (96 in total), was to (a) estimate the shaking intensity at each building location using the Dowrick & Rhoades (2005) attenuation model for MMI, (b) assign each building to a "damage state" using a probabilistic relationship between MMI and damage state (Spence et al., 1998; Cousins et al., 2008), (c) assign each person in a building to an injury state using relationships developed by Spence et al. (1998), and (d) estimate repair costs using a relationship between damage state and damage ratio (Cousins et al., 2008). Numbers of dead and injured and total repair costs were obtained by summing the results over all buildings in the model. Each simulation was repeated 10,000 times.

5 RESULTS AND DISCUSSION

Tables 2 and 3 present basic results for Wellington, the representative city in a region of high seismic hazard. The main trends are illustrated in Figures 1 and 2, and then extended to other sizes of city and level of seismic hazard on a comparative basis. Note (a) that the horizontal axis scale in the two figures is not necessarily linear, and (b) that the minimum %NBS in the original model is difficult to define, but will be greater than 0%. It has been taken as 10% for plotting purposes only.

5.1 High-hazard models – trends with minimum strength

As the minimum allowable building strength was increased from original state to 100% of NBS, the loss ratio for Wellington buildings decreased steadily to about 75% of the initial value, regardless of the shaking intensity at the CBD (Figure 1). Very similar trends were obtained for Hastings and Greytown except that the overall decreases were smaller, to 85% and 90% respectively.

The changes in casualty rates with %NBS were more dramatic (Figure 2), and there were clear differences between (a) night and day population distributions, and (b) MMI levels. Perhaps the most notable is the rapid decrease in night-time death rates, which is almost certainly due to upgrade of the pre-1980, non-timber, deficient, buildings which are home to 32% of the night-time occupants. This large decrease was not present in the trends for the small city (Hastings) and town (Greytown) cases, and is probably a reflection of the low or zero numbers of multi-storey apartments in those places.

Table 2. Potential reductions in losses and casualties in scenario earthquakes as a result of raising the minimum allowable quality of buildings, for a city located in a region of high seismic hazard.

MMI at CBD	Min. Strength (% NBS)	Repair Cost ($m)	Collapses (number)	Day Deaths	Day Injuries	Night Deaths	Night Injuries
11.0	Original model	5500	200	1520	6700	300	910
	33%	5200	150	1180	6200	160	710
	67%	4700	83	690	5100	86	600
	100%	4200	48	450	4100	42	430
10.0	Original model	3300	41	380	3000	77	400
	33%	3100	31	290	2700	36	310
	67%	2800	17	140	2200	14	260
	100%	2500	10	84	1800	7	180
9.0	Original model	1400	5	29	750	4	100
	33%	1300	4	20	700	1	73
	67%	1200	2	8	550	0	55
	100%	1100	1	5	420	0	37
8.0	Original model	420	0	0	88	0	10
	33%	400	0	0	80	0	7
	67%	370	0	0	55	0	5
	100%	320	0	0	41	0	3

Table 3. Same data as for Table 2, presented as loss and casualty ratios. "D" is death, "I" in injury.

MMI at CBD	Min. Strength (% NBS)	Loss Ratio	Collapse Rate	Day D Rate	Day I Rate	Night D Rate	Night I Rate
11.0	Original model	0.36	0.053	0.0074	0.033	0.016	0.047
	33%	0.34	0.039	0.0057	0.030	0.0084	0.037
	67%	0.31	0.021	0.0034	0.025	0.0044	0.031
	100%	0.27	0.012	0.0022	0.020	0.0022	0.022
10.0	Original model	0.21	0.011	0.0019	0.015	0.0040	0.021
	33%	0.20	0.0080	0.0014	0.013	0.0019	0.016
	67%	0.18	0.0044	0.00069	0.011	0.00072	0.013
	100%	0.16	0.0026	0.00041	0.0087	0.00036	0.0092
9.0	Original model	0.092	0.0013	0.00014	0.0037	0.00021	0.0049
	33%	0.087	0.0010	0.00010	0.0034	0.00005	0.0038
	67%	0.079	0.0005	0.00004	0.0027	0	0.0028
	100%	0.069	0.0003	0.00002	0.0020	0	0.0019
8.0	Original model	0.027	0	0	0.00043	0	0.00052
	33%	0.026	0	0	0.00039	0	0.00036
	67%	0.024	0	0	0.00027	0	0.00026
	100%	0.021	0	0	0.00020	0	0.00015

5.2 **Low-hazard models – trends with minimum strength**

The trends with %NBS were very similar for both the low-hazard and the high-hazard versions of the models, for both relative loss ratio and relative death and injury rates. The only clear and consistent difference was that the death rates in the city low-hazard model were consistently higher than their high-hazard counterparts for the 100%NBS case. This was probably due to the retention of a proportion of deficient buildings in the low-hazard model.

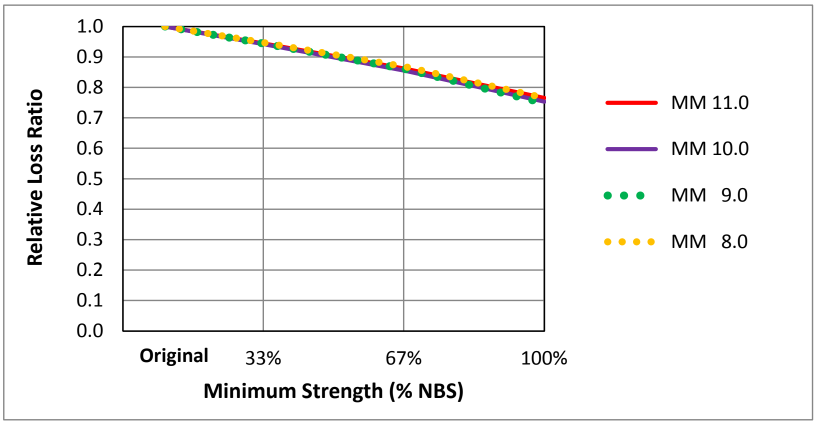

Figure 1. Normalised variation in loss ratio with minimum allowable building strength, for a city in a region of high seismic risk (Wellington). Loss ratios are expressed as fractions of the “Original model” values.

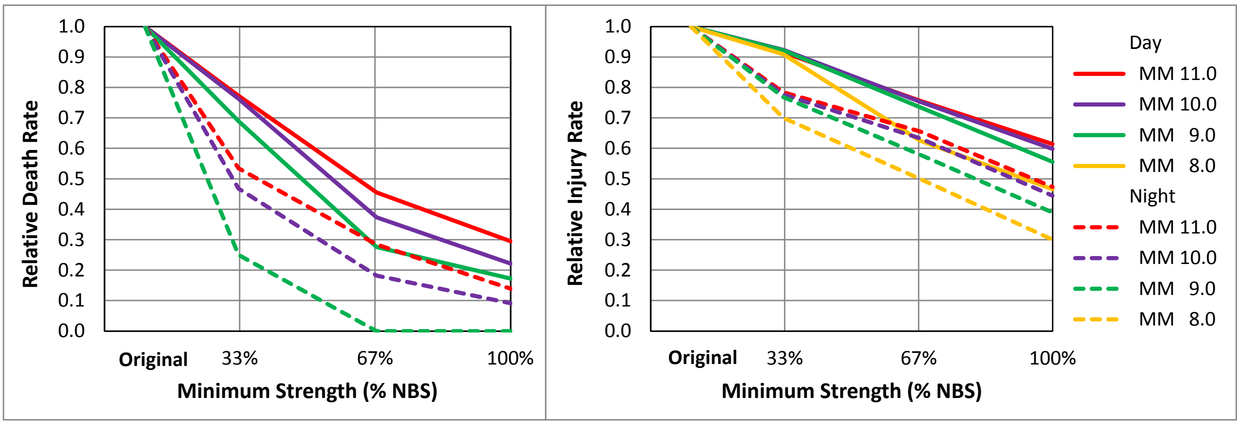

Figure 2. Normalised variation in death and injury rates, as functions of minimum allowable building strength, for a city in a region of high seismic risk (Wellington). There were no deaths at MM8.0.

5.3 Effect of city size

The size of the locality had a relatively small influence on the loss ratio, but had a large influence on the casualty rates with the death rates in particular being dramatically lower in the town than in the city (Table 4). The results in Table 4 are averages over high and low hazard cases, and also over all MMI levels that gave non-zero results, for the original (un-strengthened) assets models.

Table 4. Loss, collapse and casualty rates as percentages of their equivalents from the city results.

Size of locality	Loss Ratio	Collapse Rate	Day Death Rate	Day Injury Rate	Night Death Rate	Night Injury Rate
Small city	85%	50%	35%	55%	15%	50%
Town	95%	30%	2%	35%	0	30%

A likely reason for the relatively low death rates in the small city case is the smaller proportion of medium and high-rise buildings compared with the city case. Reasons for the miniscule death rates in the town case are (a) the complete lack of medium and high-rise buildings, and (b) the high proportion of timber construction.

5.4 Summary

The modelled benefits of strengthening are (a) relatively modest for damage costs (Figure 1), (b) significant for injuries (Figure 2), and (c) highly significant for deaths (Figure 2).

6 AN ALTERNATIVE APPROACH

If a single building is of interest then the above city-wide approach might not be particularly helpful. For a single building, however, it is valid to combine a probabilistic hazard estimate with the building's fragility function to create a probabilistic risk function. It then is possible to compare the risk levels in different types of building and/or places exposed to different levels of seismic hazard. Using this approach, Figure 3 demonstrates the simulated benefit of strengthening a building from <33%NBS (solid line) to a minimum of 33% (dashed line) and then to 100% (dotted line), in Wellington. The overall reduction in risk of death is about a factor of 10 for this particular building type, and is typically 10 to 20 for most building types at most places in New Zealand.

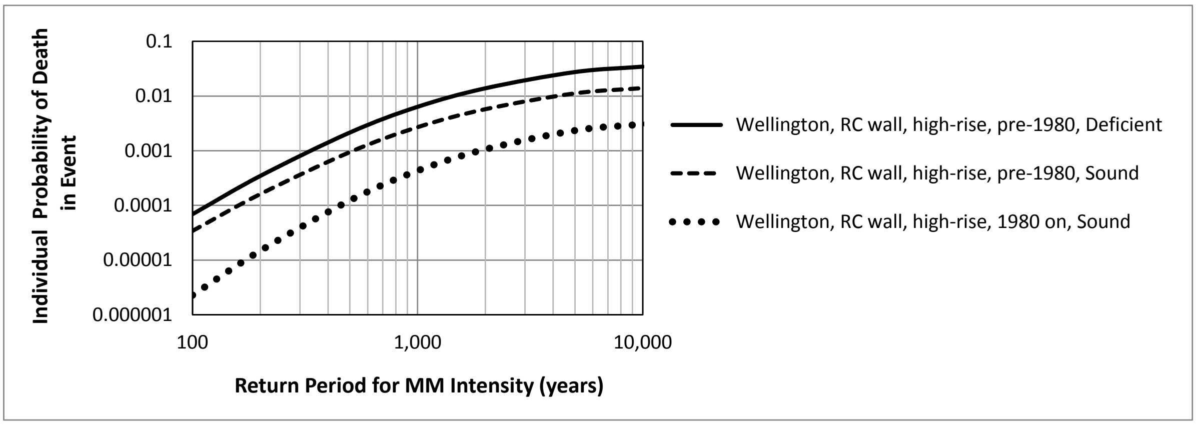

Figure 3. Reductions in death rates due to strengthening a common urban building type from Deficient to Sound quality, and then from pre-1980 to post-1980 design standard. "RC wall" is reinforced-concrete shear-wall.

Figure 4 compares the individual risk of death in a post-1980 and sound version of the most lethal type of building (RCmrf), located in Wellington, with the risks of death in old and un-strengthened URM buildings in places of moderate seismic hazard (Tauranga) and low seismic hazard (Auckland). The Wellington building, being modern and sound, is deemed to present an acceptable level of risk, whereas the other two buildings, being old and deficient, are generally regarded as unacceptable. The relative risks of death as portrayed in Figure 4 do seem to make it difficult to argue a case for blanket strengthening all old URM buildings in places of moderate to low seismic hazard. Bear in mind also that modern high-rise concrete buildings are likely to have many more occupants than old URM buildings.

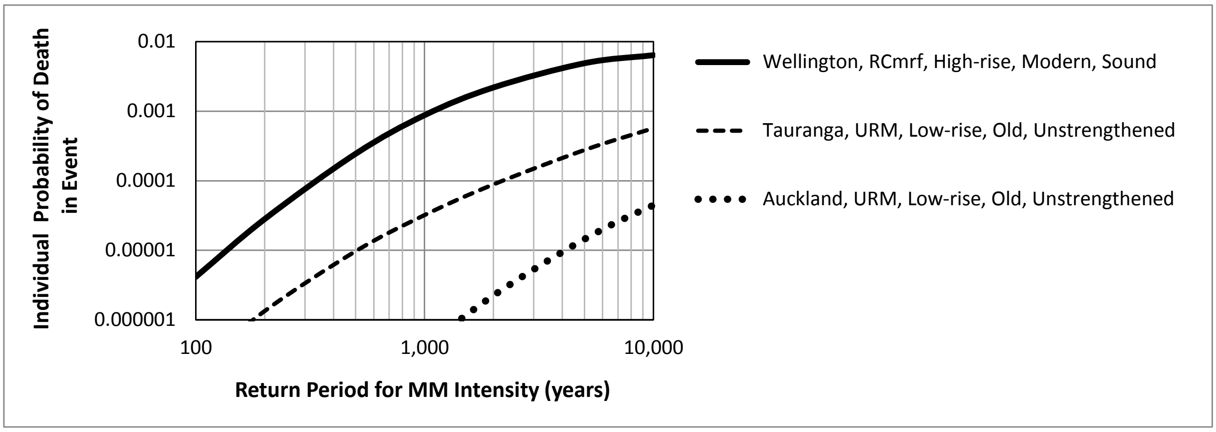

Figure 4. Comparison of death risks in an "acceptable" building type in Wellington and "unacceptable" building types in Tauranga and Auckland.

7 DISCUSSION

A key part of the modelling was the upgrade of substandard buildings to 33% of NBS, then to 67% and 100%. Reiterating the statement from above, it was not possible to base the upgrading on formal engineering calculation, hence it was simulated by making judgement-based changes to the attributes of the buildings in the assets models.

Some validation of the city-scale asset model and the losses calculated using it is provided by the results of recent modelling of the accumulated losses from the sequence of earthquakes that started with the Darfield Earthquake of 3 September 2010 (Cousins et al, 2012). The estimated $17 billion sequence loss for damage to buildings in Christchurch seems reasonable.

Applying similar casualty modelling to the 22 February 2011 Christchurch earthquake gave low numbers of deaths. The median death estimate was 17 (84^{th} percentile 35) for people killed inside buildings, compared with an actual number of 160 (Pomonis et al., 2012). However, deducting the deaths in the CTV (Canterbury Television) building reduces the actual number of deaths to 41, which is not unreasonably higher than the 84^{th} percentile estimate. Note also that the modelling did not allow for the effects of prior damage, or for abandonment of previously damaged buildings.

The collapse of the CTV building does raise the question "how bad is deficient". In the modelling reported here a person in a deficient reinforced-concrete building had 2.5 to 5 times the death risk of a person in a sound one (Figure 3). It must be remembered, however, the modelling was for classes of buildings, and that there can be great variation from one building to another within each class. The relative risks portrayed in Figure 4 do not, therefore, preclude the collapse of a very weak multi-storey building in places of low seismic hazard, even though the likelihood of such an event may be very low. With that in mind the main points to be taken from the above modelling are, (a) strengthening to 100% of new building standard has clear benefits in places of high seismic hazard, (b) blanket strengthening of all older buildings seems difficult to justify in places of low seismic hazard, and (c) there is a need to identify and strengthen substandard high-occupancy buildings of all ages.

8 ACKNOWLEDGEMENTS

Russ Van Dissen and Andrew King of GNS, and an anonymous reviewer, provided thought-proving input to the work, which was funded by DBH and the GNS It's Our Fault project.

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