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FINAL REPORT ON FRAGILITY CURVES FOR RETROFITTED URM BUILDINGS IN AUSTRALIA

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INTRODUCTION

As reported in the previous project report "Fragility Curves for URM Buildings" (Derakhshan and Griffith, 2018), fragility curves are an important tool for estimating the economic loss due to earthquakes. As a follow-up to that work, this report presents fragility curves for URM buildings that have been seismically strengthened. With this additional information, it will be possible to estimate the reduced damage due to seismic retrofit for cost-benefit analyses for a range of earthquake scenarios in order to ensure cost-effective seismic strengthening policy.

With this in mind, the remainder of this report should be treated as an addendum to the previous project report (Derakhshan and Griffith, 2018), hereafter referred to as the *August 2018 report*.

In the present report, we describe the methodology used to produce empirically-based fragility curves for seismically strengthened URM buildings on the basis of performance reported for 78 heritage-listed buildings in Christchurch during the 2010 and 2011 earthquake sequence.

Empirical fragility curves for the global damage of strengthened buildings have been derived using the simplifying assumption that the PGA to cause a particular probability of a given damage state in a strengthened building can be obtained as a scalar multiple of the probability to cause the same damage state in the unstrengthened building. On the basis of this assumption, PGA scaling multipliers are calibrated which can be used to apply a rightward shift to the unstrengthened building curves (from the August 2018 report) to produce the corresponding curves for strengthened buildings. These multipliers were calibrated using the Christchurch earthquake damage data for two levels of retrofit. It was found that a multiplier of 1.4 produces good agreement for buildings with full retrofit, and a multiplier of 1.1 for buildings with partial or incomplete retrofit. It is recommended that for buildings strengthened only for improved out-of-plane wall resistance by means of bracing/ties only, a multiplier of 1.0 should be used.

METHODOLOGY

Source Information

The empirically derived fragility curves for the global performance of strengthened URM buildings developed herein are based on the following:

1) Analytically generated fragility curves for unstrengthened URM buildings as reported in the August 2018 project report (Derakhshan and Griffith, 2018). These curves define the probability of exceeding various damage levels, D1-D4, as a function of the peak ground acceleration (PGA) of the motion. The curves follow the cumulative distribution function of the lognormal distribution with the median PGA values defining the 50% probability of exceedance of a particular damage state being summarised in Table 1. The dispersion of each curve is controlled by the logarithmic standard deviation, β, defined as the standard deviation of $\log_e$(PGA), which in the August 2018 report was recommended to be taken as 0.83.
2) Empirical data for the performance of strengthened and unstrengthened heritage buildings surveyed following the September 2010 and February 2011 Christchurch, NZ earthquakes. More detail of the data is provided in the section “Empirical Data from Christchurch Earthquakes”.

Objective

The objective of this work is to quantify PGA scaling factors for that can be used to shift fragility curves for unstrengthened buildings rightwards to produce fragility curves representative of various retrofit options.

General Procedure

The procedure used to construct fragility curves for each of the three retrofit options consisted of the following steps.

Step 1: Firstly, the fragility curves proposed in the August 2018 report were condensed into a single set of “reference” curves for unstrengthened buildings. This step is necessary as the original curves were disaggregated into 1, 2 or 3 storey buildings. Ideally, the aggregated curves should reflect the actual composition of the Christchurch data set buildings. However for the purposes of the present work the aggregated curves were defined simply by the average of the median PGAs for each number of storeys as per the bottom row of Table 1. This effectively assumes a 1:1:1 distribution of 1, 2 and 3 storey buildings. The resulting curves are shown in Figure 1.

Note that whilst the choice of how these aggregate curves are defined strongly influences the benchmark PGAs determined in step 2, it has very little influence on the multipliers determined in step 3 which is the main objective of this work.

Step 2: Having defined the reference fragility curves in step 1, the next step was to determine PGAs (x-coordinates on these curves) giving the best agreement between these curves and the observed performance of unstrengthened buildings in the empirical data. These benchmark PGAs were quantified separately for the Sep 2010 and Feb 2011 data sets to define a single hazard intensity necessary to compare the damage distributions in unstrengthened and strengthened buildings in step 3.

Step 3: This step involved calibration of PGA scaling multipliers for shifting the original unstrengthened curves rightwards to produce curves for buildings strengthened using alternate retrofit options. This calibration was performed on the basis of best fit between the observed and predicted proportions of the various damage levels by minimizing the total error for the two earthquake events. The resulting multipliers can be interpreted as the increase in the level of shaking the building can withstand following retrofit. A single multiplier that gets applied simultaneously to all damage states was calibrated for each retrofit option.

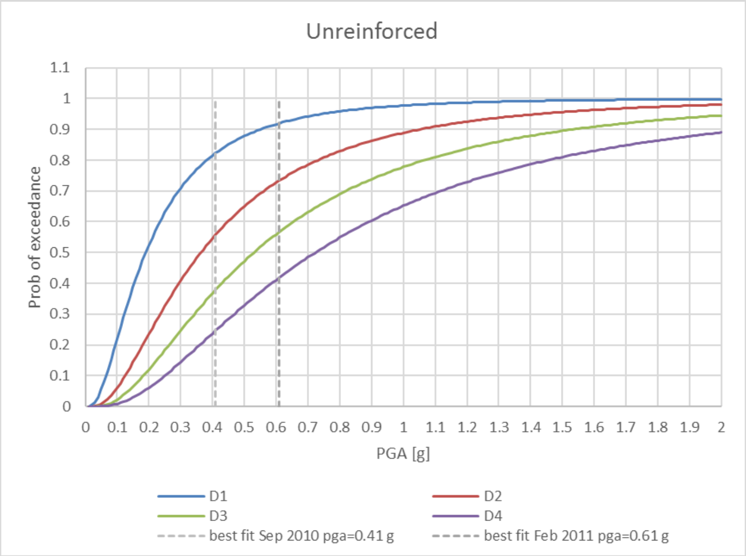
Steps 1 to 3 were repeated for a range of different β values in order to study the sensitivity of the findings on the assumed degree of dispersion.

The calibration of the respective parameters in step 2 (benchmark PGAs) and step 3 (scaling multipliers) was undertaken by maximizing the goodness-of-fit between the predicted proportions of buildings in each damage category (D0+D1, D2, D3, D4). This was done by minimization of total error taken as the sum of the squares of individual errors for each of the four damage categories:

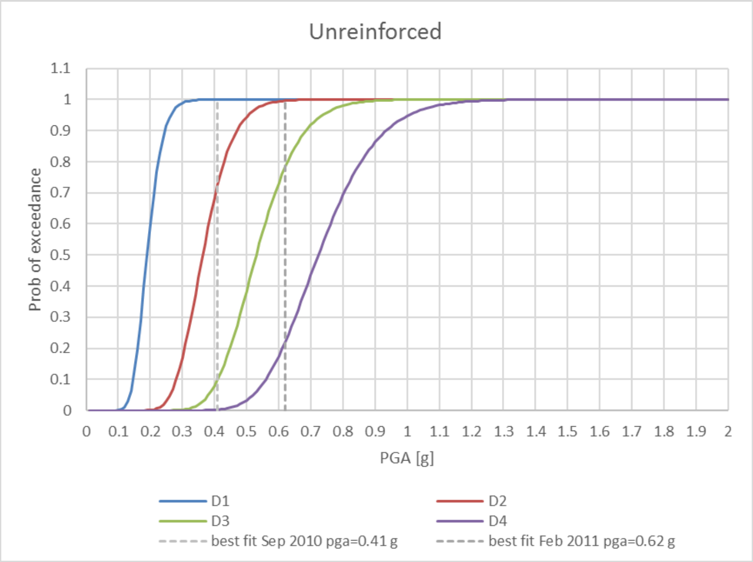
$$\text{total error} = \sum_{i=1}^{4} \left(p_{\text{obs},i} - p_{\text{ana},i}\right)^2 \ , i \in \{D0 + \text{D1}, \text{D2}, \text{D3}, \text{D4}\}$$

equation (1)

where $p_{\text{obs},i}$ and $p_{\text{ana},i}$ are the observed and predicted proportions of buildings falling into damage category *i*.



(a) β = 0.83



(b) β = 0.20

Figure 1: Reference fragility curves for unstrengthened buildings taken as the direct average of 1, 2 and 3 storey buildings. Benchmark PGAs giving best fit with empirical data for the Sep 2010 and Feb 2011 building damage data are also indicated.

Table 1: Median PGA's defining fragility curves for unstrengthened buildings (CRC report Aug 2018)

	Damage state			
No. storeys	**D1**	**D2**	**D3**	**D4**
1 storey	0.31	0.55	0.73	0.97
2 storey	0.15	0.31	0.45	0.63
3 storey	0.11	0.23	0.41	0.57
Average	0.190	0.363	0.530	0.723

Table 2: NZHPT data for number of buildings exhibiting various damage states following the September 2010 Christchurch earthquake (NZHPT, 2012).

NZHPT damage categories:	**Minimal**	**Moderate**	**Severe**	**Major**	**Collapse**	**Sums**
Interpretation:	**D0+D1**	**D2**	**D3**	**D4**	**D4**	
Full building strengthening	24	6	0	0	0	30
Partial/incomplete strengthening	7	9	0	0	0	16
Bracing/ties only	2	6	0	0	0	8
Unstrengthened	6	17	1	0	0	24
Sums	39	38	1	0	0	78

Table 3: NZHPT data for number of buildings exhibiting various damage states following the February 201 Christchurch earthquake (NZHPT, 2012).

NZHPT damage categories:	**Minimal**	**Moderate**	**Severe**	**Major**	**Collapse**	**Sums**
Interpretation:	**D0+D1**	**D2**	**D3**	**D4**	**D4**	
Full building strengthening	4	14	9	2	0	29
Partial/incomplete strengthening	1	5	9	1	0	16
Bracing/ties only	1	0	1	4	2	8
Unstrengthened	0	5	15	4	1	25
Sums	6	24	34	11	3	78

Damage Data from Christchurch Earthquakes

The building damage data used in this study was collected through damage assessment of heritage buildings following the September 2010 and February 2011 events in Christchurch, NZ. The data originates from work undertaken by the New Zealand Historic Places Trust (NZHPT, 2012) which was submitted to the Canterbury Earthquakes Royal Commission and re-reported in "Final Report: Volume 4 – Earthquake-Prone Buildings" (CERC, 2012).

The original data reported by NZHPT includes 100 heritage buildings of which 72 are URM, 15 are timber frame, and 13 were "other construction" including reinforced concrete. Whilst ideally the data set in the present study would include only URM buildings, the damage data reproduced in Tables 2 and 3 are only available in aggregated form, and therefore limiting the data to URM buildings only cannot be readily done at this stage. Of the 100 buildings, only 78 are included in the present data set with the remaining buildings having either unknown strengthening or unknown damage levels.

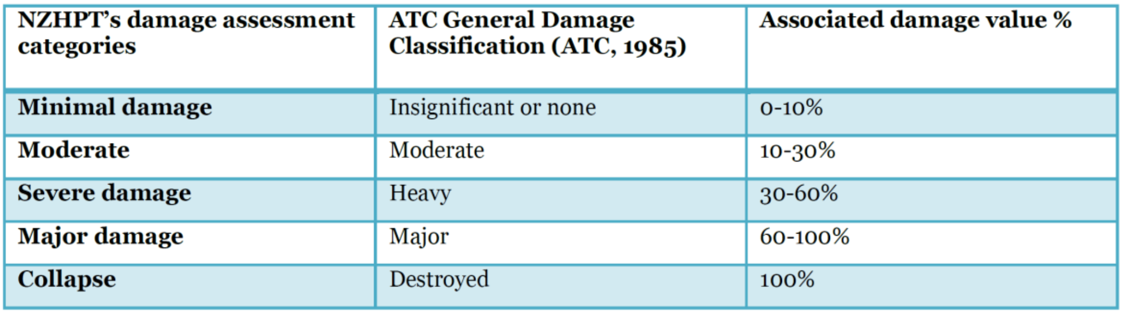
The subset of the NZHPT data used in the present study covers buildings with three levels of strengthening in addition to no-strengthening. These basic categories, including the associated descriptions as provided in the NZHPT report are as follows:

- **No strengthening** (25 buildings)
- **Bracing and ties only:** Involves bracing to secure chimneys, towers, and also parapet and gable bracing with floor, roof and ceiling ties. (8 buildings)
- **Partial/incomplete strengthening:** Refers to instances where the strengthening was incomplete or present in only one part of the building (16 buildings)
- **Strengthening of entire building**: Refers to instances where the building was substantially strengthened. Includes enhancement of building response by various techniques such as concrete shear walls, steel frames, infilling of wall openings, post-tensioning, grouting rubble filled walls. Also includes some instances of using ‘new’ techniques such as carbon FRP or stainless steel rods to reinforce masonry walls. (29 buildings)

The global building damage categories adopted in the NZHPT report are based on equivalent ATC-13 (ATC, 1985) damage categories summarised in Table 4. To align these categories with the D1-D4 categories used for the reference fragility curves (refer to August 2018 report), the conversion scheme presented in Table 5 was used. Note that “minimal damage” in the NZHPT scheme was interpreted as inclusive of damage stage D1 as well as the case of ‘no damage’ denoted here as D0. The resulting distributions of observed damage in the empirical data set in terms of D0-D4 are summarised in Tables 6 and 7.

From the mean D-levels provided in the last columns of Tables 6 and 7 it is seen that as expected, in both the Sep 2010 and Feb 2011 events the average level of damage reduces as the extent of the retrofit is increased. The exception to this is the “bracing/ties only” option in the Feb 2011 data set, which appears to have a greater average damage level than buildings that were left unstrengthened. It is not at this stage clear why this should be the case, since bracing of parapets should have minimal effect on the global damage response, and thus a possible reason for this aberration is the small number of sample buildings in this retrofit category.

Table 4: Description of global damage categories reproduced from the NZHPT (2012) report.



NZHPT's damage assessment categories	ATC General Damage Classification (ATC, 1985)	Associated damage value %
Minimal damage	Insignificant or none	0-10%
Moderate	Moderate	10-30%
Severe damage	Heavy	30-60%
Major damage	Major	60-100%
Collapse	Destroyed	100%

Table 5: Conversion from NZHPT damage categories to D-category equivalents for the global damage to URM buildings.

NZHPT report damage descriptors	Assumed D-category equivalents
Minimal damage	D1 – slight: cracking limit. Also used to encompass 'no damage' denoted here as D0
Moderate damage	D2 – structural damage: maximum capacity
Severe damage	D3 – near collapse: loss of equilibrium
Major damage	D4 – collapse
Collapse	

Table 6: Proportion of observed buildings with damage states D0+D1, D2, D3, and D4 following the September 2010 Christchurch earthquake.

NZHPT damage categories:	**Minimal**	**Moderate**	**Severe**	**Major**	**Mean D level**
Interpretation:	**D0+D1**	**D2**	**D3**	**D4**	
D level:	**0.5**	**2**	**3**	**4**	
Full building strengthening	0.80	0.20	0.00	0	0.8
Partial/incomplete strengthening	0.44	0.56	0.00	0	1.3
Bracing/ties only	0.25	0.75	0.00	0	1.6
Unstrengthened	0.25	0.71	0.04	0	1.7

Table 7: Proportion of observed buildings with damage states D0+D1, D2, D3, and D4 following the February 2011 Christchurch earthquake.

NZHPT damage categories:	**Minimal**	**Moderate**	**Severe**	**Major**	**Mean D level**
Interpretation:	**D0+D1**	**D2**	**D3**	**D4**	
D level:	**0.5**	**2**	**3**	**4**	
Full building strengthening	0.13	0.47	0.30	0.07	2.2
Partial/incomplete strengthening	0.06	0.31	0.56	0.06	2.6
Bracing/ties only	0.13	0.00	0.13	0.75	3.4
Unstrengthened	0.00	0.21	0.63	0.21	3.1

RESULTS AND DISCUSSION

Benchmark PGA's for the Sep 2010 and Feb 2011 events

For each event (Sep 2010 and Feb 2011), benchmark PGA's were calibrated as described in step 2 of in the Section "General procedure". This calibration was performed by minimizing the total error given by equation (1).

By adopting β = 0.83 as proposed in the August 2018 report, best-fit between the reference fragility curves (Figure 1a) and the Christchurch data for unstrengthened buildings (Tables 6 and 7) becomes achieved at PGA = 0.41 g for the Sep 2010 event and 0.61 g for the Feb 2011 event. Bar graphs of the associated damage state distributions are shown in Figure 2. It is seen however that the fit between the curves and observed damage distributions is poor as the damage distributions predicted by the curves are excessively dispersed between the four categories. This suggests that the assumed β value of 0.83 is too large in relation to this data set.

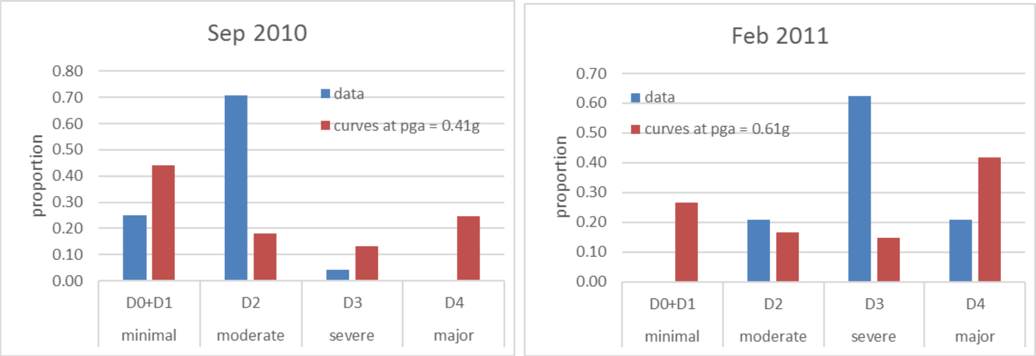


Figure 2: Fit between unstrengthened building fragility curves and empirical data at β = 0.83.

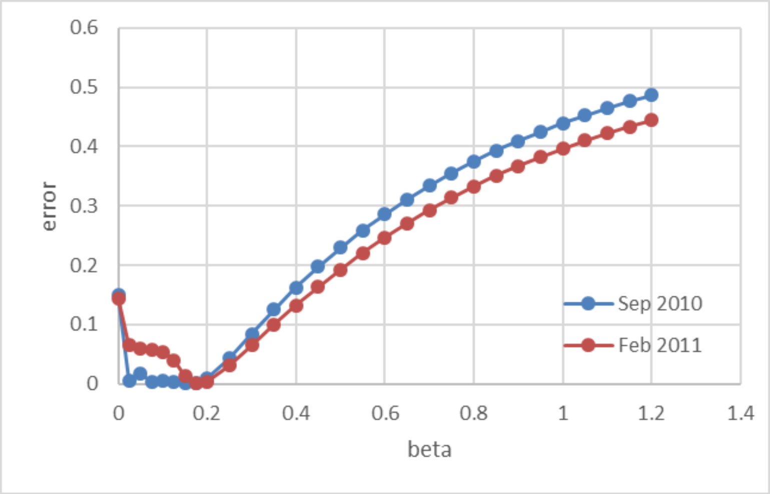


Figure 3: Error between the predicted and observed damage distributions at the optimal PGA values with reference to unstrengthened building data.

The fit between the curves and data becomes considerably better if the value of β is reduced, as indicated by the plot in Figure 3. Particularly good fit is obtained within the β range of 0.15-0.3.

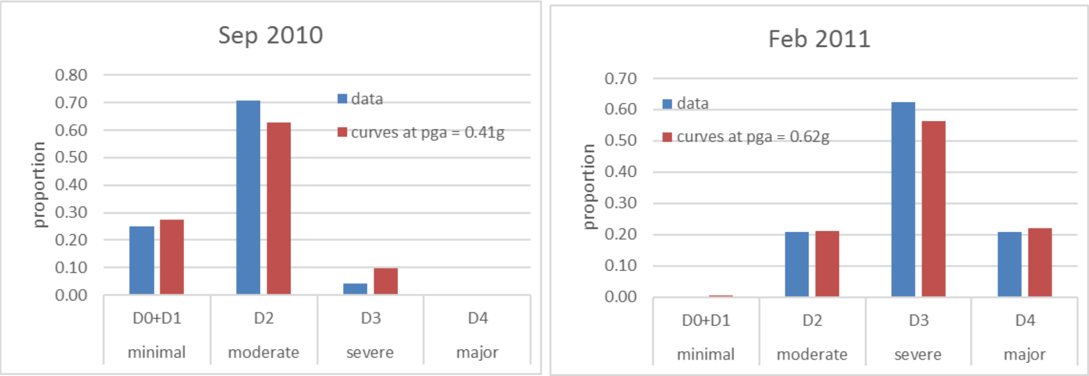


Figure 4: Fit between unstrengthened building fragility curves and empirical data at β = 0.2.

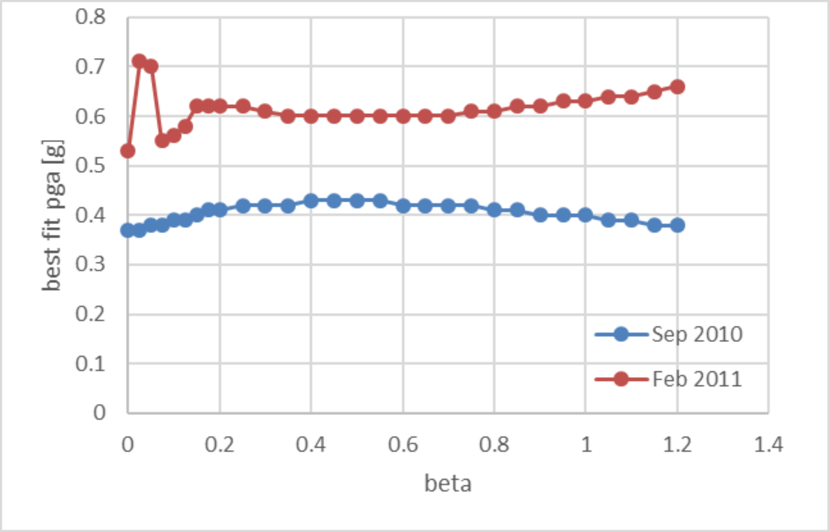


Figure 5: PGAs leading to best fit between fragility curves and unstrengthened building data for varied β.

Figure 4 shows a comparison of the data with predicted damage distribution at β = 0.2 (Figure 1b), where the fit is seen to be considerably better than in Figure 2. Best fit for β = 0.2 is achieved at benchmark PGAs of 0.41 g and 0.62 g for the Sep 2010 and Feb 2011 earthquakes respectively. It is seen that although the fit has substantially improved relative to β = 0.83, the reference PGAs have not changed significantly as a consequence of varying β. This insensitivity between the best-fit PGAs with respect to β is further demonstrated by the plot in Figure 5.

Let us compare these 'best-fit' PGAs to actual ground motion measured in the earthquake events. The mean measured PGAs within the Christchurch CBD where the majority of the reference buildings were located were 0.25 g in the September 2010 (Darfield) earthquake (Cousins and McVerry, 2010) and 0.46 g in the February 2011 earthquake (Bradley and Cubrinovski, 2011). These correspond to 61% and 74% of the best-fit PGAs deduced from the aggregated reference fragility in Figure 1. In other words, the reference fragility curves imply that the buildings should have had a higher level of capacity than was observed in the empirical data set (i.e. the curves appear to be slightly unconservative).

The following explanations are provided to account for this difference:

- The buildings in the Christchurch data set may have had a greater inherent vulnerability than the buildings used to construct the analytical fragility curves in the August 2018 report. A possible reason for this is that the latter were rectangular in shape and relatively regular in terms of their wall layouts, whereas inspection of the buildings in the NZHPT report indicates that many of buildings in the empirical data set were irregular.
- The earlier assumption of constructing reference fragility curves (Figure 1) as the 1:1:1 aggregate of 1, 2 and 3 storey buildings may not be fully accurate.
- Variability due to differences in other influencing variables such as the ground motion or constitutive material properties.

To examine the influence of the composition of the reference fragility curves (second point above), the PGA calibration process was repeated by assuming the reference curves to follow wholly the 1, 2 and 3 storey building fragility curves whose median PGA values are presented in Table 1. The results are summarised in Table 8 (with $\beta = 0.2$). It is seen that fragility curves for 3 storey building composition lead to closest agreement with the recorded PGA values of 0.29g and 0.45 g for the Sep 2010 and Feb 2011 events. If we ignore the 1 storey buildings, then the reference PGAs resulting from the alternate assumptions (2 storey, 3 storey, or 1:1:1 average) range between 0.29-0.41g for the Sep 2010 event and 0.45-0.61g for the Feb 2011 event, which provides reasonable agreement with the range of values reported by Cousins and McVerry (2010) and Bradley and Cubrinovski (2011, that is, 0.19-0.33 g for Sep 2010 and 0.37-0.52 g for Feb 2011.

Table 8: Best-fit PGAs for the Sep 2010 and Feb 2011 earthquakes under alternate assumptions regarding the composition of the reference fragility curve set. Assumed $\beta = 0.2$.

Reference curve set composition	**Best-fit PGA** **Sep 2010**	**Best-fit PGA** **Feb 2011**
1 storey only	0.59 g	0.87 g
2 storey only	0.35 g	0.53 g
3 storey only	0.29 g	0.45 g
Average (taking 1:1:1 composition of 1,2,3 storey)	0.41 g	0.61 g
Average recorded PGAs, range in brackets	*0.25 g (0.19-0.33 g)*	*0.45 g (0.37-0.52 g)*

Calibration of PGA scaling multipliers for different retrofit options

Using the empirical data presented in Tables 6 and 7, PGA scaling multipliers for each of the three retrofit options were calibrated by the procedure described in step 2 of in the Section "General procedure". The calibration was performed by minimizing the error given by equation (1) summed for the Sep 2010 and Feb 2011 events. This process assumed that the PGA intensity for the entire population of strengthened and unstrengthened buildings was equal to the benchmark PGAs determined previously (for any value of β being considered).

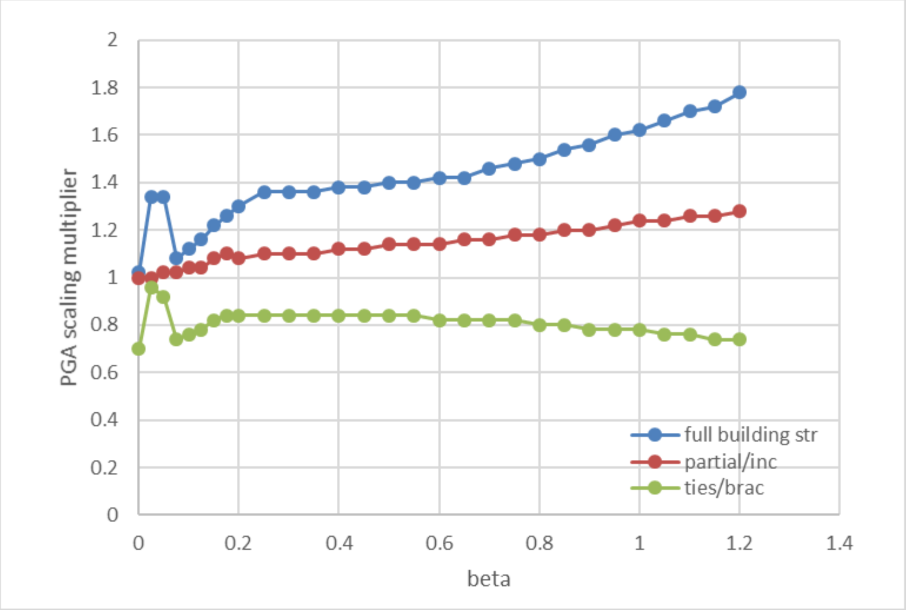


Figure 6: Best-fit PGA scaling multipliers for different retrofit options

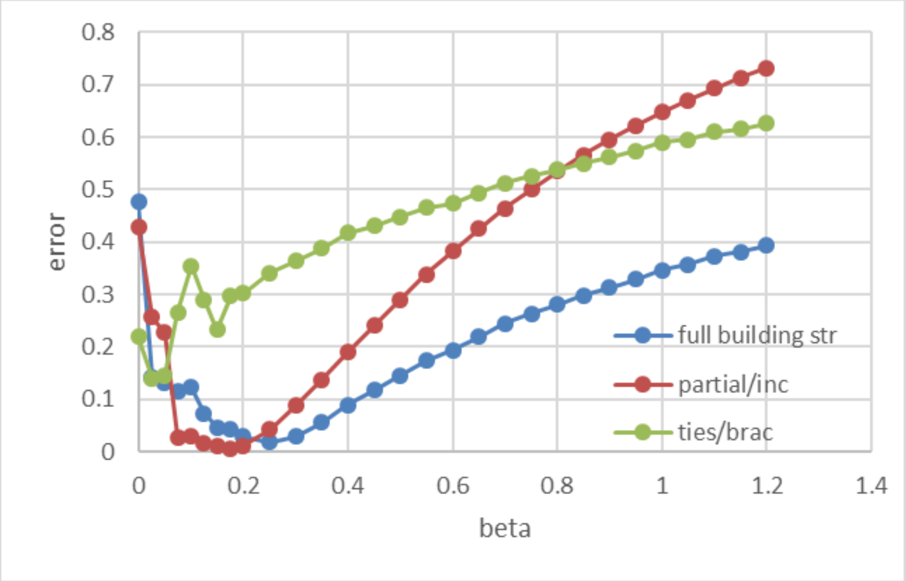
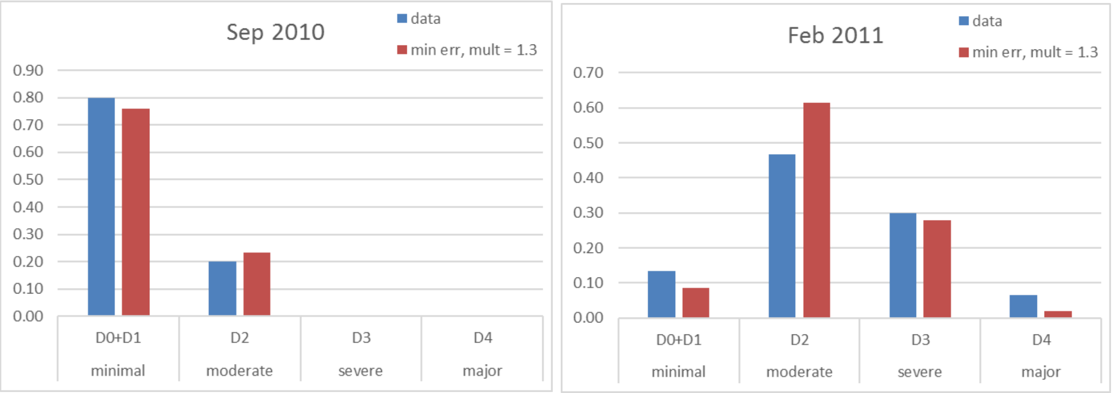


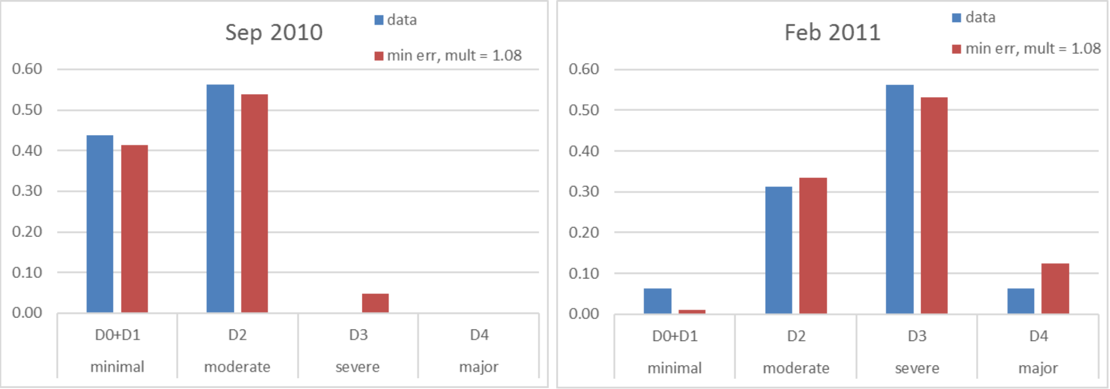
Figure 7: Calibration error corresponding to Figure 6.

The results presented in this section are based on reference fragility curves for the 1:1:1 composition of 1, 2 and 3 storey buildings (Figure 1); however, as stated earlier this assumption has little influence on the resulting multipliers.

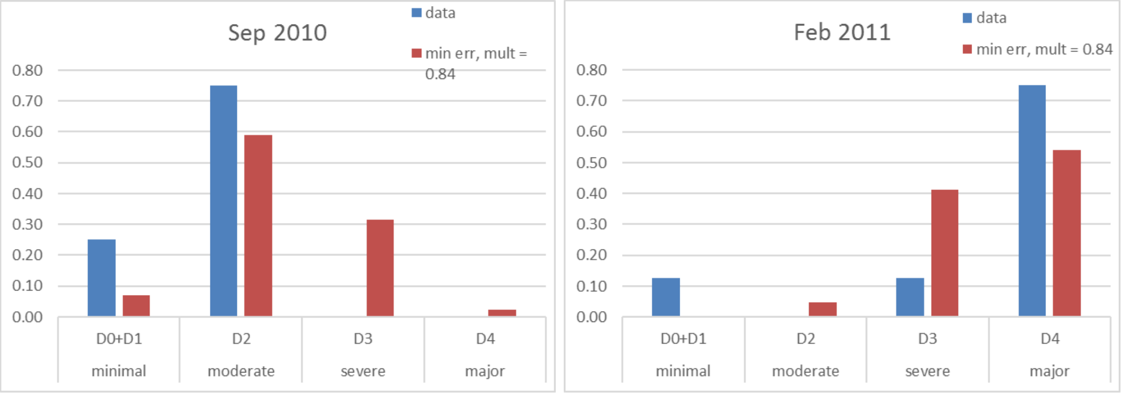
The best-fit multipliers at any assumed β value are plotted in Figure 6. The corresponding total error is plotted versus the assumed β in Figure 7. It should be noted that the calibration of the scaling multiplier for each retrofit uses the same global β that was applied to the unstrengthened curved in quantifying the benchmark PGAs. From Figure 7 it is seen that for each retrofit option, the quality of the fit is poor at β = 0.83, and that the lowest error occurs for β ranging approximately between 0.15-0.3.



(a) Full building strengthening



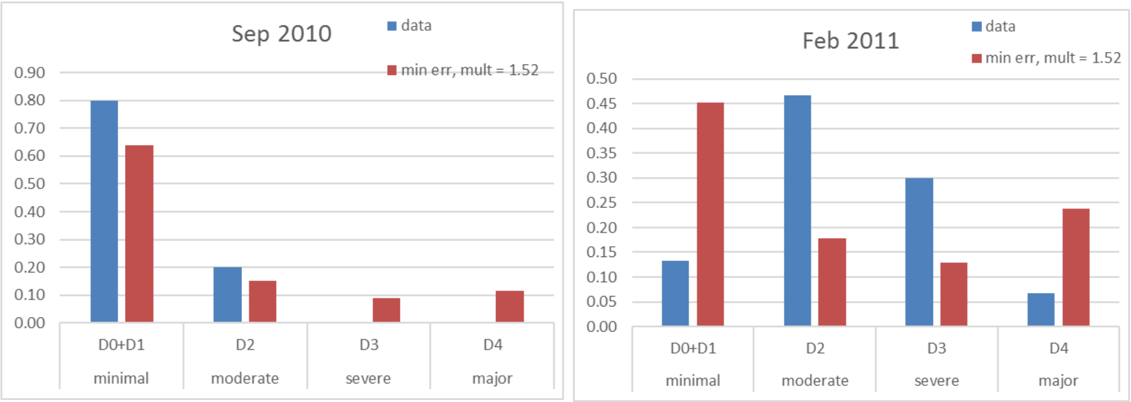
(b) Partial/incomplete strengthening



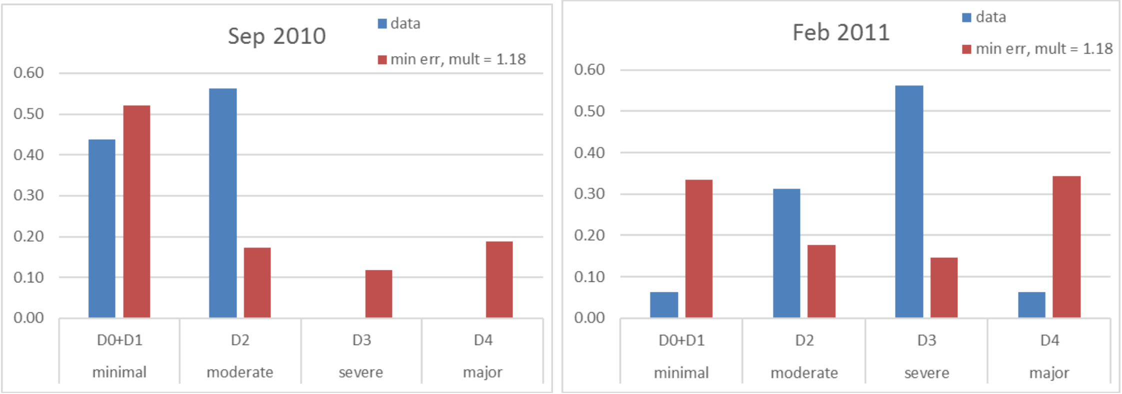
(c) Bracing/ties only

Figure 8: Comparison of observed and predicted damage distribution for various strengthening options (β = 0.2)

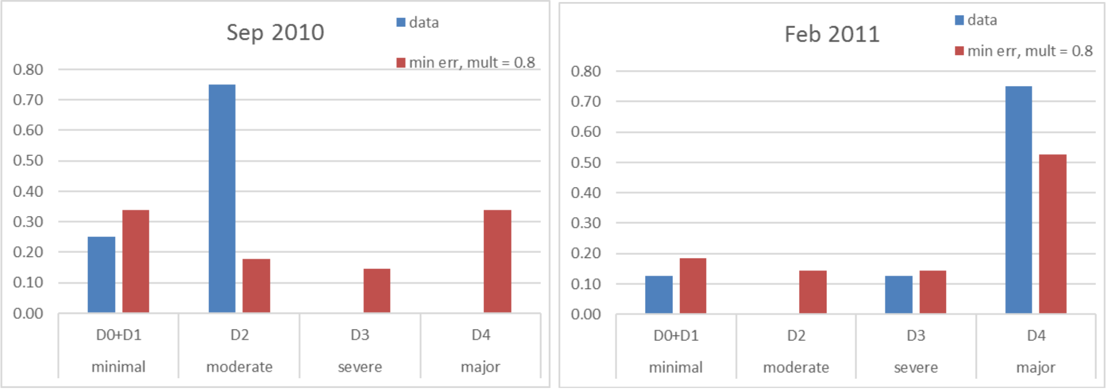
For illustrative purposes, taking β = 0.2 the predicted and observed distributions of the different damage states are plotted in Figure 8, which shows good general agreement for each retrofit option. For comparison, the same plot is provided in Figure 9 using the original β value of 0.83, where it is seen that the predictions become excessively dispersed between the different damage categories similarly to the case for the unstrengthened building data set (refer Figure 2).



(a) Full building strengthening



(b) Partial/incomplete strengthening



(c) Bracing/ties only

Figure 9: Comparison of observed and predicted damage distribution for various strengthening options (β = 0.83)

Although it has been demonstrated that lower β values ranging between 0.15-0.3 lead to the better agreement between the fragility curves and empirical data, this can be partially explained by the low uncertainty in relation to the regional hazard intensity. That is, in each of the Sep 2010 and Feb 2011 events, the population of buildings in the data set was subjected to an approximately uniform 'regional' intensity even though local variation is still present due to variability in site effects. Thus, for the purposes of making blind predictions (rather than validation using an empirical data set), adopting a higher value of β remains justifiable to account for uncertainty in the regional hazard. Based on personal communication with Derakhshan (2018), an overall β value of 0.57 is thought to be reasonable to allow for the aggregated uncertainty related to the material, structural form, and seismic hazard.

The calibrated scaling multipliers within these alternate ranges of β are presented in Table 9. The final recommended values, irrespective of the adopted β are given in the last column. It is recommended that a value of 1.4 can be used for full building strengthening and 1.1 for partial/incomplete retrofit. In the case of retrofit using bracing/ties only we recommend using a value of 1.0 (i.e. no effect on global behaviour), even though the calibration suggests that a lesser value should be used.

Plots of the final fragility curves for the global damage in strengthened buildings are not presented here in graphical form since this is a trivial task but would be obtained simply by scaling the median PGAs in Table 1 by the multipliers in Table 9.

Table 9: Calibrated PGA scaling multipliers for alternate retrofit options.

Retrofit option	PGA scaling multipliers			
	For β = 0.15-0.3	At β = 0.57	At β = 0.83	**Final recommended**
Full building strengthening	1.22 - 1.36	1.42	1.52	**1.4**
Partial/incomplete strengthening	1.08 - 1.10	1.14	1.18	**1.1**
Bracing/ties only	0.82 – 0.84	0.84	0.80	**1.0** *

* For the ties/bracing-only option, a value of 1.0 is recommended as the calibrated values are thought be lack reliability as they are based on only a small number of data points.

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