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PROGRESS REPORT ON COSTING OF LIMITED DUCTILE REINFORCED CONCRETE BUILDINGS

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TABLE OF CONTENTS

ABSTRACT

PROGRESS REPORT ON COSTING OF LIMITED DUCTILE REINFORCED CONCRETE BUILDINGS

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"Cost-effective mitigation strategy development for building related earthquake risk" under the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) aims to develop knowledge to facilitate evidence-based informed decision making in relation to the need for seismic retrofitting, revision of codified design requirement, and insurance policy. Previous report has presented vulnerability assessment of two types of reinforced concrete (RC) buildings, RC buildings that are mainly supported laterally by limited ductile RC walls and buildings that are supported jointly by limited ductile RC walls and RC frames. The analyses demonstrate buildings that are jointly supported by RC walls and frames to be more vulnerable.

This report presents summary findings of the vulnerability analyses along with descriptions for the types of damage observed for each performance levels with the aim of estimating cost of repair for this type of buildings.

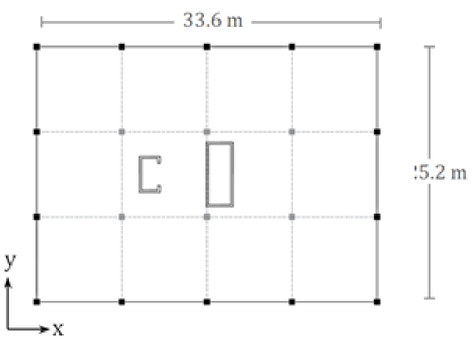
INTRODUCTION

This report presents progress on the work currently carried out on estimating the repair cost of limited ductile reinforced concrete (LDRC) buildings under earthquake loadings. The report follows on the report previously submitted on the construction of fragility curves for this type of buildings which has highlighted the vulnerability of RC buildings that are jointly supported by RC frames and RC walls. A summary of the vulnerability analyses, the performance levels and the associated fragility curves for these buildings are first presented. The failure mechanism associated with each performance levels and the associated typical damages observed are then described.

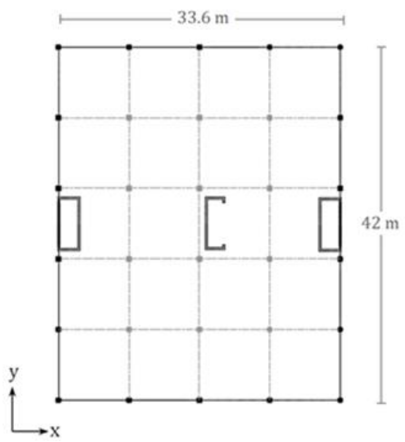
VULNERABILITY OF RC BUILDINGS SUPPORTED BY RC WALLS AND FRAMES

In the previous report, fragility curves have been constructed for three types of buildings, buildings that are mainly supported by shear or core walls, buildings that are supported by shear walls and moment resisting frames and podium-tower buildings featuring a transfer structure. It was demonstrated that buildings supported by shear walls and RC frames (Referred to RC frames building herein) are generally more vulnerable in an earthquake compared to RC shear walls and podium-tower RC buildings. The building investigated, the definition of performance levels and the outcomes of fragility analyses for the buildings are summarised in this section.

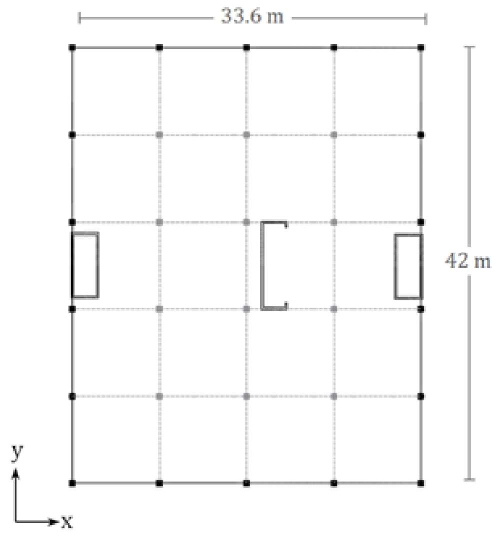
Three reinforced concrete buildings were assessed which are 2-storey, 5-storey and 9-storey high, representing low-, medium- and high-rise buildings. The buildings are representative of older RC buildings constructed in Australia prior to the requirement for seismic load and design to be mandated on a national basis. The buildings have been designed in accordance with AS 3600:1988 Concrete Structures Standard, AS 1170.2:1983 Wind Actions Standard, and guidance from experienced practicing structural engineers. The frames were designed as ordinary moment resisting frames (OMRFs). The core walls have low longitudinal reinforcement ratio (approximately 0.23 %) with no confinement. The building plans are provided in Figure 1.



(a) 2-storey (low rise)



(b) 5-storey (medium rise)



(c) 9-storey (high rise)

FIGURE 1 IDEALISED RC FRAMES BUILDINGS

Four performance levels were considered: i) slight damage (also often referred to as operational, serviceability or immediate occupancy limit state); ii) moderate damage (also often referred to as damage control or repairable damage limit state); iii) extensive damage (also often referred to as life safety limit state); and iv) complete damage (also often referred to collapse prevention limit state). A summary of the adopted performance levels is provided in Table 6. More details can be found in Amirsardari [1]. The fragility curves for the RC frames buildings are presented in Figure 2.

TABLE 1 PERFOMANCE LEVELS

Performance level	**Limits**		
	Primary structure	Secondary structure	Non-structural limit
Slight Damage / Serviceability (S)	Wall reaching initial yield limit	Frame component reaching nominal yield rotational limit	ISD reaching 0.004
Moderate Damage/ Damage Control (DC)	Wall reaching a compressive strain of 0.002, or tensile strain of 0.015, whichever occurs first	Frame component reaching rotation which is at mid-point between yield and ultimate rotational limits	ISD reaching 0.008
Extensive Damage/ Life Safety (LS)	Wall reaching ultimate rotational limit, corresponding to a compressive strain of 0.004, or tensile strain of $0.6\varepsilon_{su}$, whichever occurs first	Frame component reaches the rotation corresponding to shear failure	ISD reaching 0.015
Complete Damage/ Collapse Prevention (CP)	NA	Frame component reaches the rotation corresponding to 50 % reduction in ultimate lateral strength	ISD reaching 0.002

NA: Not applicable; ID: Inter-storey drift

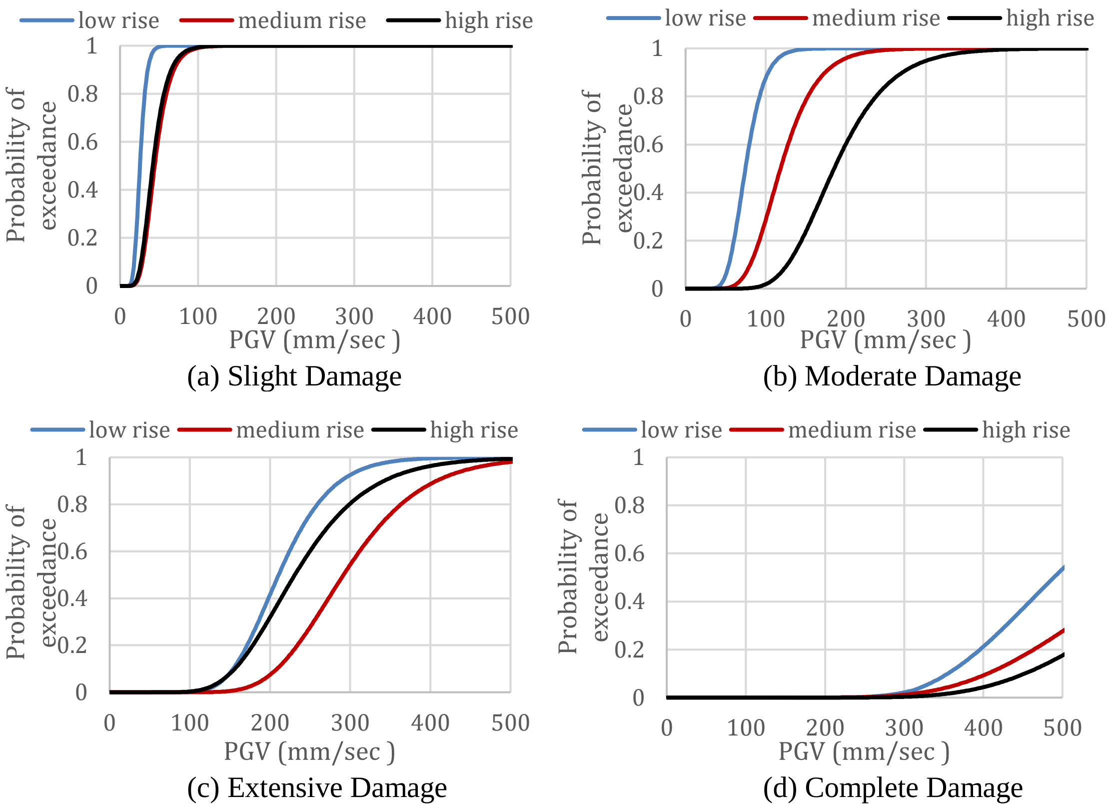


FIGURE 2 FRAGILITY CURVES FOR RC FRAMES BUILDING

SUMMARY OF TYPICAL FAILURE MECHANISMS AT EACH PERFORMANCE LEVEL

This section summarises typical failure mechanisms observed from the analyses when each performance level has been exceeded.

Slight Damage:

The slight damage performance levels were mostly governed by the reinforced concrete walls reaching the initial yield limit. Only for a very small proportion of the buildings analysed (less than 10%) have the performance level governed by the beam-column joint exceeding its serviceability limit state.

Moderate Damage:

The moderate damage performance levels were generally governed by the RC walls reaching their rotational limit corresponding to a compressive strain of 0.002, or tensile strain of 0.015, whichever occurs first. Only a small proportion of the buildings have the inter-storey drift limit of 0.8% reached first (before other failure mechanism).

Extensive Damage:

For most buildings, the extensive damage performance levels were reached when the RC walls reaching their ultimate rotational limit, corresponding to a compressive strain of 0.004, or tensile strain of 0.6 ε_{SU}, whichever occurs first. For medium- and high- rise buildings there is a proportion of the buildings (less than 20%) have the inter-storey drift limit of 1.5% being exceeded, whilst a small proportion (less than 10%) have the columns and joints reaching the life safety limit state (which is defined as the point when the lateral load starts to decrease). For low-rise buildings, a small proportion of the buildings have the beam-column joint exceeding the life safety limit state.

Complete Damage:

For low-rise buildings, typically the inter-storey drift limit of 2% is reached first (note this interstorey limit was set as a structural (rather than non-structural) inter-storey drift limit since the response of the wall is not modelled up to axial load failure). A proportion of low-rise buildings (around 20%) have the beam-column joints reaching their collapse prevention limit state. For the medium- and high-rise buildings, a large proportion of buildings have their inter-storey drift limit being exceeded. But, there are also some proportion (around 25%) have their columns reaching their collapse prevention limit, whilst there are very small proportion (around 10%) have the beam-column joints reaching their limit.

Location of failure

When the RC walls reach a performance level (or limit state), the damage generally occurs at the base of the walls. When the columns and beam-column joints reach a performance level, it is more difficult to exactly identify where the failure occurs. However, based on the building behaviour, up to the extensive damage limit state, the failure is most likely to occur on the frame elements in the top storeys. This is because the drifts tend to be larger at the top storeys when the RC wall is governing the response of the building. For the complete damage level, the failure of the frame elements may occur at the top storeys (due to accumulation of damage which has occurred during earlier stages of loading). Alternatively, the failure of the elements may occur at the base of the building; especially for the columns, since columns with high axial load have significantly lower drift capacities. Also, once the walls lose their lateral stiffness, the building response could be largely governed by the moment resisting frames and hence causing large drifts the bottom storeys.

DESCRIPTION OF DAMAGE

Typical damage observed associated with each performance level is summarised in Table 2 (shown in the following page).

TABLE 2 DAMAGE DESCRIPTION FOR RC FRAMES BUILDINGS [1-4]

Performance levels	Inter-story drift limit	Primary Structure (Wall Elements)		Secondary Structure (Frame Elements)	
		Behaviour	**Damage Description**	**Behaviour**	**Damage Description**
Slight	0.004	Reaching initial yield rotational limit	Minor Hairline Cracking (widths up to 1mm), Injection grouting not required	Reaching nominal yield rotational limit	Flexural cracking in beams and columns
			Single crack forming at base		Minor spalling in few places
					Minor shear cracking in joints (<0.0025mm)
			No significant remedial action should be needed		No significant remedial action should be needed
Moderate	0.008	Reaching a rotational limit corresponding to: • Compressive strain= 0.002 Or • Tensile strain= 0.015 Whichever occurs first	Crushing of concrete	Reaching rotation which is at mid-point between nominal yield and shear failure rotational limits	Crushing of concrete
			Spalling of concrete cover, requiring replacement		Top Storey Frames vulnerable
			Wide residual flexural cracks, requiring injection grouting to avoid corrosion		Spalling of concrete cover, requiring replacement
			Shear cracking		Extensive cracking in ductile elements
			Minor joint cracks		Severe damage in short columns
					Limited cracking and/or Splice failure in some nonductile columns
Extensive	0.015	Reaching ultimate rotational limit corresponding to: • Compressive strain= 0.004 Or • Tensile strain= 0.6ε_{su}	Extensive cracking	Reaching the rotation corresponding to shear failure	Extensive cracking
			Crushing		Splice failure of some columns
			Spalling		Top Storey Frames vulnerable
			Limited buckling of bars		Extensive spalling in columns and beams
			Rupture of longitudinal bars		Severe joint damage

		Whichever occurs first * *ε_{su} is the strain of reinforcement at ultimate tensile strength*	Core walls behaviour critical at this stage		Some buckling of reinforcement
Complete	0.020		Already failed	Reaching the rotation corresponding to 50% reduction in ultimate lateral strength	At limit, some components reach axial load failure.
					Ground level columns (at the base) are likely to fail first
					Axial load failure will be reached by other components almost immediately.

CONCLUDING REMARKS

This report presents a summary of vulnerability assessment that has been conducted on limited ductile reinforced concrete buildings that are jointly supported by walls and moment resisting frames. The buildings have been identified to be vulnerable in an earthquake. It was observed from the analyses that for the slight, moderate and extensive damage levels, the majority of the buildings have their RC walls exceeding their damage limit state. For the extensive damage limit state, most buildings have the inter-storey drift limit being exceeded whilst a small proportion of the buildings have their columns and the joints exceeding their damage limit state. Typical damages associated with each performance level are described.

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