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FINAL REPORT ON PUSHOVER ANALYSIS OF CLASSES OF URM BUILDINGS TO CHARACTERISE DRIFT RATIOS FOR DIFFERENT DAMAGE LEVELS

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ABSTRACT

ESTABLISHING THE RELATIONSHIP BETWEEN THE BUILDING DAMAGE AND ITS LATERAL DEFORMATION

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It is widely considered that building structural damages during earthquakes can be calibrated against building's lateral drift. A study of this relationship assists in the development of fragility curves, which can be used as part of large-scale seismic risk evaluation. In the current study, pushover analyses were conducted on four prevalent Australia/New Zealand unreinforced masonry (URM) building typologies to study this relationship. The buildings were modelled as equivalent frames using a commercial software, and the damage progress within the building under increasing lateral drifts were recorded. Limits of displacements corresponding to different damage states were established and compared to the values found in other studies and/or recommended by ASCE guidelines. The earlier studies that were used in the comparison included two NZ-based numerical research that were aimed at reproducing damages that were occurred to 3 buildings during the recent New Zealand (Gisborne 2007 and Christchurch 2011) earthquakes. The comparisons suggest that storey drift limits recommended in ASCE guidelines can be used to conservatively estimate building damage state.

INTRODUCTION

The purpose of this pushover study was to investigate characteristic response of typical Australian URM buildings subjected to earthquake forces. The information that is obtained through pushover analysis will be useful in generating fragility curves. Specifically, damage limit states can be characterised as a function of the building drift, which then can be related to earthquake intensities.

Globally, URM construction type and details vary significantly among different regions. The differences are due to both materials, structural configuration, and construction practice. However, for countries that feature a relatively narrow timespan of construction, it has been found (Russel 2010) that the constructed buildings can be classified into a few prevalent forms. Such classification enables large scale seismic evaluations possible by considering only a few building typologies. The start of Australian URM construction dates back to early 19th century, and therefore URM building age is mostly less than 200 years.

This relatively narrow timespan combined the shared construction practices with Victorian countries, including that of USA, has resulted in the predominance of certain building types. A detailed architectural classification of New Zealand buildings has been conducted by Russel (2010). Griffith et al. (2013) has documented that older Australian URM buildings have similar structural configurations to NZ buildings. Despite the decline of NZ URM building construction post Hawkes Bay's 1935 earthquake, URM buildings are still built in Australia resulting in newer building typologies. However, with the advent of seismic loading codes in the middle of 20th century, the newer buildings mostly include detailing that have resulted in a better expected seismic performance. This study is focused on older URM buildings that have been built without any consideration given to seismic forces.

This progress report on pushover analysis of URM building typologies includes a literature review on building damage Limit States, for which data has been generated typically using pushover analysis. The review includes recent New Zealand studies on 3 earthquake damaged buildings. The review is followed by a report of pushover analyses done on a few building typologies.

LITERATURE REVIEW

Three buildings that are shown in Figure 1 were damaged in the 2007 Gisborne earthquake (first building) or in the February 2011 Christchurch earthquake (the other two buildings). The buildings were either two-storey or three-storey and had timber floors and roofs.

Lancaster House (LH) Royal Hotel (RH) Avonmore House (AH)

Figure 1: Three buildings that were studied in Cattari et al. (2015) and Marino et al. (2016)

The buildings were modelled using TREMURI (Lagomarsino et al. 2013) and also using more detailed finite element (FE) package (DIANA). Both pushover analysis and nonlinear time history analyses using the site earthquake motions were done in Cattari et al. (2015) and Marino et al. (2016). The main outcome of the studies were matching the damage pattern in the building numerical models to that observed in the earthquakes.

It was found that relatively small building drift ratio of 0.06% (i.e. compared to existing literature, ASCE 2014) was responsible for sustained damages in LH building. However, the reported damages were extensive and can be assessed to be between Life Safety and Immediate Occupancy states. Such a limit is typically termed as Damage Control, DC, in which the building is not occupiable and significant repairs may be necessary while the human life has not been threatened. The drift ratio for that level can be estimated from the ASCE guidelines (Figure 2) to be between 0.3% and 0.6%, hence greatly exceeding the 0.06% that is estimated for LH building. Similarly, the ASCE (2014) guideline suggests trigger drift ratios of 1% and 0.6%, respectively, for collapse prevention and life safety limit states. However, pushover analyses in large displacement range as reported by Cattari et al. (2015) suggested a CP limit ratio can be associated to a drift ratio of only 0.2%.

A possible explanation for larger drift ratios in ASCE document is that the NZ studies reported only building drift and that wall drifts could be up to 3 times the building drift if the damage was concentrated on a specific storey of the 3-storey building. The damage photos suggest that the distribution of the damage with building height were likely focused on certain storey in some walls but it was 'distributed' with height in some other walls (Cattari et al. 2015).

		Structural Performance Levels		
		Collapse Prevention (S-5)	Life Safety (S-3)	Immediate Occupancy (S-1)
Unreinforced Masonry (Noninfill) Walls	Primary	Extensive cracking; face course and veneer may peel off. Noticeable in-plane and out-of-plane offsets.	Extensive cracking. Noticeable in-plane offsets of masonry and minor out-of-plane offsets.	Minor (< 1/8-in. width) cracking of veneers. Minor spalling in veneers at a few corner openings. No observable out-of-plane offsets.
	Secondary	Nonbearing panels dislodge.	Same as primary.	Same as primary.
	Drift	1% transient or permanent.	0.6% transient; 0.6% permanent.	0.3% transient; 0.3% permanent.

Figure 2: ASCE recommendations for URM wall drift limits

Two other NZ buildings (Figure 1b and 1c) that were damaged in the Canterbury earthquakes were studied by Marino et al. (2016) in a similar fashion as explained above. The buildings were 2-storey (RH; Figure 1b) or 3-storey (AH; Figure 1c) with a height of, respectively, 7.17 m and 11.15 m. Similar to the above-discussed building (LH), the walls of these two buildings were considerably thicker than the typical geometries reported in Russel (2010). Wall thickness in RH was 4 leaves and 3 leaves, respectively, in the lower and upper floor. In the other building, the wall thicknesses were 6 leaves, 5 leaves, and 4 leaves, respectively, in ground, first and second levels.

Of particular importance was the seismic retrofit of AH building in 1994, whereby the floor diaphragms were stiffened and the wall-diaphragm connections in the form of adhesive anchors and perimeter steel angles were installed.

Of the important findings of the study by Marino et al. (2016) was the estimated period of 0.13-0.2 sec and 0.17-0.19sec depending on the direction, respectively for the 3-storey AH and 2-storey RH buildings. Marino et al. (2016) concluded that the AH building maximum drifts were 0.14% and 0.33% for the two perpendicular directions of earthquake loading that were considered. The study also concluded that the drift ratios were between 0.07% and 0.09% for RH building.

Although both buildings were demolished, the damage level in the two-storey RH building was significantly less extensive than that in the 3-storey AH building. Based on the reported damage patterns, one can assess the building states after the earthquakes to be Damage Control and Collapse Prevention limits, respectively for RH and AH buildings. The DC drift limit of ~ 0.08% (average of 0.07% and 0.09% from two pushover analyses) is comparable to that for building LH (0.06%), with both drift ratios being considerably smaller than ASCE suggested value of between 0.3% and 0.6%. Similarly, the CP drift limit of between 0.14% and 0.33% appear to be significantly smaller than the ASCE suggested value of upwards of 1%.

Similar to the other study (Cattari et al. 2015), this study did not identify wall or storey drifts. The reported drift ratios are building drift ratios and can translate to trifold storey drifts if damage in concentrated on a certain storey. Although this could not be verified using building damage photos (Figure 3), the photos do suggest some uneven distribution of the damage with building height, e.g. see visible shear damage in all of the 4 top-storey piers in AH building vs. shear damage to only one pier in ground storey and no pier in the first storey.

It is the objective of the numerical studies presented in the subsequent sections to calculate building and storey drift ratios for a better understanding of the damage distribution although the models cannot be validated by testing.

Control limit

Figure 3: AH and RH building damage

In summary from the 3 buildings that were analysed by New Zealand investigators, the following information can be gathered:

A building drift ratio of 0.06~0.1% are associated with Damage in ASCE (2014), which suggests a storey drift of between 0.3% and 0.6% for this damage state. Immediate Occupancy limits can be significantly smaller.

A building drift ratio of between 0.14% to 0.33% appear to correspond Life Safety limit state, which has a 'wall' drift ratio of 1% as per ASCE.

The building drift ratios appear to be roughly a third (1/3) of the wall drift limits suggested in the ASCE document. At least some of this smaller drifts can be associated to concentration of the damage in certain stories.

PUSHOVER ANALYSIS OF BUILDING TYPOLOGIES

Four building models (Figure 4 to Figure 7) were created in TREMURI and pushover analyses were conducted. The buildings are symmetrical in Direction 2, for which analyses were performed. TREMURI is capable of modelling failure mechanism of in-plane loaded URM walls but the stiffness of the out-of-plane loaded walls are ignored. The out—of-plane wall mass is directly applied to in-plane loaded walls. Another limitation is that a standard analysis does not allow for proper modelling of in-plane diaphragm displacements. However, an approach was suggested by Nakamura et al. (2017) to overcome this limitation by still using the same software.

Relatively smaller values of masonry Young's modulus and compressive strength (Table 1) were assumed, representing older URM buildings. Two other material data inputs for Tremuri are macro-element average cohesion and friction properties that depend on the dimensions of the individual piers and spandrels. These parameters were selected such that a mixed shear and rocking failure could occur in the buildings, with the obtained hysteresis behaviour being shown in Figure 8 and Figure 9. A density of 1900 kg/m for masonry, a floor dead load of 1.8 kPa, a roof dead load of 1.5 kPa, and a reduced uniform floor live load of 1.2 kPa (including a seismic live load factor of 0.3 in accordance with AS 1170.1) were assumed.

Force-displacement behaviour

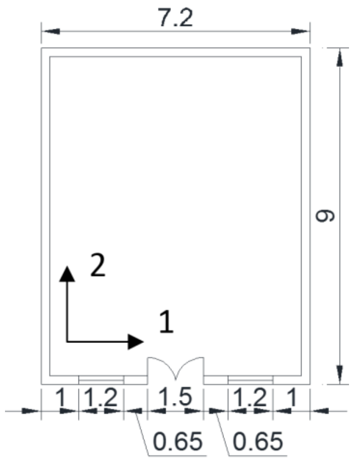
The building behavioural data (Figure 4 to Figure 7) were obtained from pushover analyses of buildings with rigid diaphragm(s), with the control node being at the roof mid-span. The bilinear plateau force (Hu) was assumed to be equal to 0.85 time the maximum recorded strength. The initial stiffness was obtained by connecting the origin to a point on the backbone curve that corresponds to 0.75Hu. The ultimate displacement corresponds to a reduction of 20% in the maximum recorded strength. These bilinear properties are summarised in Table 2. It is noted that irrespective of the building symmetry, the pushover curves in + and – directions are slightly different due to progressive URM damage. Both the bilinear models and the values in Table 2 correspond to loading in the + direction. Significant modal periods and corresponding effective mass ratios are detailed in Table 2. For three of the buildings the effective mass ratio for the first mode is greater than 91%, but 2 modes were included in Table 2 for Building 4.

Table 1. Masonry material properties

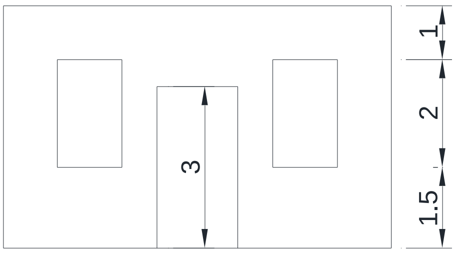
Young's modulus	Shear modulus	Compressive strength	cohesion	Friction coefficient
1385 MPa	740 MPa	5.74 MPa	0.130 MPa	0.111

The obtained period of the buildings are slightly greater than those calculated for NZ building mainly due to the wall thicknesses being significantly less. As discussed earlier the modelled NZ building included atypically thick walls. An ongoing work on these building models is to establish building drift ratios associated with different damage levels.

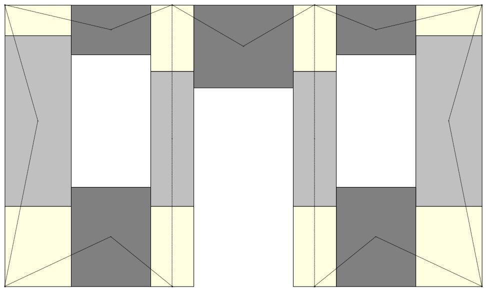
(a) Example building (Russle 2010)



(b) Building plan



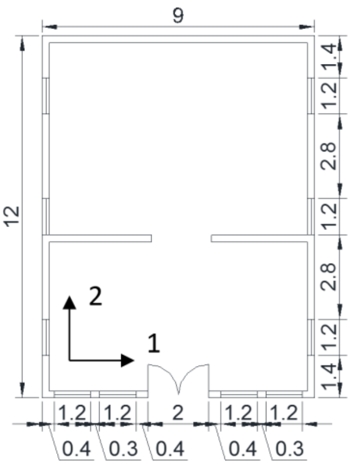
(c) Front elevation



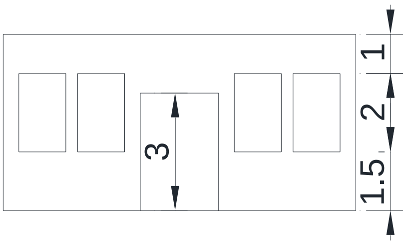
(d) Front wall model in Tremuri

Figure 4: Building 1

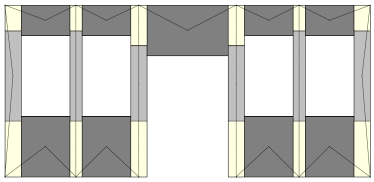
(a) Example building



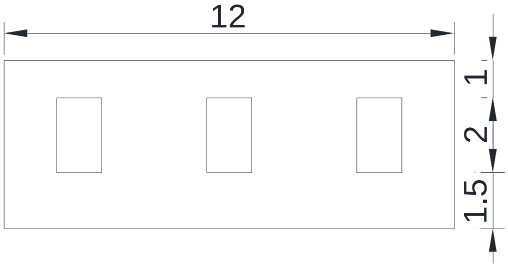
(b) Building plan



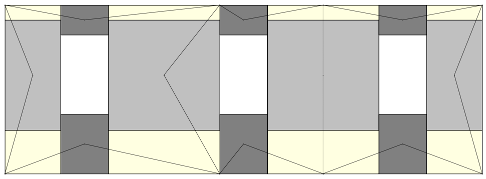
(c) Front elevation



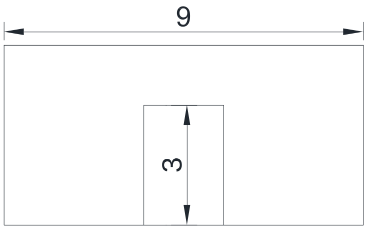
(d) Front wall model in Tremuri



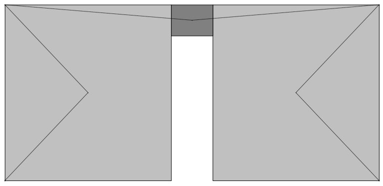
(e) Side wall elevation



(f) Side wall model in Tremuri



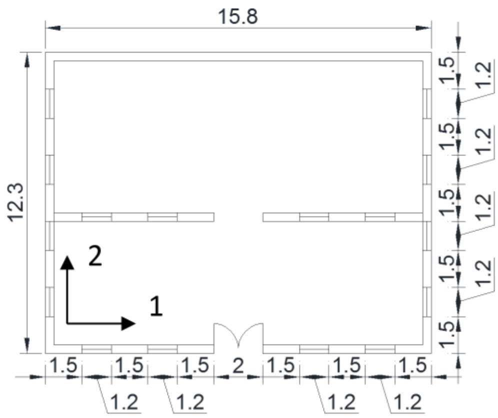
(g) Interior wall elevation



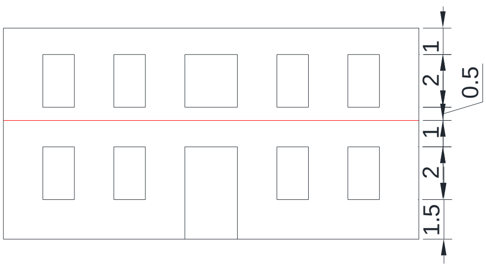
(h) Interior wall model in Tremuri

Figure 5: Building 2 (Russle 2010)

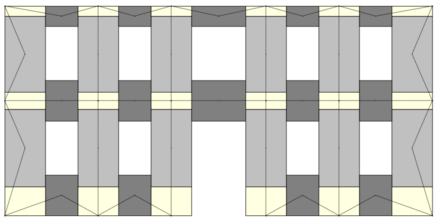
(a) Example building (Russle 2010)



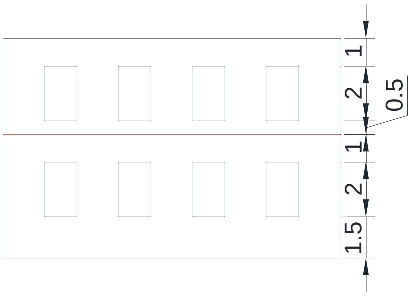
(b) Building plan



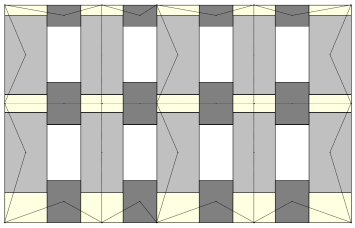
(c) Front and interior wall elevation



(d) Front and interior wall model in Tremuri



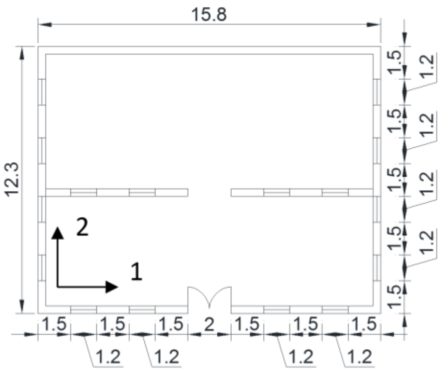
(e) Side wall elevation



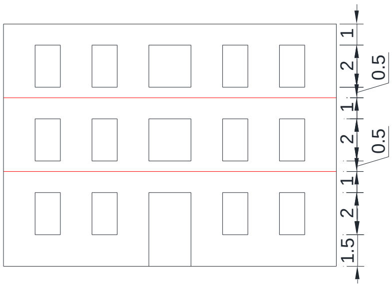
(f) Side wall model in Tremuri

Figure 6: Building 3

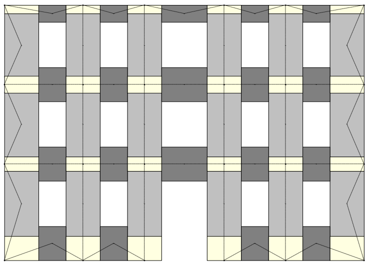
(a) Example building (Russle 2010)



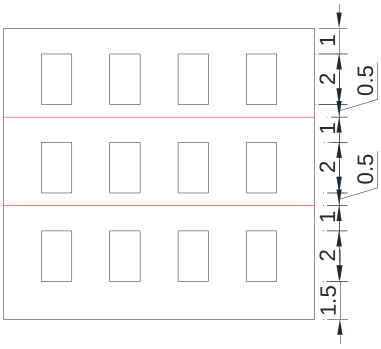
(b) Building plan



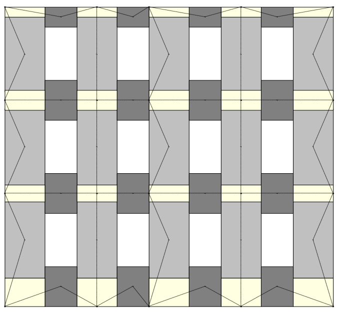
(c) Front and interior wall elevation



(d) Front and interior wall model in Tremuri



(e) Side wall elevation

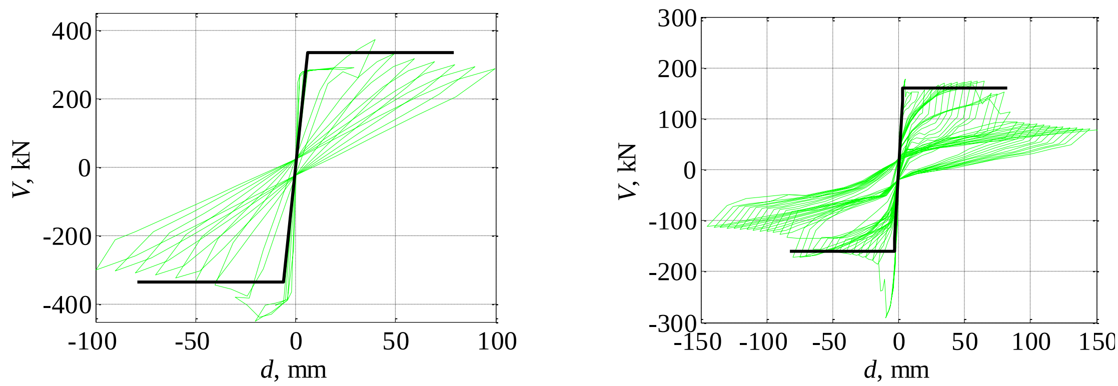


(f) Side wall model in Tremuri

Figure 7: Building 4

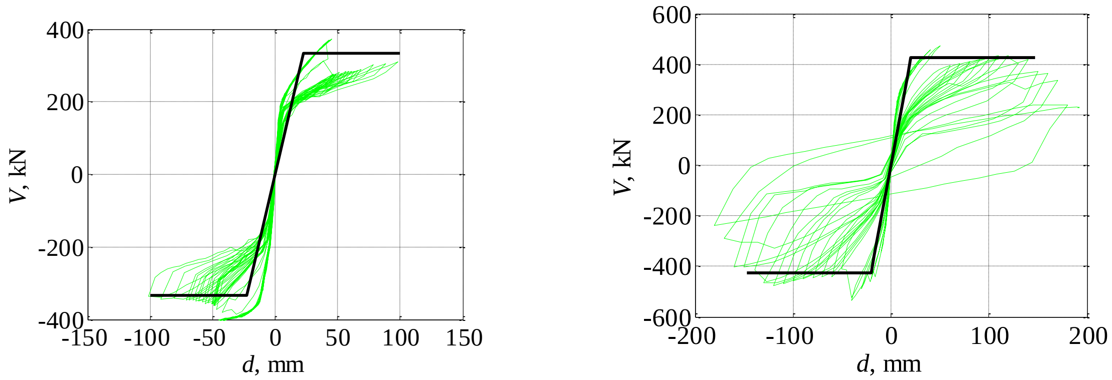
Identifying damage limit states from computer analysis

As discussed earlier piers and spandrels are modelled as macro-elements in TREMURI. The macro-element has a linear shear response followed by slight nonlinearity until the element reaches its peak shear response. This progressive damage is represented by a factor, α, which is zero for elastic response, a value smaller than 1 for an element with minor to moderate damage, and 1 or greater than 1 for an element that has undergone diagonal shear failure.



a) Building 1 b) Building 2

Figure 8: Pushover curves for Buildings 1 and 2



a) Building 3 b) Building 4

Figure 9: Pushover curves for Buildings 3 and 4

Table 2. Bilinear and modal properties

Model	H_u[1], kN	d_e[2], mm	d_u[3], mm	μ	T_k[5], sec	Effective mass ratio, $m_{eff,k}/M$[6]
1	335.3	6.0	79	13.2	0.06	0.97
2	160.7	3.2	82	25.6	0.10	0.99
3	334.8	23.0	100	4.3	0.25	0.91
4	427.2	20.4	147	7.2	0.38; 0.15	0.84; 0.14

1: maximum bilinear force; 2: yield displacement; 3: ultimate displacement; 4: calculated from pushover curve as discussed in the text; 5: from modal analysis; 5: $m_{eff,k}$ is the effective mass in mode k and M is the building seismic mass

It was hypothesised that the state of damage in the buildings throughout pushover analysis can be determined by reviewing α outputs for all piers and spandrels but also guided by the idealised pushover curve (Figure 9). While the macroelement shear damage can be detected directly by observing changes in a (a value of equal or greater than 1 corresponds to shear failure), the building may remain stable for individual pier a values of greater than 1 due to redistribution of the internal forces as piers undergo damage.

A summary of the macroelement shear damage output are listed in Table 3 to Table 6. The values are given for drift ratios corresponding to de and du from Table 2 and two other intermediate states. The two extreme values were assumed to be representing Immediate Occupancy (D1) and Collapse Prevention (D4) limit states. Although these values were obtained from idealised pushover curves, the corresponding limited and extensive shear damage in piers is also evident, respectively, in the second and the last columns of Tables 3 to 6.

The α output mainly assisted in establishing drift ratios for intermediate damage states. Critical changes in the values for piers and spandrels were captured and associated with two intermediate damage states, D2 and D3. For example for Buildings 2 and 4 (Table 4 and Table 6), Damage Control (DC; D2) state was determined as a point where the average and maximum of α in spandrels reached 1 while the piers were still in low to moderate damage range. Life Safety (LS; D3) is the stage that the pier that has the lowest capacity to demand ratio reach diagonal shear failure (α_{max}>1) although for Building 2 the average and maximum α exceeded 1 at the same time.

Table 3: Building 1 Shear damage index, α

Roof disp., mm	6	30	55	79
Drift ratio	0.14	0.71	1.29	1.86
Piers α_{ave}	0.24	0.62	>1.00	>1.00
Piers α_{max}	0.24	0.62	>1.00	>1.00
Spandrels α_{ave}	N/A	N/A	N/A	N/A
Spandrels α_{max}	N/A	N/A	N/A	N/A
Indicative limit	IO	DC	LS	CP

Table 4: Building 2 shear damage index, α

Roof disp., mm	3	15	50	82
Drift ratio	0.07	0.35	1.18	1.93
Piers α_{ave}	0.06	0.28	>1.00	>1.00
Piers α_{max}	0.09	0.81	>1.00	>1.00
Spandrels α_{ave}	0.20	>1.00	>1.00	>1.00
Spandrels α_{max}	0.38	>1.00	>1.00	>1.00
Indicative limit	IO	DC	LS	CP

Similar approach was followed to determine D2 and D3 for Buildings 1 and 3 (Table 3 and Table 5) although damage progression among piers and spandrels were steeper than that for Buildings 1 and 4. D2 was determined on the basis that both the weakest pier and spandrel were close to undergo diagonal tensile failure. D3 was established to be a point between D2 and D4 as this level could not be determined solely based on α values.

Table 5: Summary of shear damage index, α, for Building 3

Roof disp., mm		20	46	75	100
Drift ratio		0.26	0.59	0.97	1.29
Piers α_{ave}	Lvl. 1	0.11	0.19	0.19	0.19
	Lvl. 2	0.10	0.24	>1.00	>1.00
Piers α_{max}	Lvl. 1	0.14	0.30	0.30	0.30
	Lvl. 2	0.31	0.95	>1.00	>1.00
Sp. α_{ave}	Lvl. 1	0.22	0.34	0.35	0.35
	Lvl. 2	0.14	0.24	>1.00	>1.00
Sp. α_{max}	Lvl. 1	0.46	0.70	0.71	0.71
	Lvl. 2	0.23	0.44	>1.00	>1.00
Indicative limit		IO	DC	LS	CP

Table 6: Summary of shear damage index, α, for Building 4

Roof disp., mm		20	50	80	147
Drift ratio		0.18	0.44	0.72	1.31
Piers α_{ave}	Lvl. 1	0.13	0.37	0.42	>1.00
	Lvl. 2	0.16	0.39	>1.00	>1.00
	Lvl. 3	0.06	0.18	0.18	0.22
Piers α_{max}	Lvl. 1	0.18	0.46	0.67	>1.00
	Lvl. 2	0.23	0.53	>1.00	>1.00
	Lvl. 3	0.16	0.51	0.51	0.63
Sp. α_{ave}	Lvl. 1	0.30	>1.00	>1.00	>1.00
	Lvl. 2	0.35	>1.00	>1.00	>1.00
	Lvl. 3	0.13	0.40	0.40	>1.00
Sp. α_{max}	Lvl. 1	0.34	>1.00	>1.00	>1.00
	Lvl. 2	0.47	>1.00	>1.00	>1.00
	Lvl. 3	0.15	0.85	0.85	>1.00
Indicative limit		IO	DC	LS	CP

A summary of building and storey drift ratios vs identified damage levels are outlined in Table 7 and Table 8, respectively. From this summary it is clear that the building drift ratios corresponding to damage levels D2 to D4 decreases with building height. The reason for this decrease is that damage was concentrated on specific piers and therefore the building lateral displacement was uneven throughout the building height. To address uneven damage, storey drift ratios were calculated as summarized in Table 8, which includes shaded columns for critical storeys. The average of the drift ratios for critical storeys are 0.23%, 0.64%, 1.34%, and 2.25%, respectively for D1, D2, D3, and D4 damage levels.

Table 7: Summary of building drift ratios (%) vs damage levels

Building model	1	2	3	4	Average (COV)
D1	0.14	0.07	0.26	0.18	0.16
D2	0.71	0.35	0.59	0.44	0.52
D3	1.29	1.18	0.97	0.72	1.04
D4	1.86	1.93	1.29	1.31	1.60

Table 8: Summary of storey drift ratios (%) vs damage levels

Building model	1	2	3		4			Average for critical storey
Building Level	Lvl. 1	Lvl. 1	Lvl. 1	Lvl. 2	Lvl. 1	Lvl. 2	Lvl. 3	---
D1	0.14	0.07	0.5	0.1	0.3	0.2	0.1	0.23
D2	0.71	0.35	1.0	0.2	0.7	0.5	0.2	0.64
D3	1.29	1.18	2.0	0.1	0.8	0.9	0.5	1.34
D4	1.86	1.93	2.7	0.1	1.1	2.5	0.6	2.25

The average storey drift ratio that were obtained for damage level D1 are consistent with the values recommended in ASCE (2014), e.g. 0.23% for D1 vs. 0.30% from Figure 2 for IO limit state.

Larger storey drift ratios were obtained for Collapse Prevention (D4), 2.25% vs. 1% recommended in ASCE. The drift ratio for intermediate D2 and D3 levels obtained in this study (0.64% and 1.34%) also exceed ASCE recommendations (0.6% for D3).

One critical aspect that needs to be addressed in building analysis is the potentially uneven distribution of structural damage with building height, which needs to be addressed before expected drifts on URM walls can be determined. This would not be an issue if the building can indeed be idealised as a SDOF 'regular' structure but the definition of structural irregularity is not very well understood in the context of URM buildings that can have walls with different thicknesses in different stories.

SUMMARY AND CONCLUDING REMARKS

The relationship between lateral drift ratios and the damage sustained by the building was investigated from several perspectives. Both building drift and storey drift were calculated. The damage state was determined both at component level, i.e. piers, and building level, i.e. overall stability. The results were compared to the values reported in the literature, which includes an empirical study utilising recent New Zealand earthquake data.

A direct comparison of the results for 'critical' storeys in the 4 studied buildings with ASCE recommendations suggests that the latter corresponds to a conservative evaluation of storey drift ratios responsible for different damage states.

The empirical studies in NZ only calculated building drifts (not storey drifts), hence it is difficult to make a comparison with ASCE recommendations. As discussed, post-earthquake building damage photos were not conclusive on how damage was distributed and the distribution was different for different walls. However, the damage photos do suggest some uneven damage distribution, hence some of the smaller drifts identified in NZ study can be attribute to this observation. The building drift ratios in the reported NZ studies were about a third of the ASCE recommended values, which if re-attributed to a single critical storey equates roughly to the same storey drifts as that of ASCE.

The study identified a critical gap in the literature relating to uneven distribution of structural damage with building height. It is essential to accurately establish storey drifts from analyses, rather than an overall building drift, to be able to assess the building damage. This may be straightforward for regular buildings, but the definition of regular URM building merits further investigation. This is especially important as URM buildings can have drastic changes in the wall thicknesses in adjacent stories.

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