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Melbourne CBD Case Study: URM Retrofit Effectiveness in Avoiding Mass Casualties

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Abstract

Earthquakes occur without warning and human mobility during strong shaking is difficult. This has implications for casualty outcomes from such rapid onset events. Unreinforced masonry (URM) in particular presents a great risk in the high pedestrian exposure precincts of major cities. Surveys of major Australian cities have indicated that almost half of the central business district (CBD) buildings by number are of older URM construction and have elements that could fall onto pedestrians in a major shake. With a focus on the greater CBD of Melbourne, this risk and mitigation options for it have been studied.

In a case study undertaken as part of the Bushfire and Natural Hazards CRC (BNHCRC), the casualties, damage and broader economic consequences of a major earthquake in central Melbourne have been modelled. This research directly utilised BNHCRC vulnerability research on URM by the authors and separate work by Geoscience Australia on modelling human exposure in a major business precinct. Through a virtual retrofit of the high risk URM buildings the benefits of retrofit were demonstrated. In particular, the prioritising of areas of high human exposure in a manner similar to that being used in New Zealand was found to achieve greater reductions of injuries.

Keywords: earthquake, risk, business precincts, casualties, masonry, retrofit.

1 Introduction

The BNHCRC project Cost Effective Mitigation Strategy Development for Building Related Earthquake Risk developed retrofit measures to improve the resilience of older URM buildings to earthquakes and examined the benefits of retrofit. The project included a case study of a large earthquake close to the Melbourne CBD which examined the impacts of such an earthquake and how retrofit of URM buildings could reduce them. In addition to modelling building damage, losses from damage to building contents, economic losses incurred by businesses, casualties within buildings and casualties outside buildings were also estimated. This paper describes the estimation of the last impact component: casualties outside buildings. The focus was on casualties caused by masonry falling from damaged URM buildings into streets with pedestrian densities typical of a CBD environment. Two retrofit scenarios were examined: firstly where a fraction of randomly selected URM buildings were assumed to be retrofitted and secondly where the URM buildings to be retrofitted were specifically selected as those fronting the busiest streets. The change in the casualty logistics is examined.

2 Scenario Earthquake

A single scenario earthquake was selected so that the peak ground acceleration of the simulated mean ground motion at Melbourne CBD matched the PGA value for 1% probability of exceedance in 50 years based on NSHA18 (Allen et al, 2018). Details of earthquake selection are given in Ryu et al, 2021. The parameter values of the scenario event are set out in Table 1 and is a similar event to the Newcastle Earthquake of the 28th November 1989 (M_w 5.4) and smaller than the 21st September 2021 Woods Point Earthquake (M_w 5.9) in Victoria that damaged Melbourne buildings.

Table 1 Parameter values of the scenario event.

Magnitude (Mw)	***Depth (km)***	***Epicentre (Long, Lat)***	***Distance from Melbourne CBD (km)***	***PGA (g)***
5.5	10.0	145.011, -37.705	12.5	0.124

The ground motion fields were simulated using the *OpenQuake* software application (Version 3.10.1; Pagani et al., 2014). A single ground motion field was generated by taking a weighted average of the simulated mean ground motions through adopting the same logic tree of ground motion models used in NSHA18.

The simulated bedrock hazard shown in Figure 1 was found to be very uniform across the study region but greater variability resulted from the incorporation of the surface soil effects is shown in Figure 2. The majority of the study area experienced shaking of MMI 6 to 6.5.

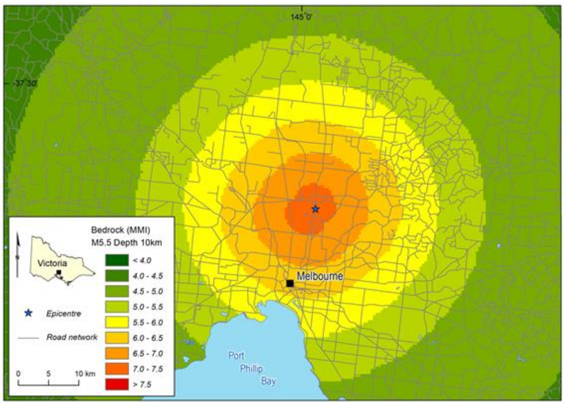

Figure 1 Simulated ground motion field at bedrock presented in terms of Modified Mercalli Intensity (MMI).

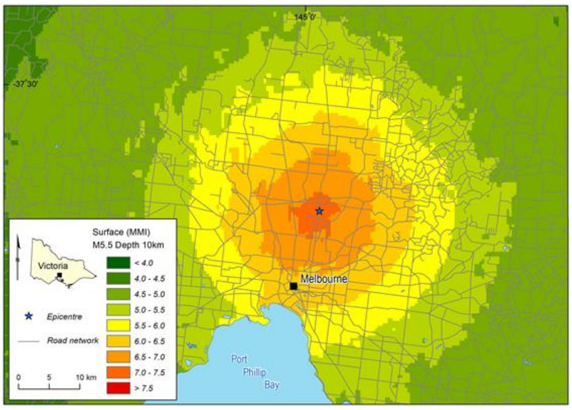

Figure 2 Simulated ground motion field at surface presented in terms of MMI. The amplifying effects of soils beneath the Melbourne CBD are evidenced.

3 Exposure Collection and Building Classification

The exposure database for the study was developed from a 2009 survey carried out by Geoscience Australia and updated in 2020. The area encompasses the Melbourne CBD ‘block’ together with buildings in Southbank and Docklands. The surveyed buildings are shown in

Figure 3. To enable impact modelling additional attributes were added to the database for all buildings including 3 categorisations, site class, floor area, value and contents value. For URM buildings, the length of the building perimeter fronting the street or streets was measured.

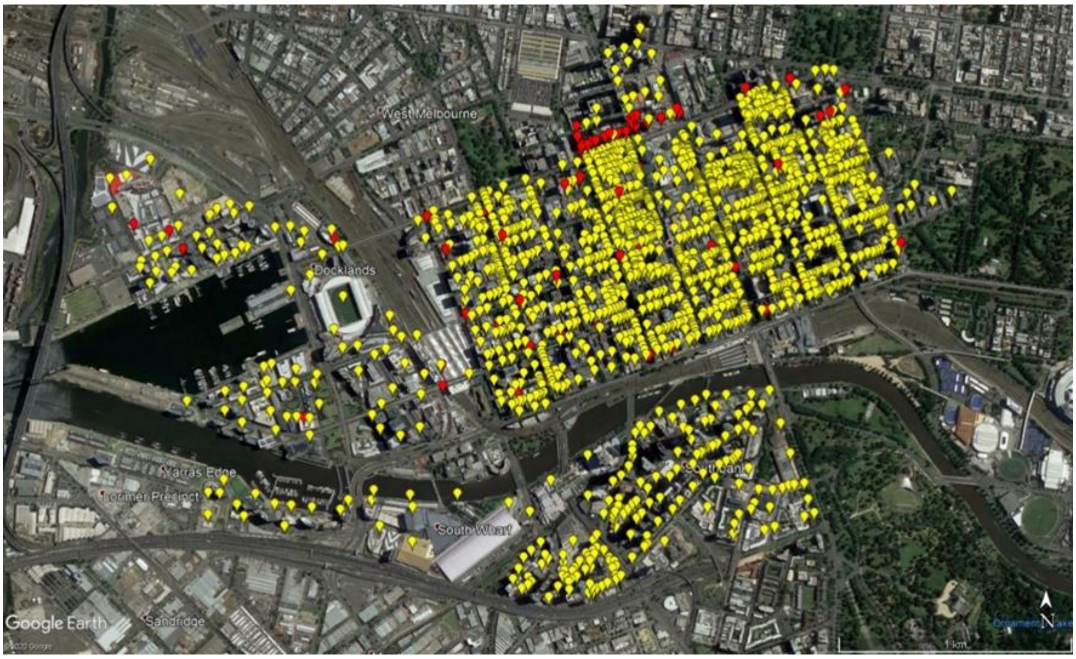

Figure 3 Study area buildings denoted by pins. Red denotes buildings added during the 2020 update.

The project used a concise list of building types dictated by the limited number of available vulnerability curves. The classification of URM building types was subdivided because:

- The case study focussed on the effects of retrofitting URM buildings and hence a more detailed classification of URM buildings would be of use;
- URM buildings made up a surprisingly large proportion of the total building stock by number (approximately 45%);
- A range of vulnerability curves were available from the preceding utilisation project "Earthquake Mitigation of WA Regional Towns: York case Study" that applied to a more detailed classification of URM building types (Wehner et al, 2020); and
- Experience from the Christchurch earthquake sequence in New Zealand showed that collapse of URM buildings into the streets can contribute significantly to the number of casualties (Moon et al, 2014, Abeling et al, 2020).

Table 2 lists the building types used in this case study. In addition to the GA Building Class each building was also assigned a HAZUS (FEMA, 2006) Building Class. Table 3 lists the finer classification of load bearing masonry building types used in this case study.

Table 2 Building types used in this case study and numbers of buildings of each type encountered in the study area.

GA Building Class	***Description***	***Frequency***
13_LBM_T	1 to 3 storey load bearing masonry with timber internal framing	101
13_LBM_S	1 to 3 storey load bearing masonry with steel internal framing	286
13_LBM_C	1 to 3 storey load bearing masonry with concrete internal framing	131

GA Building Class	***Description***	***Frequency***
13_C_URM	1 to 3 storey concrete frame with URM external facades	42
13_C_O	1 to 3 storey concrete frame with non URM external facades	62
13_S_URM	1 to 3 storey steel frame with URM external facades	2
13_S_O	1 to 3 storey steel frame with non-URM external facades	29
47_LBM_T	4 to 7 storey load bearing masonry with timber internal framing	9
47_LBM_S	4 to 7 storey load bearing masonry with steel internal framing	110
47_LBM_C	4 to 7 storey load bearing masonry with concrete internal framing	50
47_C_URM	4 to 7 storey concrete frame with URM external facades	55
47_C_O	4 to 7 storey concrete frame with non URM external facades	127
47_S_URM	4 to 7 storey with steel frame and URM external facades	5
47_S_O	4 to 7 storey steel frame with non-URM external facades	8
835_C	8 to 35 storey with concrete shear walls and frame	402
835_S	8 to 35 storey with steel frame	37
36_C	36+ storey with concrete frame	80
36_S	36+ storey with steel frame	6
ISS_SS_S	Single steel storey portal frame shed with steel clad walls and roof	1

Table 3 Finer classification of load bearing masonry building types.

GA URM Class	***Description***	***Frequency***
URM1	1 storey residential house	3
URM2	2 storey pub	3
URM3	1 storey retail	35
URM4	2 storey retail	159
URM5	2 storey post office	18
URM6	2 storey bank	94
URM7	3-5 storey commercial	309
URM8	6+ storey commercial	59
URM9	Church	7
URM10	Town hall	0

4 Estimating Population Exposure

Central to the case study was the estimation of indoor and outdoor populations as to distribution across the study area and how they varied with time of day and day of week. This involved combining a wide range of disparate source data sets as described below.

Population was estimated by Destination Zone (DZN). Often this geography maps directly to SA1s as used by the Australian Bureau of Statistics (ABS) or sometimes to a group of SA1s.

In this case study the Melbourne CBD comprised 70 DZNs, Southbank 15 DZNs and Docklands 13 DZNs. Each of the three localities is a SA2.

Both indoor and outdoor population within a given DNZ will vary by time of day and weekday. To limit the number of population estimates required the variation of population through some example weeks was examined using telecommunications derived data (modelled DNZ population numbers based on mobile phone tower access), an example is shown in Figure 4, and identifying four time domains (Night, Morning, Day and Evening) and four week-day domains (Monday to Thursday, Friday, Saturday and Sunday).

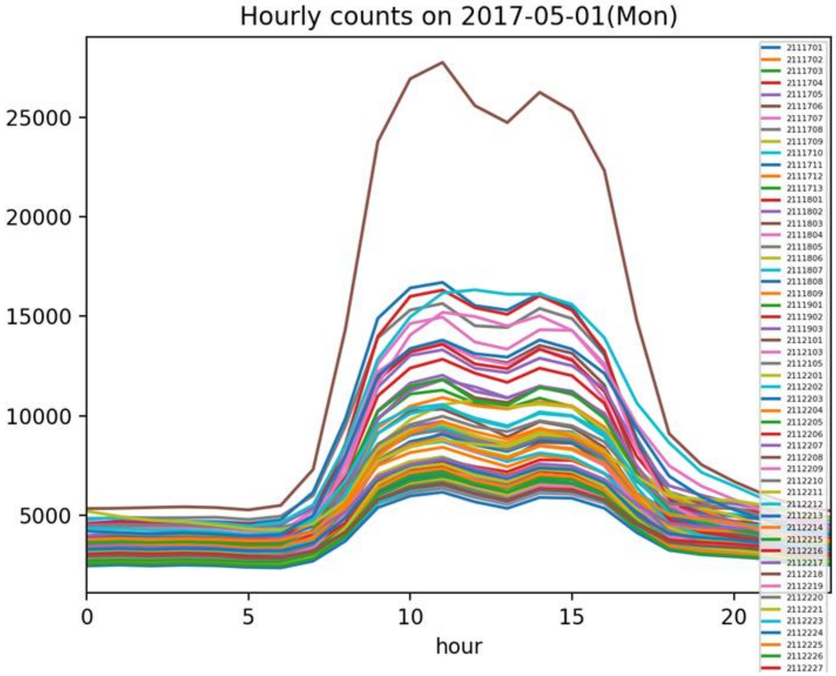

Figure 4 Estimated hourly counts of persons on Monday 01 May, 2017 by DZN.

4.1 Source Datasets

A range of datasets was used as input to the population estimates. These are summarised in Table 4.

Table 4 Summary of input datasets to population estimates.

Dataset	***Description***	***Use***
Telecommunications mobile telephone data	Modelled counts by DZN at hourly intervals of 18 year olds and older based on mobile tower access.	Direct estimate of total number of people 18 year olds and older by DZN over time
ABS Census of Population and Housing	Counts of residents by DZN: • Unemployed • Working in home DZN • Working outside home DZN	Used to swell the telecommunication derived data to the full age demographic.
Pedestrian movements (City of Melbourne Pedestrian Counting System)	Counts of pedestrians passing each pedestrian movement monitor	Estimate footpath pedestrian density
Sydney Coordinated Adaptive Traffic System (SCATS)	Counts of vehicles by lane and intersection at 15 minute intervals	Estimate vehicle numbers, vehicle mix and hence vehicle passenger numbers
Aerial and satellite imagery	-	Identify locations of human activity and estimate vehicle numbers, vehicle mix and hence vehicle passenger numbers

4.2 Indoor Population

The indoor population was estimated using the telecommunications data (inflated to allow for the under 18 population) and the estimated outdoor population (pedestrians and vehicle passengers). It was estimated over the combinations of the four day domains and the four time domains. For each DZN, the indoor population was computed by subtracting both the pedestrian count and the passenger count from the adjusted telecommunications data. The resulting indoor population was distributed proportionally to the floor area within the DZN to estimate the indoor population for each building.

4.3 Outdoor Population

The outdoor population was considered to comprise pedestrians and passengers in vehicles (cars, trucks, buses and trams). The latter was only required to enable the estimation of the indoor population. The pedestrian population was required as it was considered to be the population exposed to masonry falling from damaged URM buildings.

Passenger numbers

A relationship between SCATS counts and counts of vehicles by type was developed using aerial imagery taken at the same time as the SCATS counts. Vehicle types were categorised as cars, trucks, buses and trams with statistics developed for the mix. From this relationship the SCATS counts were translated into vehicle densities on an hourly basis. Using counts of vehicle types and representative passenger numbers the vehicle density was translated into a human population on the road on an hourly basis.

Pedestrian numbers

Pedestrian activity across all three SA2's (Melbourne, Docklands and Southbank) was manually defined into 5 categories of pedestrian density. The categories were based on local knowledge and pedestrian monitor readings. The five categories of pedestrian density were; "Transport Hubs" (Southern Cross Station, Flagstaff Station and Flinders Street Station), "Very High", "High", "Medium" and "Low".

Using City of Melbourne open data footpath centrelines were created, classified (into the five pedestrian activity categories) and the segment lengths calculated (Figure 5). The footpath centrelines were also intersected with the DNZ boundaries giving them a DNZ ID for later aggregation.

Pedestrian monitor counts per time domain and weekday were averaged and the distance of potential travel divided by this average. This yielded an average distance between pedestrians, an inverse density, hereafter referred to as a 'density'. All values for each footpath category were averaged across the study area. Figure 6 shows the variation in pedestrian density by time domain and day of week. In this chart "low" has been excluded as the detail of the higher density categories is lost. The "low" pedestrian density ranges from around one person per 3 metres to one person per 13 metres.

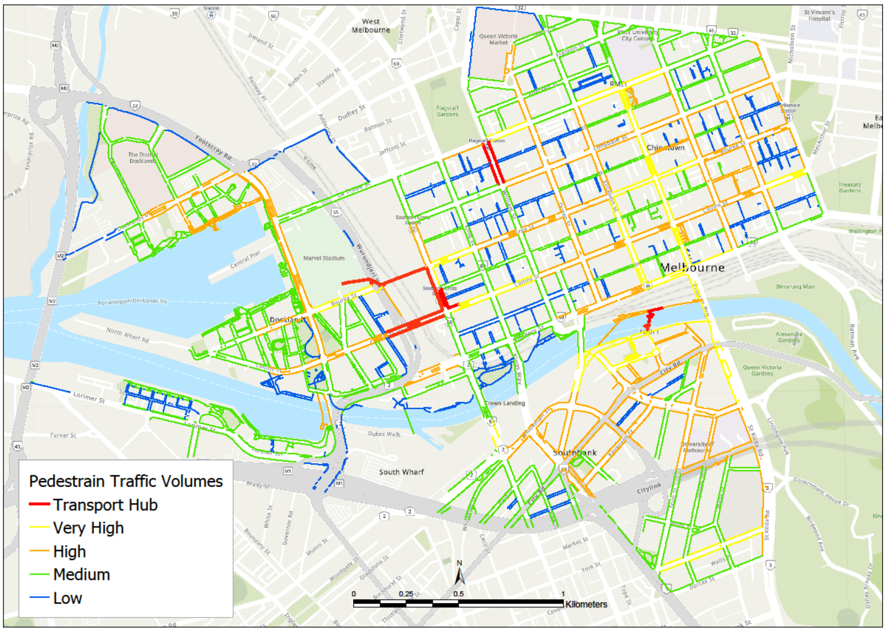

Figure 5 Categorisation of footpaths within the study area based on pedestrian activity.

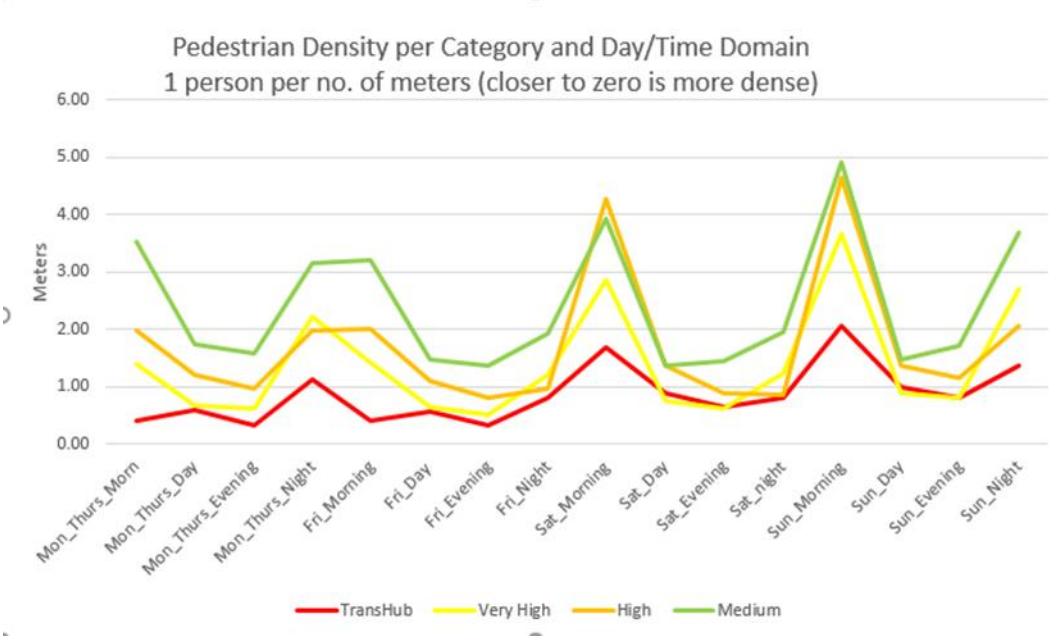

Figure 6 Pedestrian 'density' (meters length of footpath per person) by footpath category and day and time.

5 Modelling Casualties

For the casualty estimation, the scenario was assumed to occur at 11 AM on a weekday other than Friday. Casualties were estimated following the methodology presented in FEMA, 2006 with adjustments for outdoor casualties as described below. Table 5 shows the casualty rates for low-rise URM (URML) buildings extracted from FEMA, 2006. The outdoor casualty rates in Table 5 are extremely low. These were reviewed against photographs of damaged URM buildings in Christchurch, 2011, such as Figure 7, which showed the quantity and extent of fallen masonry. Clearly if the degree of collapse shown in Figure 7 occurred onto a footpath with a pedestrian population typical of a CBD street the casualty rates could be expected to exceed the percentages given in Table 5. Hence, revised casualty rates for outdoor populations were adopted as given in Table 6. The figures in take into account estimated values for:

- for each damage state the proportion of buildings where masonry collapses into the street; and
- the proportion of exposed people in each casualty severity level allowing for the ability of people in the street to effectively move during earthquake shaking to escape falling masonry.

Table 5 Casualty rates from FEMA, 2006 expressed as percentages of exposed population in each casualty severity level. The figures for complete damage state assume 15% of buildings in that damage state are collapsed and 85% are not.

Damage State	***Indoor population***				***Outdoor population***			
	Casualty Severity Level				***Casualty Severity Level***			
	1	***2***	***3***	***4***	***1***	***2***	***3***	***4***
None	0	0	0	0	0	0	0	0
Slight	0.05	0	0	0	0	0	0	0
Moderate	0.35	0.4	0.001	0.001	0.15	0.015	0.0003	0.0003
Severe	2	0.2	0.002	0.002	0.6	0.06	0.0006	0.0006
Complete	14.5	4.7	0.767	1.517	5	2	0.4	0.6

Table 6 Heuristic outdoor casualty rates adopted for the project (percentage of exposed population in casualty severity level by building damage state).

Building damage State	***Proportion of buildings with masonry fallen into street (%)***	***Proportion of outdoor population in each casualty severity level if masonry falls into the street (%)***				***Proportion of outdoor population in each casualty severity level (%)***			
		Casualty Severity Level				***Casualty Severity Level***			
		1	***2***	***3***	***4***	***1***	***2***	***3***	***4***
None	0	5	5	10	60	0	0	0	0
Slight	0	5	5	10	60	0	0	0	0
Moderate	25	5	5	10	60	1.25	1.25	2.5	15
Severe	75	5	5	10	60	3.75	3.75	7.5	45
Complete	90	5	5	10	60	4.5	4.5	9	54

The casualty severity levels in Table 5 and Table 6 are described in FEMA, 2006 and reproduced in Table 7.

Table 7 Description of casualty severity level.

Injury Severity Level	***Injury Description***
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals.

Injury Severity Level	***Injury Description***
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as X-rays or surgery but are not expected to progress to a life threatening status.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously.
Severity 4	Instantaneously killed or mortally injured

Figure 7 Collapsed URM facades in Christchurch. Photo: Alamy.

6 Results and Discussion

Three scenarios were modelled, each with the same source earthquake:

1. Baseline, existing exposure and vulnerability, i.e. no retrofit of URM;
2. Retrofit of URM buildings. 162 out of 687 URM buildings of types URM4, URM5 or URM7 were randomly nominated for retrofit.
3. Targeted retrofit of URM buildings. 162 URM buildings were nominated for retrofit. However, those chosen were concentrated along those streets with the highest pedestrian densities.

The number of URM buildings retrofitted represented approximately 25% of the total URM population which is what was judged achievable over a 30 year campaign of mitigation. The estimated numbers of outdoor casualties are given in Table 8 and the estimated numbers of damaged buildings are given in Table 9 for each of the three scenarios. It was noted that random retrofit reduced deaths by 18% whereas targeted retrofit achieved a 34% reduction.

Table 8 Estimated outdoor casualties for the scenario event.

Injury Severity Level	***No retrofit***	***Random retrofit***	***Targeted retrofit***
1	45	37	29
2	44	35	29
3	89	73	59
4	535	438	352

Table 9 Estimated damage to URM buildings: numbers of buildings by damage state.

Damage State	***No retrofit***	***Random retrofit***	***Targeted retrofit***
Slight	99	129	132

Moderate	47	14	15
Extensive	10	2	2
Complete	1	0	0

Retrofit of URM resulted in a reduction in the number of URM buildings in the higher damage states and also reduced the number of outdoor casualties outside URM buildings. Targeted retrofit, where retrofit was selectively applied to URM buildings along streets with high pedestrian densities reduced outdoor casualties further although did not significantly change the modelled damage to URM building stock.

The modelling has indicated that retrofit of older URM buildings can effectively reduce the damage incurred by the URM building stock during a strong earthquake and also reduce the number of casualties caused by masonry falling into the street from URM buildings.

7 Summary

The case study has highlighted the prevalence of older URM in Australian communities with 45% of buildings in the Melbourne study region of this type. It has also highlighted the risk they pose in high pedestrian environments. Had the Woods Point Earthquake of the 21st September 2021 occurred closer to Melbourne and not during a COVID lock-down period mass casualties across Melbourne could have been expected. The case study, informed by a detailed population movement model, has highlighted how targeted retrofit of 25% of buildings in the greater Melbourne CBD can achieve a 34% reduction in deaths from such an event.

8 References

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