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The performance of unreinforced masonry buildings in the 2010/2011 Canterbury earthquakes

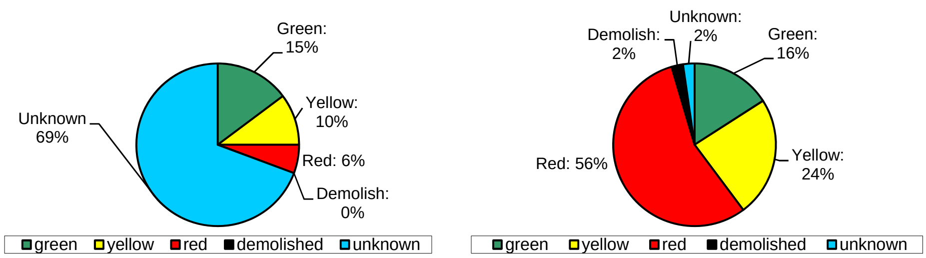
Jason Ingham

ENG.ING.0004.2

Part 4: Observations following the 22 February 2011 earthquake

General damage statistics for stone masonry buildings

Figure 3.28: Distribution of safety evaluation placarding applied to stone masonry buildings



(a) After September 2010 **(b) Data updated 07 June 2011**

- 90 natural stone unreinforced masonry buildings identified
- Building stock not common throughout rest of New Zealand
- Many stone masonry buildings earthquake strengthened

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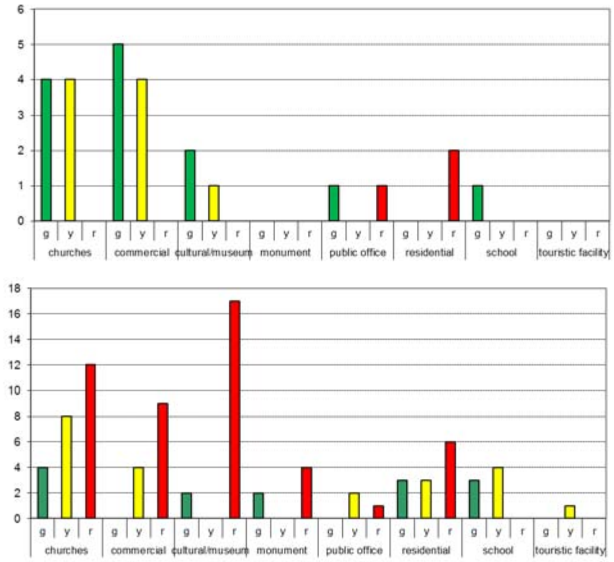
Figure 3.29 Distribution of safety evaluation placarding applied to stone masonry buildings differentiated by building usage



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Performance of unreinforced masonry buildings in the CBD

General damage statistics

ENG.ING.0004.7

Figure 3.1 Location of URM buildings included in this study

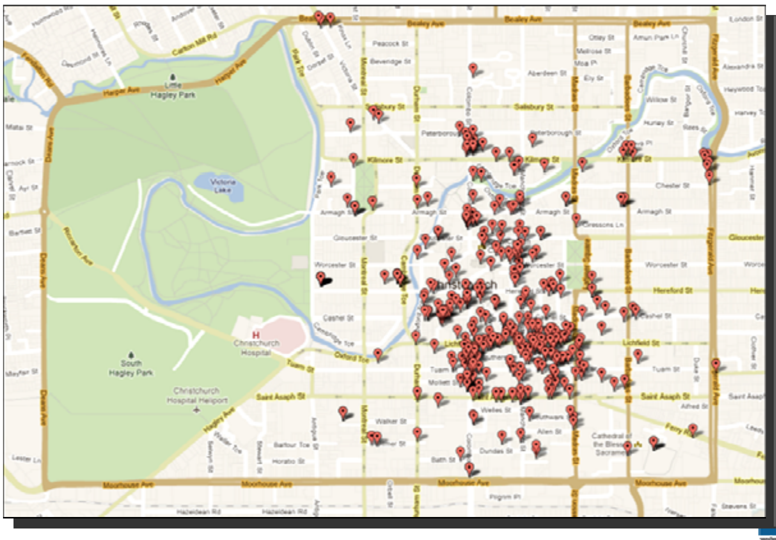

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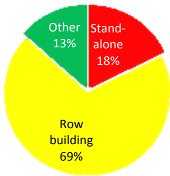
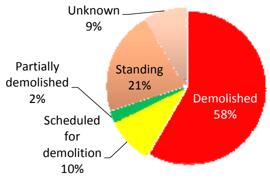
Table 4.4 Construction material type

Material type	No. of buildings	% of buildings
Clay brick	333	90%
Stone	13	4%
Clay brick and stone	24	6%
Total	**370**	**100%**

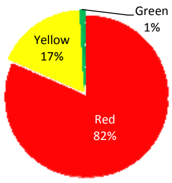
Figure 4.1 General building characteristics



(c) Row buildings

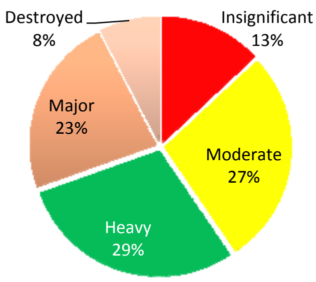


(d) State of buildings

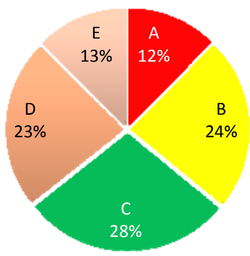


(e) Level 1 placarding data (known building placards only, 337 buildings total)

Figure 4.2 Damage level using two different classifications schemes



(a) ATC 38/13 Classification



(b) Wailes and Horner Scale

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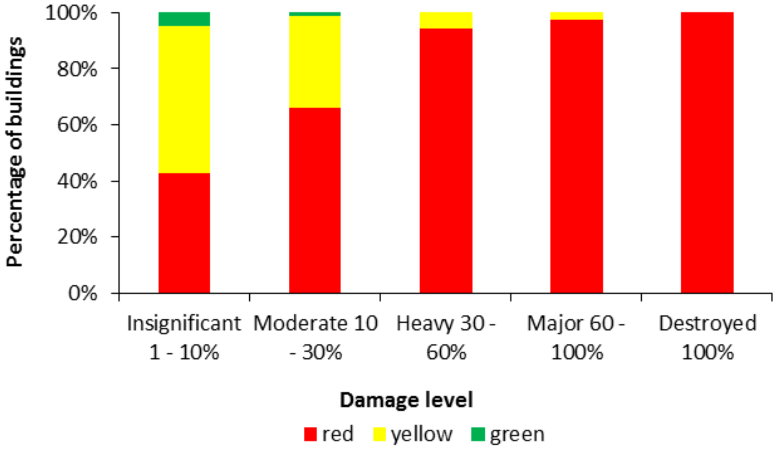
Figure 4.3 Plot of damage levels vs. placard data (level 1)



- Shows tendency to assign Red placard to buildings not necessarily too badly damaged

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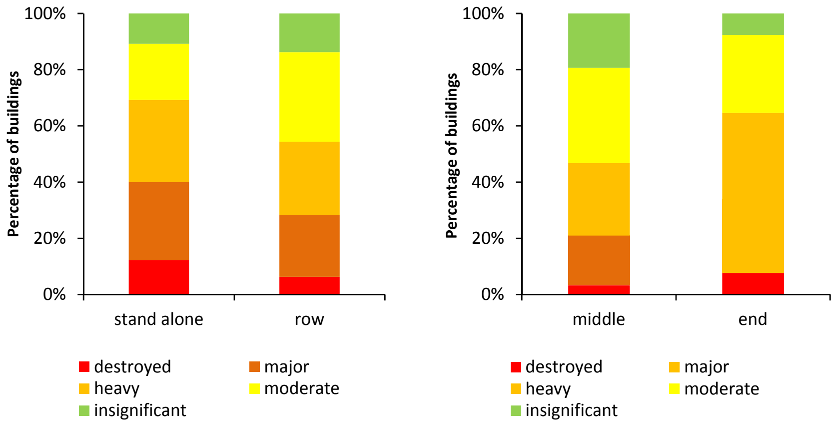
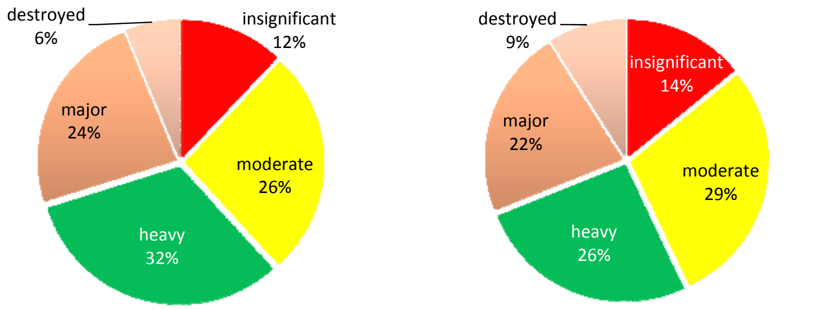
Figure 4.5 ATC 38/13 damage classification for stand-alone and row buildings



(a) Damage levels for stand-alone vs. row buildings

(b) Damage levels for row buildings depending on position

Figure 4.7 Damage classifications for heritage and non-heritage buildings



(a) Heritage and protected buildings

(b) Neither heritage nor protected buildings

- Damage distribution very similar

Table 4.12 Demolished and retained buildings

	Heritage listed	**Other**	**Total**
Demolished (incl. scheduled)	128 (67% of 192)	130 (73% of 178)	258 (70%)
Standing	52 (27% of 192)	28 (16% of 178)	80 (22%)
Unknown	12 (6% of 192)	20 (11% of 178)	32 (8%)
Total	**192 (52% of 370)**	**178 (48%)**	**370 (100%)**

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The Performance of Earthquake Strengthening Techniques

ENG.ING.0004.16

Earthquake strengthening classes

- 1. Parapet restraints
- 2. Type A earthquake strengthening
  - Securing gable ends
  - Installing connections between walls-floors, walls-walls etc
  - Floor and roof improvements
- 3. Type B earthquake strengthening
  - Strong-backs installed either internally or externally
  - Steel moment frames
  - Steel brace frames
  - Concrete moment frames
  - Addition of cross walls
  - Shotcrete
  - FRP
  - Post tensioning

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Performance of parapets

	No. of cases	% of parapets
restrained	149	34%
unrestrained	89	21%
unknown	197	45%
Total	**435**	**100%**

Damage classification	Restrained Parapet	Unrestrained Parapet
none	35 (23%)	5 (6%)
moderate	36 (24%)	7 (8%)
heavy	13 (9%)	2 (2%)
partial collapse	29 (20%)	25 (28%)
full collapse	36 (24%)	50 (56%)
Total	**149 (100%)**	**89 (100%)**

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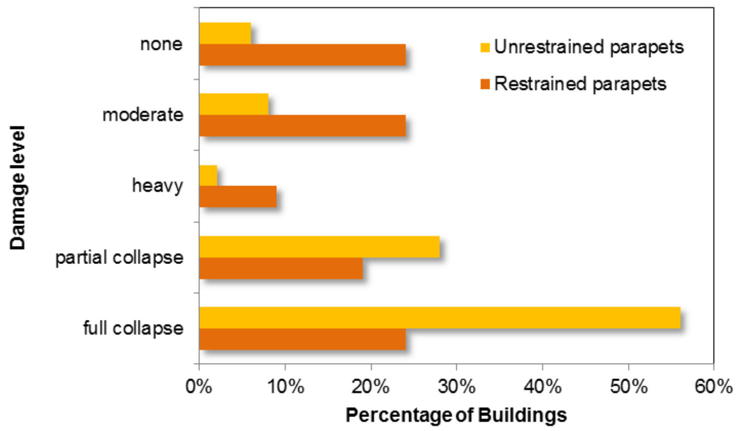
Figure 5.3 Performance of unrestrained and restrained parapets



- Unrestrained parapets twice as likely to collapse
- Disappointing result for restrained parapets

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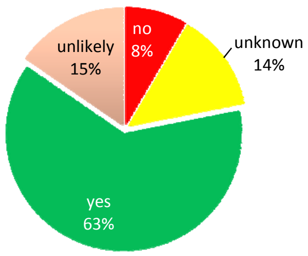
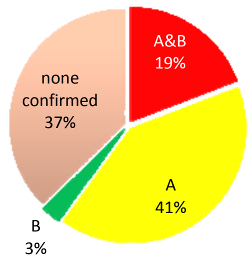
Figure 5.2 Distribution of Type A and Type B installed earthquake strengthening types



(a) Proportion of earthquake strengthened buildings



(b) Identified type of earthquake strengthening

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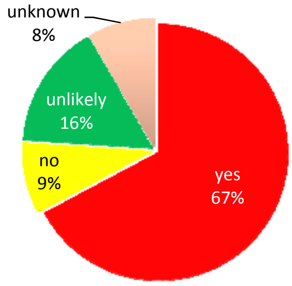
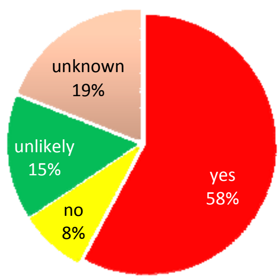
Figure 5.1 Distribution of earthquake strengthening implementation



(a) Heritage and protected buildings



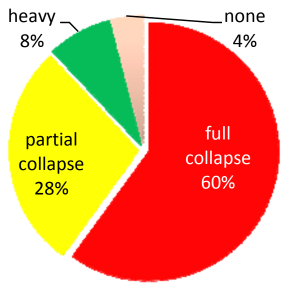
(b) Non-heritage buildings

Gable restraint details

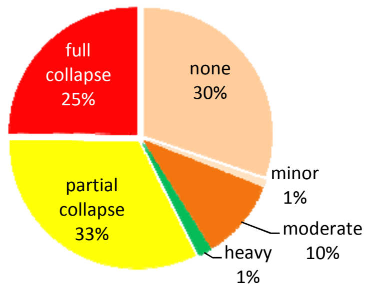
Type of restraint	Number (%)
no restraint present	25 (14%)
gable restraints identified	129 (70%)
unknown	31 (17%)
Total	**185 (100%)**

Restraint types	% of gables (out of 129 gables)
original	14 (10%)
through ties	108 (84%)
adhesive anchors	5 (4%)
through ties + concrete beam	1 (1%)
other	1 (1%)
Total	**129 (100%)**

Figure 5.4 Gable damage levels



(a) Damage levels to unrestrained gables, all elevations



(b) Damage levels to restrained gables, all elevations

- 88% unrestrained vs 58% restrained gables
- Disappointing result for restrained gables

Figure 5.5 Damage distribution for gables restrained using through ties

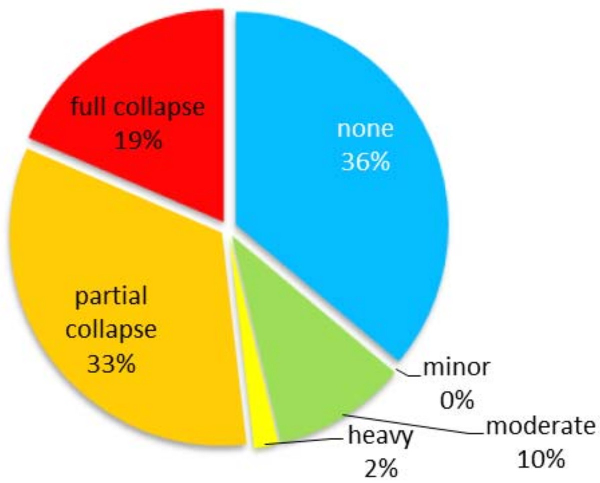


Table 5.13 Distribution of Type B strengthening techniques encountered

Strengthening technique	No. of buildings	% of buildings
steel moment frames	24	22%
steel brace frames	14	13%
strong-backs - internal	14	13%
strong-backs - external	4	4%
concrete moment frames	22	20%
addition of cross walls	13	11%
shotcrete	10	9%
FRP	1	1%
post tensioning	2	2%
other	5	5%
Total	**109**	**100%**

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Figure 5.6 Building damage distribution for various Type B earthquake strengthening techniques

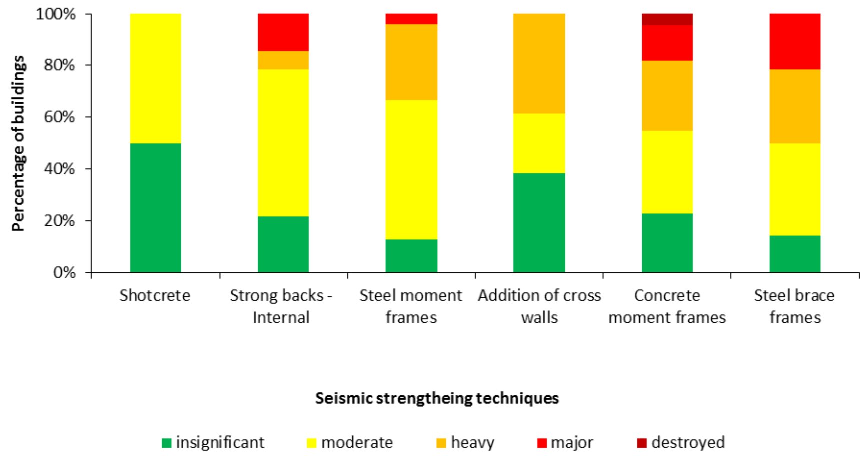

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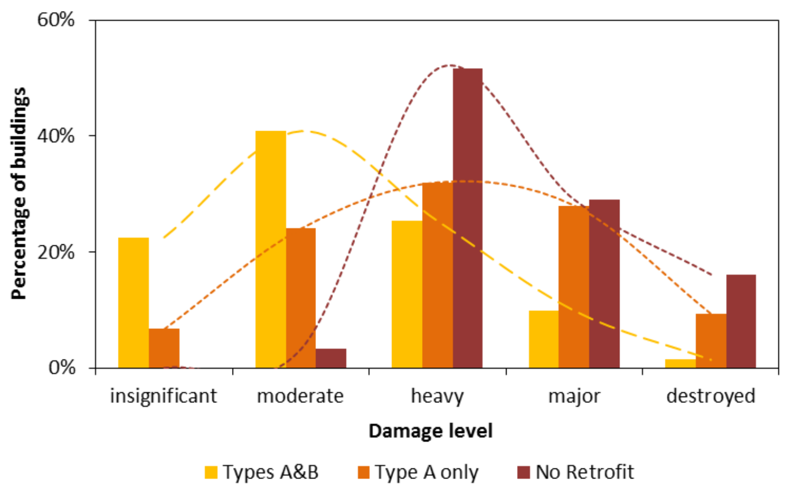
Figure 5.7 Plot of damage level against seismic strengthening types



Influence of earthquake strengthening level on observed damage and assessed hazard

Table 6.1 Distribution of %NBS classifications for 94 earthquake strengthened URM buildings

%NBS Retrofit level	No. of buildings	% of buildings
%NBS < 33	15	16%
33 ≤ %NBS < 67	18	19%
67 ≤ %NBS < 100	**50**	**53%**
%NBS ≥ 100	11	12%
Total	**94**	**100%**

- Confirmed 94 retrofitted buildings
- Confirmed 31 unretrofitted buildings <u>but no %NBS assigned</u>

Table 6.2 Damage levels for different %NBS categories

	%NBS ≥ 100		67 ≤ %NBS < 100		33 ≤ %NBS < 67		%NBS < 33		No retrofit	
Insignificant 1 - 10%	8	73%	10	20%	1	6%	1	7%	0	0%
Moderate 10 - 30%	3	27%	28	56%	4	22%	5	33%	1	3%
Heavy 30 - 60%	0	0%	10	20%	9	50%	5	33%	16	52%
Major 60 - 100%	0	0%	2	4%	4	22%	1	7%	9	29%
Destroyed 100%	0	0%	0	0%	0	0%	3	20%	5	16%
Combined Heavy, Major and Destroyed	**0 of 11**	**0%**	**12 of 50**	**24%**	**13 of 18**	**72%**	**9 of 15**	**60%**	**30 of 31**	**97%**
Total	**11**		**50**		**18**		**15**		**31**	

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Figure 6.1 Damage levels for different levels of %NBS earthquake strengthening

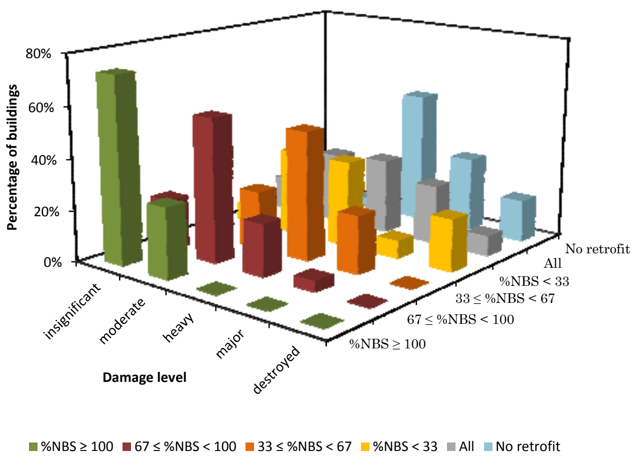

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Figure 6.1 Damage levels for different levels of %NBS earthquake strengthening

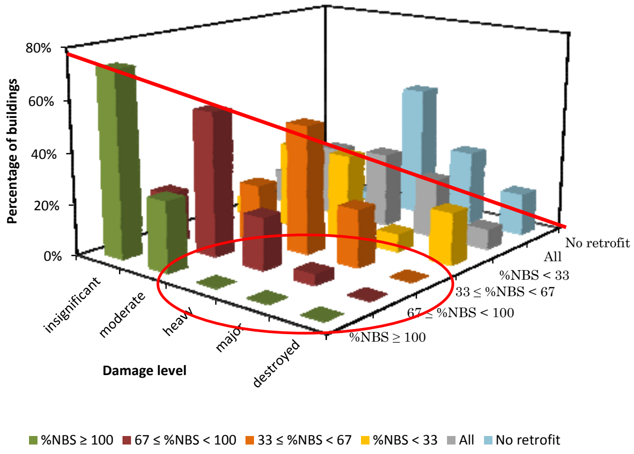


Figure 6.3 Damage comparison between URM buildings strengthened to <u>less than 33%NBS and no retrofit</u>

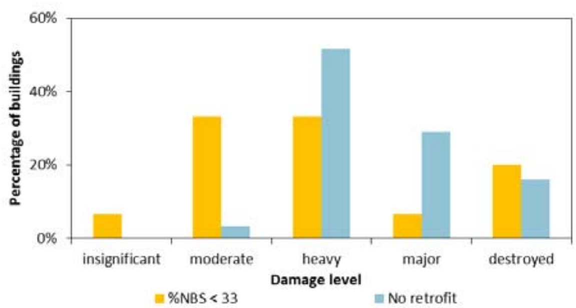
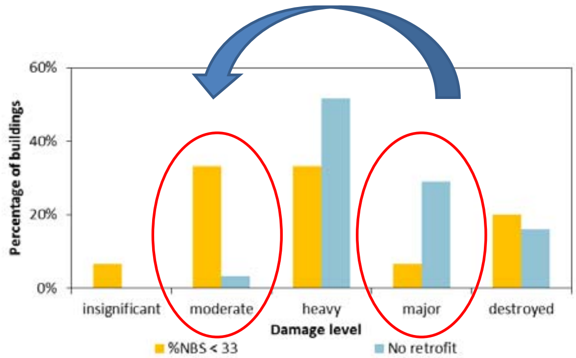


Figure 6.3 Damage comparison between URM buildings strengthened to <u>less than 33%NBS and no retrofit</u>



- URM buildings strengthened to **less than 33%NBS** performed in a **similar** manner to **unstrengthened** URM buildings
  - did result in a significant **reduction** from **major** damage to **moderate** damage

Figure 6.4 Damage comparison between URM buildings strengthened to <u>34%NBS and no retrofit</u>

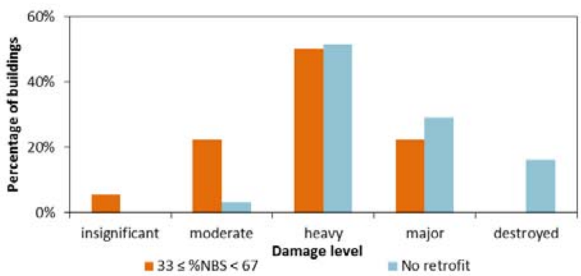


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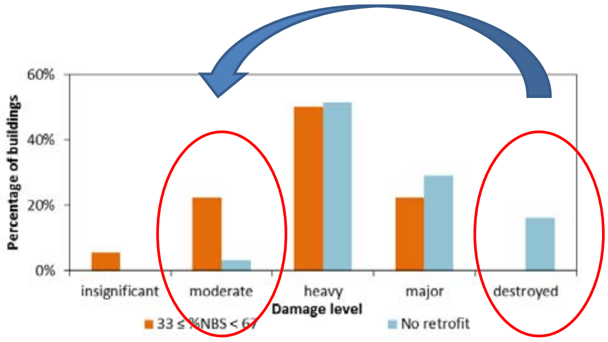
Figure 6.4 Damage comparison between URM buildings strengthened to 34%NBS and no retrofit



- URM building strengthened to **34%NBS** avoided being destroyed (100% damage), but otherwise their performance was **not greatly better than for unstrengthened buildings**

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Table 6.2 Damage levels for different %NBS categories (for Damage Index)

	%NBS ≥ 100		67 ≤ %NBS < 100		33 ≤ %NBS < 67		%NBS < 33		No retrofit	
Insignificant 1 - 10%	8	73%	10	20%	1	6%	1	7%	0	0%
Moderate 10 - 30%	3	27%	28	56%	4	22%	5	33%	1	3%
Heavy 30 - 60%	0	0%	10	20%	9	50%	5	33%	16	52%
Major 60 - 100%	0	0%	2	4%	4	22%	1	7%	9	29%
Destroyed 100%	0	0%	0	0%	0	0%	3	20%	5	16%
Combined Heavy, Major and Destroyed	**0 of 11**	**0%**	**12 of 50**	**24%**	**13 of 18**	**72%**	**9 of 15**	**60%**	**30 of 31**	**97%**
Total	**11**		**50**		**18**		**15**		**31**	

DI for %NBS ≤ 33

$$= 5\% \times \frac{1}{15} + 20\% \times \frac{5}{15} + 45\% \times \frac{5}{15} + 80\% \times \frac{1}{15} + 100\% \times \frac{3}{15} = 47$$

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Table 6.3 Damage index for different levels of earthquake strengthening

%NBS Retrofit Level	Damage "index"
no retrofit	63
%NBS < 33	47
33 ≥ %NBS < 67	45
67 ≥ %NBS < 100	24
%NBS ≥ 100	9
all buildings	45

DI for %NBS ≤ 33

$$= 5\% \times \frac{1}{15} + 20\% \times \frac{5}{15} + 45\% \times \frac{5}{15} + 80\% \times \frac{1}{15} + 100\% \times \frac{3}{15} = 47$$

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Table 6.3 Damage index for different levels of earthquake strengthening

%NBS Retrofit Level	Damage "index"
no retrofit	63
%NBS < 33	**47**
33 ≥ %NBS < 67	**45**
67 ≥ %NBS < 100	24
%NBS ≥ 100	9
all buildings	45

DI for %NBS ≤ 33

$$= 5\% \times \frac{1}{15} + 20\% \times \frac{5}{15} + 45\% \times \frac{5}{15} + 80\% \times \frac{1}{15} + 100\% \times \frac{3}{15} = 47$$

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Figure 6.6 Damage comparison between URM buildings strengthened to <u>0-33%NBS or to 34%NBS</u>

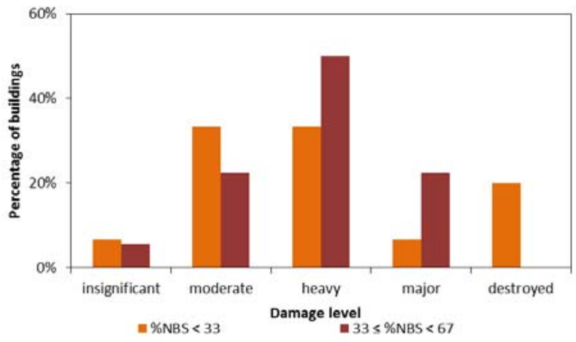

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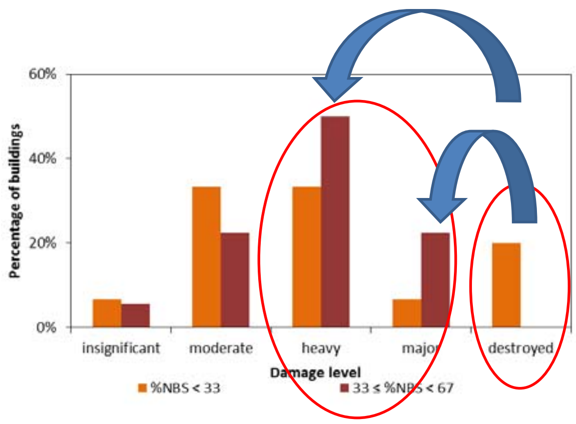
Figure 6.6 Damage comparison between URM buildings strengthened to <u>0-33%NBS or to 34%NBS</u>



- URM building strengthened to **33-67%NBS** avoided being destroyed (100% damage), but otherwise their performance was **not greatly better than for unstrengthened buildings**

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Figure 6.5 Damage comparison between URM buildings strengthened to 67%NBS and no retrofit

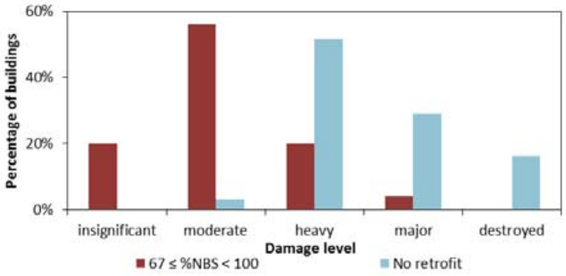

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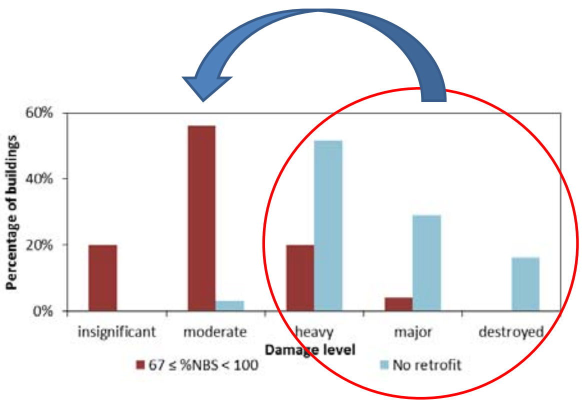
Figure 6.5 Damage comparison between URM buildings strengthened to 67%NBS and no retrofit



- It is neither practical nor feasible to state conclusively that the public can be effectively protected from "all" falling hazards and that "strengthened URM buildings will survive severe earthquake ground motions."

Figure 6.7 Damage comparison between URM buildings strengthened to 34%NBS or 67%NBS

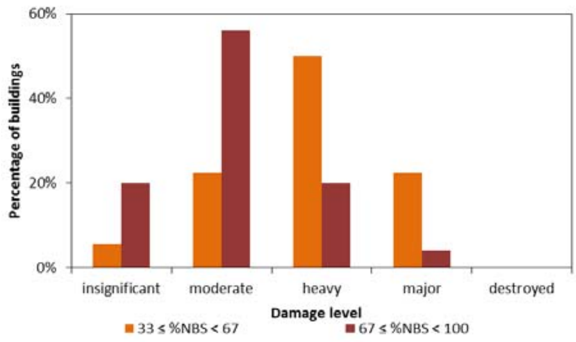
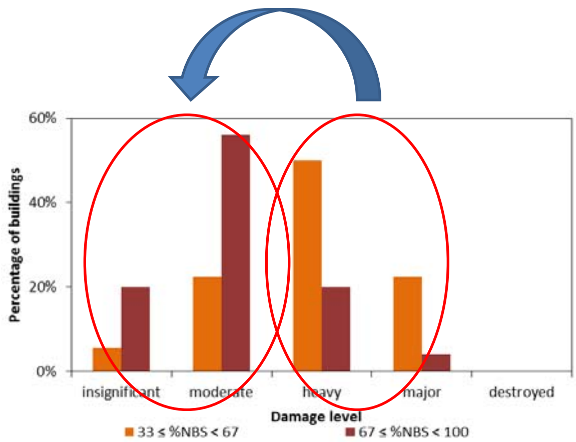


Figure 6.7 Damage comparison between URM buildings strengthened to 34%NBS or 67%NBS



- URM buildings strengthened to **67%NBS** performed **much better** than both URM buildings having **no strengthening** and URM buildings strengthened to **lower levels** of earthquake resistance

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All %NBS data included

NBS Retrofit Level	Damage "index"	Number of buildings
$0 \leq$ %NBS < 11	90	2
$11 \leq$ %NBS < 22	41	5
$22 \leq$ %NBS < 33	41	8
33 $\leq$ %NBS < 44	49	16
44 ≤ %NBS < 55	**5**	**1**
55 ≤ %NBS < 67	**20**	**1**
67 $\leq$ %NBS < 78	23	49
78 ≤ %NBS < 89	**80**	**1**
89 ≤ %NBS < 99	**-**	**0**
%NBS $\geq$ 100	9	11
no retrofit	63	
all buildings	45	

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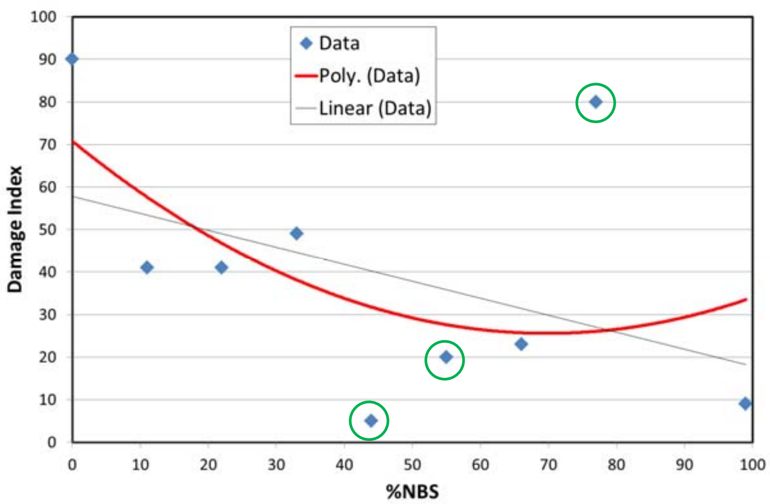
Damage vs %NBS level



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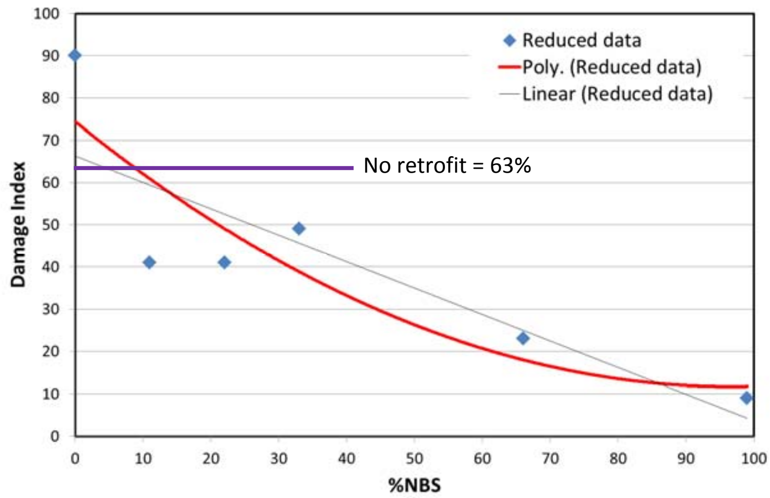
Remove data where just 1 entry



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6.1.1 Damage interpretations

- URM buildings strengthened to **less than 33%NBS** performed in a **similar** manner to **unstrengthened** URM buildings
  - did result in a significant **reduction** from **major** damage to **moderate** damage
- URM building strengthened to **34%NBS** avoided being destroyed (100% damage), but otherwise their performance was **not greatly better than for unstrengthened buildings**
- URM buildings strengthened to **67%NBS** performed **much better** than both URM buildings having **no strengthening** and URM buildings strengthened to **lower levels** of earthquake resistance

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Risk to building occupants and passers-by

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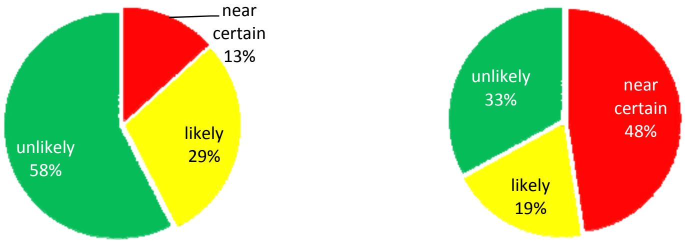
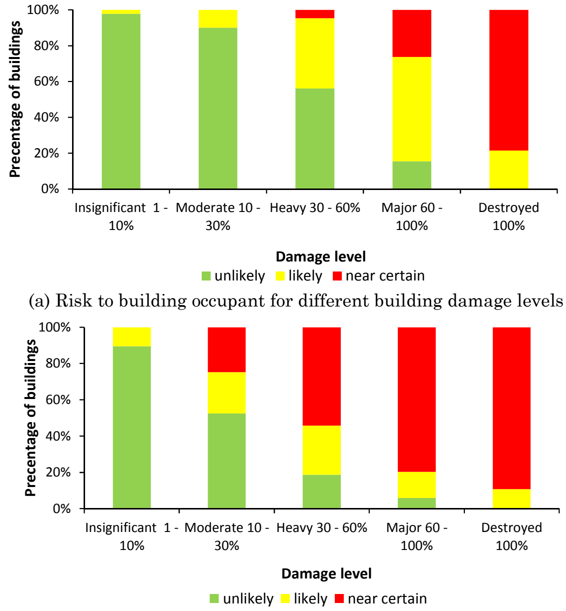
Figure 6.8 Risk of fatality or injury to building occupants and public space occupants



(a) Risk to building occupants

(b) Risk to passers-by



(a) Risk to building occupant for different building damage levels

(b) Risk to passer-by for different damage levels

Figure 6.9 Fatality and injury risk for different building damage levels