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FINAL REPORT ON VULNERABILITY OF AS-BUILT AND RETROFITTED URM BUILDINGS

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INTRODUCTION

As reported in the previous project reports "Fragility Curves for URM Buildings" (Derakhshan and Griffith, 2018) and "Fragility Curves for Retrofitted URM Buildings" (Vaculik and Griffith, 2018), fragility curves are an important tool for estimating the economic loss due to earthquakes. In this report, *Fragility* is used as a proxy for *Vulnerability*. As a follow-up to the work presented in the previous two reports, this report presents fragility curves for 'as-is' and 'retrofitted' URM buildings in terms of 'probability of exceedance' versus 'peak ground acceleration' (PGA) for four damage ratios, D1 – D4. 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 two project reports (Derakhshan and Griffith, and Vaculik and Griffith, 2018), hereafter referred to as the *August and October 2018 reports*.

In the October 2018 report, we described 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 a *full building strengthening* level of retrofit, and a multiplier of 1.1 for buildings with *partial or incomplete strengthening*. These relatively low values are a result of the fact that the unreinforced masonry buildings in Christchurch were retrofitted as many as 50 years ago when seismic strengthening technologies for URM buildings were in their infancy. With advances in our understanding and improved retrofit technologies of today, where the seismic strengthening techniques have been experimentally validated, slightly higher scaling multipliers of 1.25 and 1.6 are justified and were used to generate the fragility curves for partial and full seismic retrofit, respectively.

DEVELOPMENT OF FRAGILITY CURVES

Descriptions of Damage States

The global building damage categories adopted in the NZHPT (2012) report, which were used in the damage reconnaissance of strengthened and unstrengthened buildings following the Christchurch earthquakes (and the development of strengthened building fragility curves as reported in the October 2018 report) are based on equivalent ATC-13 (ATC, 1985) damage categories summarised in Table 1. 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 2 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 3 and 4.

From the mean D-levels provided in the last columns of Tables 3 and 4 it is seen that as expected, in both the Sep 2010 and Feb 2011 Christchurch 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 1: 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 2: 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 3: 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 4: 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

Descriptions of Retrofit Levels

The subset of the NZHPT (2012) empirical data used in developing fragility curves for strengthened buildings (October 2018 report) covered buildings with three levels of strengthening as well as buildings without 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 extent of the strengthening was incomplete or present in only one part of the building (16 buildings). The methods of retrofit themselves are understood to be the same as described under the "strengthening of entire building" level of retrofit".
- **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)

In the October 2018 report it was observed that buildings retrofitted by the "bracing and ties only" option showed no improvement in terms of mitigating global building damage relative to unstrengthened buildings. Therefore, in the present report, only retrofit levels corresponding to "partial/incomplete strengthening" = <u>partial retrofit</u> and "strengthening of entire building" = <u>full retrofit</u> are considered.

It is important to note that the adopted retrofit levels—i.e. "partial/incomplete strengthening" and "strengthening of entire building"—are descriptors of the *extent* of the retrofit works throughout the building, rather than indicators of the strengthening performance targets. Notably, the strengthening performance targets, which are conventionally expressed as a percentage of the New Building Standard (%NBS), were largely unknown for the buildings within the data set in the NZHPT (2012) study and hence the October 2018 report. The NZHPT report does state however that based on expert opinion, 8 of the 100 buildings were likely to have been strengthened to above 67% NBS, 11 buildings to 33-67% NBS, 7 buildings to less than 33% NBS and the remaining 74 buildings were unknown (also encompassing unstrengthened buildings).

Final Fragility Curves

The fragility curves developed as part of this work undertaken (August and October 2018 reports) are presented in Figures 1-3. The curves follow the lognormal distribution, and can be generated using the formula

$$P = \Phi\left(\frac{\log x - \log \mu}{\beta}\right)$$

Where Φ(..) is the cumulative distribution function of the standard normal distribution, x is the PGA value, μ is the median PGA for exceedance of the particular damage level (indicated on each curve). The standard deviation β, was taken as 0.83 for all curves which encapsulates various sources of uncertainty (refer August 2018 report).

Figure 1 shows the analytically derived fragility curves for unstrengthened 1, 2 or 3 storey buildings as reported in the August 2018 report.

Figures 2 and 3 provide corresponding curves for retrofitted buildings at the partial/incomplete and full-building levels of retrofit. These curved were produced by a rightward shift of the unstrengthened building curves using scaling factors of 1.25 and 1.6 respectively. Note that these were increased from 1.1 and 1.4 respectively, for reasons justified in the Introduction of the present report.

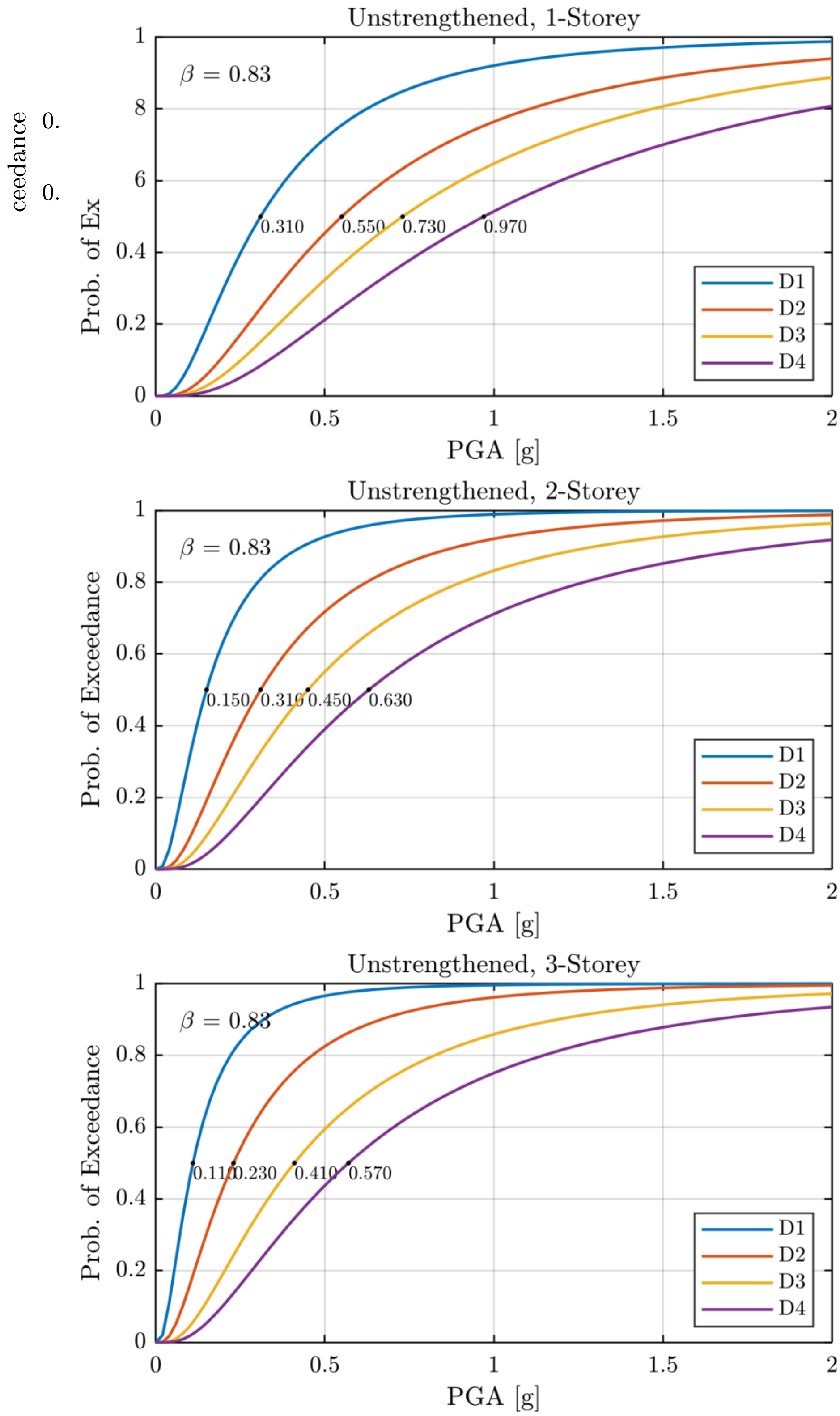

Figure 1: Fragility curves for unstrengthened buildings: 1, 2 and 3 storey.

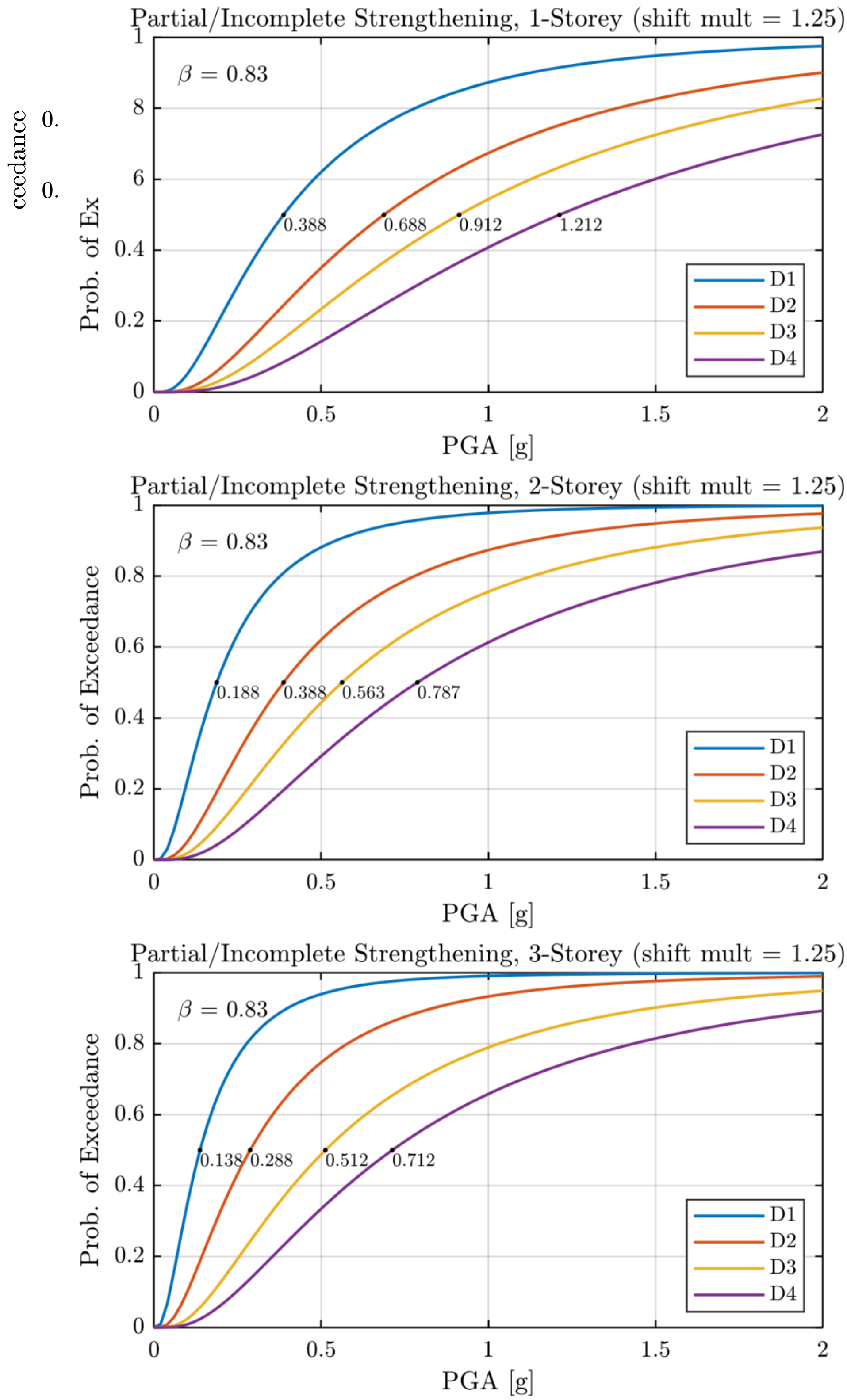

Figure 2: Fragility curves for buildings with partial/incomplete strengthening: 1, 2 and 3 storey.

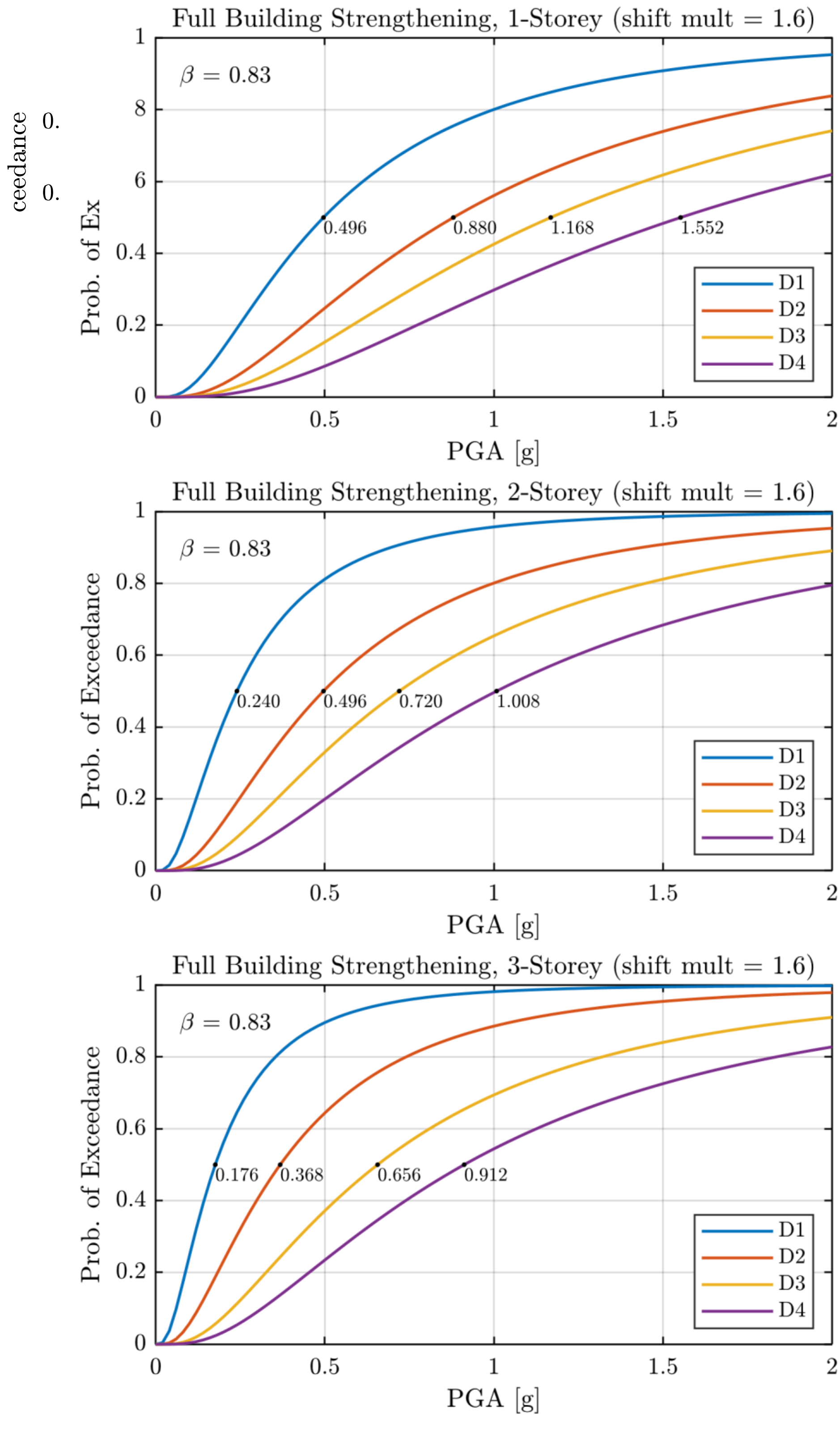

Figure 3: Fragility curves for buildings with full building strengthening: 1, 2 and 3 storey.

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