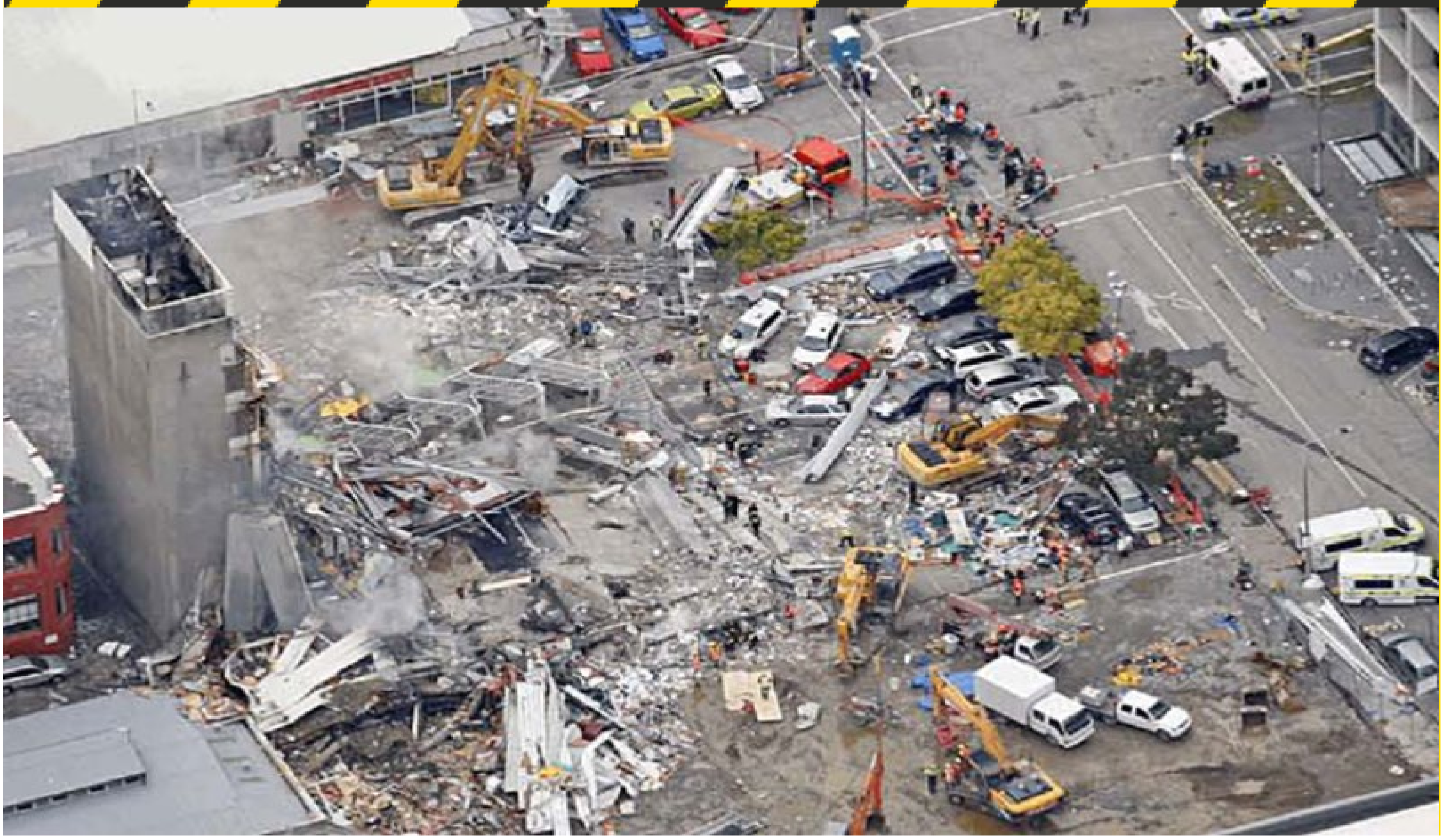
bnhcrc.com.au

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

Elisa Lumantarna[1], Nelson Lam[1], Hing-Ho Tsang[2], Emad Gad[2] & John Wilson[2]
University of Melbourne[1], Swinburne University of Technology[2]



Version	Release history	Date
1.0	Initial release of document	13/03/2020

Australian Government
Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program

Publisher:
Bushfire and Natural Hazards CRC

March 2020

Citation: Lumantarna, E, Lam, N, Tsang, H, Gad, E & Wilson, J 2020, Final report on vulnerability of as-built and retrofitted LDRC buildings, Bushfire and Natural Hazards CRC, Melbourne.

Cover: Building wreckage.

TABLE OF CONTENTS

ABSTRACT

Elisa Lumantarna, *Department of Infrastructure Engineering, The University of Melbourne, VIC*

Previous Bushfire and Natural Hazard CRC (BNH CRC) reports have presented the fragility curves for reinforced concrete buildings that are supported by reinforced concrete walls and moment resisting frames, and the fragility curves for this type of buildings with four retrofitting options. This study presents the vulnerability curves for these buildings presented in terms of damage factor, which is the ratio of the repair cost to the replacement cost for the buildings. This report contributes to the project "Cost-effective mitigation strategy development for building related earthquake risk" which is aimed 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.

INTRODUCTION

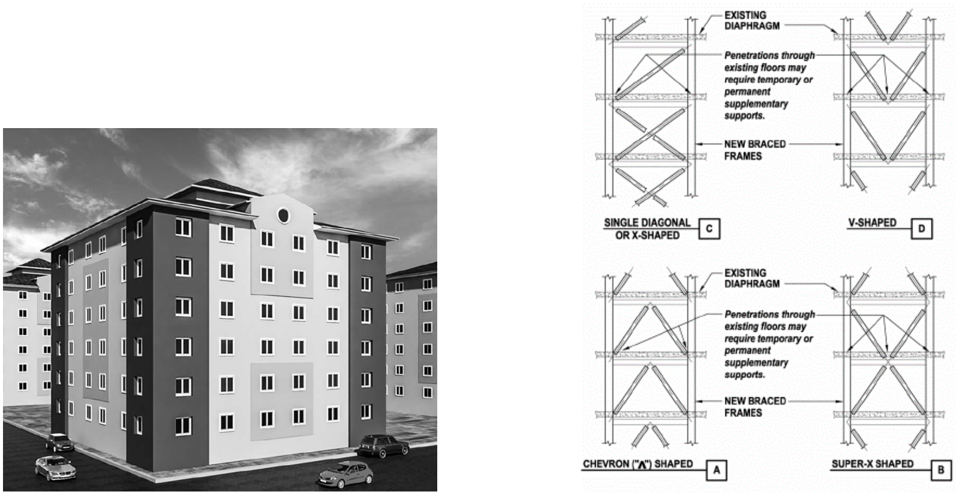
This report is concerned with the retrofitting of limited ductile reinforced concrete (LDRC) buildings which make up the bulk of built infrastructure in the central business districts and high-density residential areas in Australian capital cities. Four different types of retrofitting methods have been investigated: i) addition of bracing system; ii) addition of infill walls; iii) fibre reinforced polymer (FRP) jacketing; and iv) steel jacketing. The impact of applying the retrofitting methods on the response behaviour of limited ductile reinforced concrete (RC) buildings were evaluated.

Sets of vulnerability curves will be presented for retrofitted buildings that are supported by limited ductile reinforced concrete walls and moment resisting frames. These sets of vulnerability curves were constructed based on the fragility curves for as built and retrofitted archetypal buildings that have been presented in the previous BNH CRC reports [1,2]. Sets of fragility curves will be presented for retrofitted limited ductile reinforced concrete frames. The constructed fragility curves will be compared with the fragility curves for limited ductile RC buildings presented in previous BNH CRC report). A brief overview of the four retrofitting methods investigated in this study will be presented along with the fragility curves for the retrofitted buildings. Vulnerability curves in the form of damage factor (%) will be presented based on the constructed fragility curves. The information presented in this report are based on the up to date knowledge of the project team. It is noted that there are ongoing works on this topic, being carried by in conjunction with PhD students who are financially supported by this BNH CRC project.

RETROFITTING METHODS

GLOBAL RETROFIT STRATEGIES

Global retrofit strategies include providing additional lateral load resisting elements such as infill wall, shear wing wall, buttress walls, steel braced frames, external precast and prestressed concrete frames, energy dissipation and base isolation devices, to improve the strength and stiffness of the structure [3, 4, 5]. The impact of global retrofit strategies by adding infill walls and bracing systems as shown in Figure 1 were investigated in this study.



(a) (b)

FIGURE 1 RETROFITTING BUILDING BY (A) ADDING EXTERNAL SHEAR WALL [5, 6], AND (B) BRACED STEEL FRAMES [6]

The bracing system used to retrofit the frame is the eccentric bracing consisting of chevron pattern and a vertical shear link (Figure 2). The steel member used for the brace members and the link is 150UB14.0 and the link is approximately 300 mm long attached centrally to the beam.

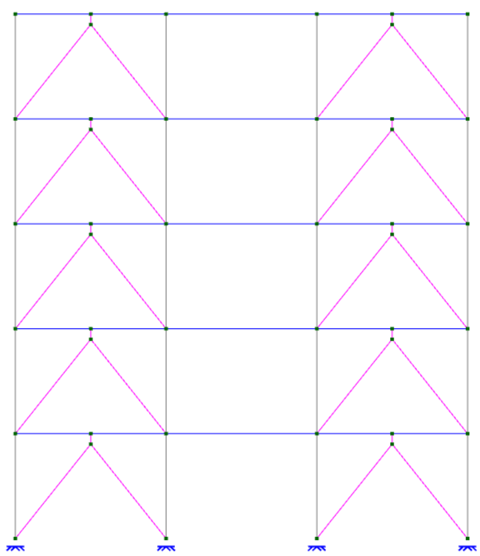


FIGURE 2 ECCENTRICALLY BRACED RC FRAME

The material selected for the infill walls is reinforced concrete since it provides greater strength than masonry. As shown in Figure 3, the infill walls were modelled using the "equivalent diagonal strut" which functions as a compression brace. This is a simplified method widely used by engineers to model infill walls and it consists of the same material and thickness as the infill panel [7]. The width of the equivalent compression strut was determined based on Ref. [8].

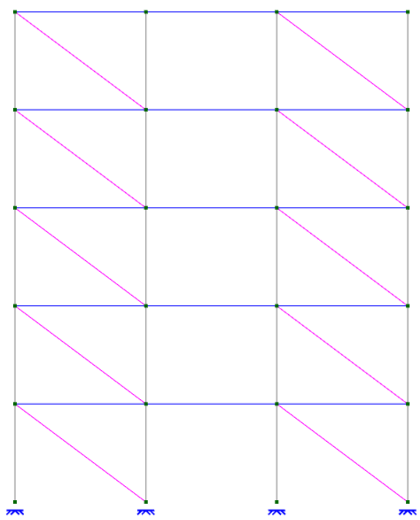
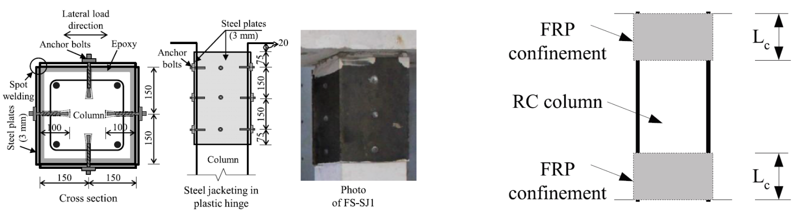


FIGURE 3 RC INFILLED FRAME

LOCAL RETROFIT STRATEGIES

Local retrofit strategies focus on local structural elements such as columns, beams and joints. The study investigated the effect of local retrofitting of reinforced concrete columns by steel jacketing and fibre-reinforced polymer (FRP) sheet (Figure 4).



(a) Steel jacketing [9] (b) FRP jacketing [10]

FIGURE 4 RETROFITTING OF REINFORCED CONCRETE COLUMN

The material model for FRP jacketing of columns was adapted from the American standard ACI440.2R [11] (Table 1). The confining pressure due to the FRP jacketing vary linearly with the number of FRP sheets used for confinement. This relationship is represented in Table 2. Three layers of FRP were adopted int this study

TABLE 1 FRP MATERIAL PROPERTIES

Tensile modulus (MPa)	thickness (mm)	Strain level at section failure (mm/mm)	No of layers n
150,000	1.4	0.00825	variable

TABLE 2 STRENGTHS OF JACKET AND CONFINED COLUMN POST RETROFIT.

	n=1	n=2	n=3	n=4
f_l (MPa)	3.758	7.516	11.27	15.03
f'cc (MPa)	47.6	62.7	77.81	92.91

Steel jackets were modelled as a column with two steel plates either side (in the plane of the lateral force) along the entire length of every first storey column. This was done to simulate a rigid member fixed to the side of the columns. The steel jackets on the other sides of these columns (along out-of-plane faces) were not considered for this modelling, since it was assumed that these elements would contribute negligible benefits to the performance of the frame. The steel member assumed for the modelling was a 40mm x 300mm.

FRAGILITY CURVES

Fragility curves for three archetypal reinforced concrete buildings presented in Figure 5 have been constructed and presented in the previous BNH CRC report [1]. The effects of different retrofitting techniques have been investigated. Fragility curves have been constructed for the archetypal reinforced concrete buildings retrofitted by different techniques. The details of the study can be found in the previous BNH CRC report [2]. The fragility curves for different retrofitting techniques are presented in Figures 5 and 6 along with the fragility curves for non-retrofitted RC concrete frames (bare frame).

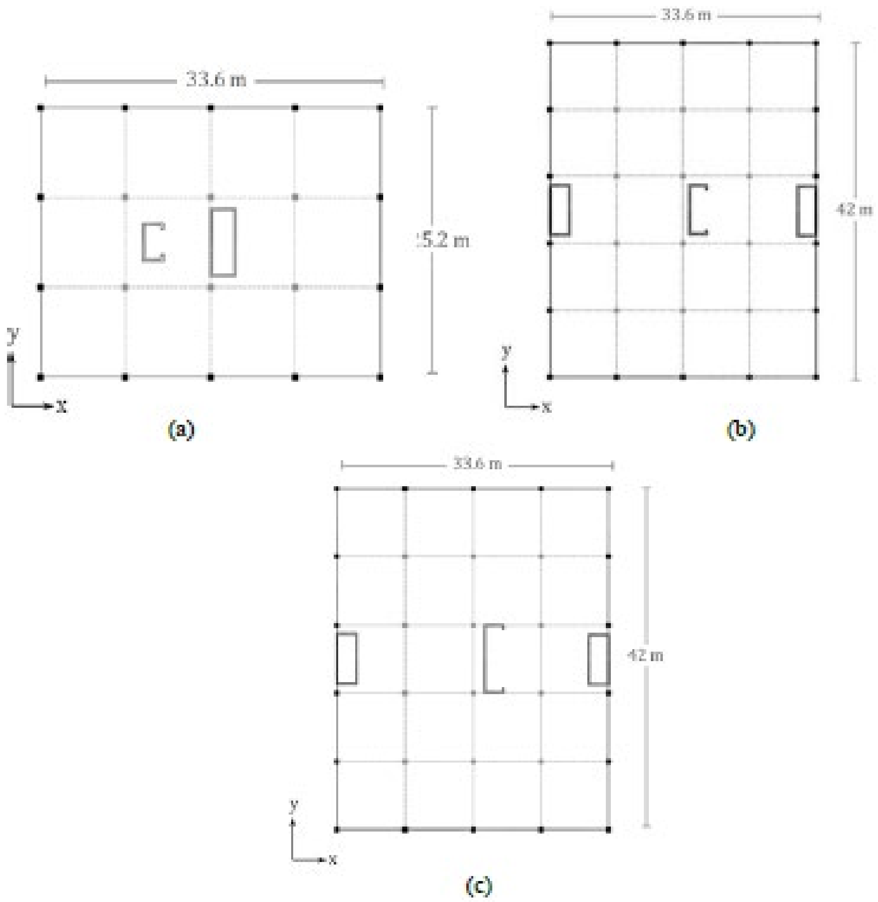
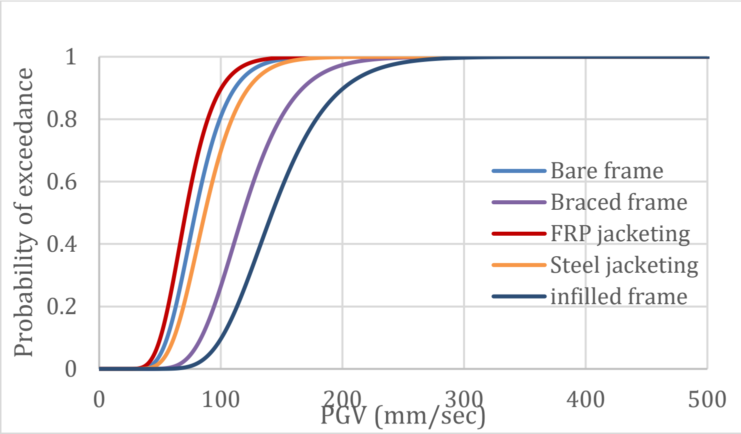
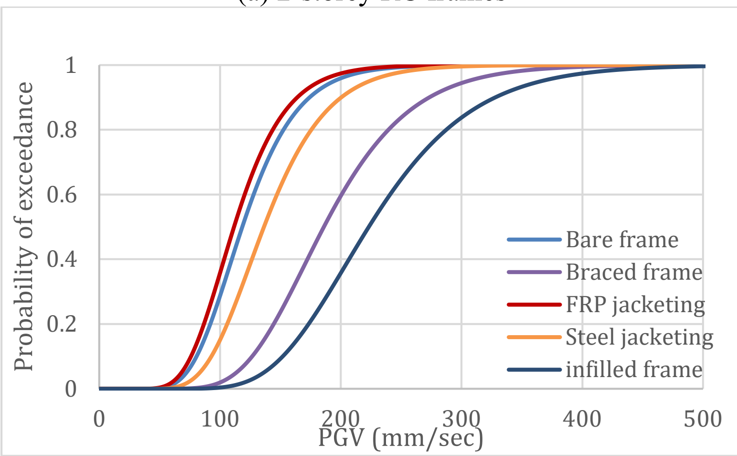


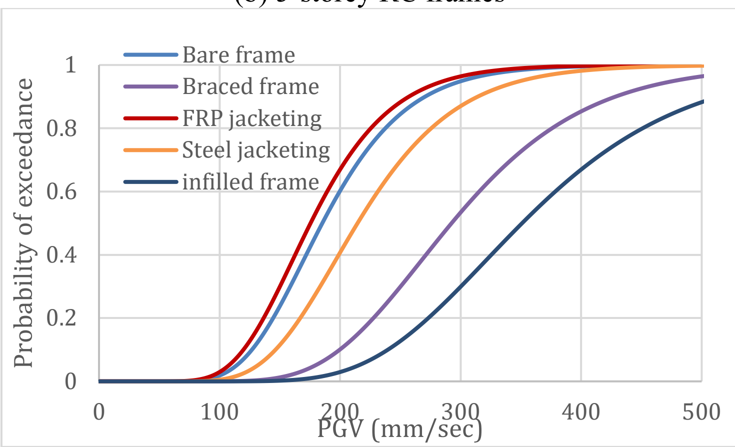
FIGURE 5 BUILDING PLANS OF ARCHETYPAL REINFORCED CONCRETE BUILDINGS, (A) 2-STOREY, (B) 5-STOREY, AND (C) 9-STOREY [1]



(a) 2-storey RC frames

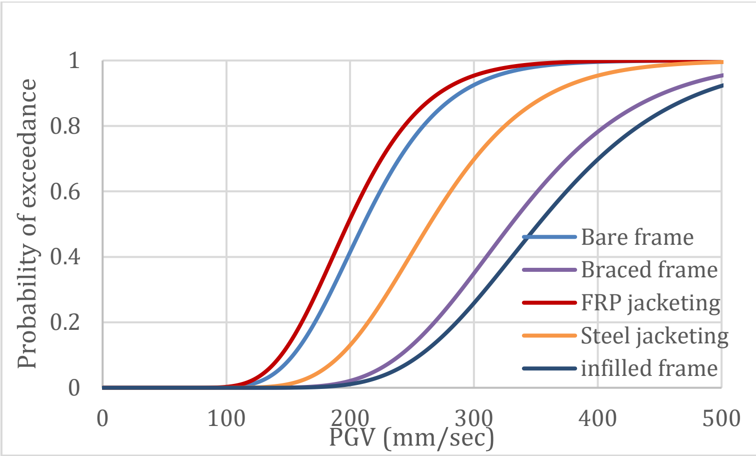


(b) 5-storey RC frames

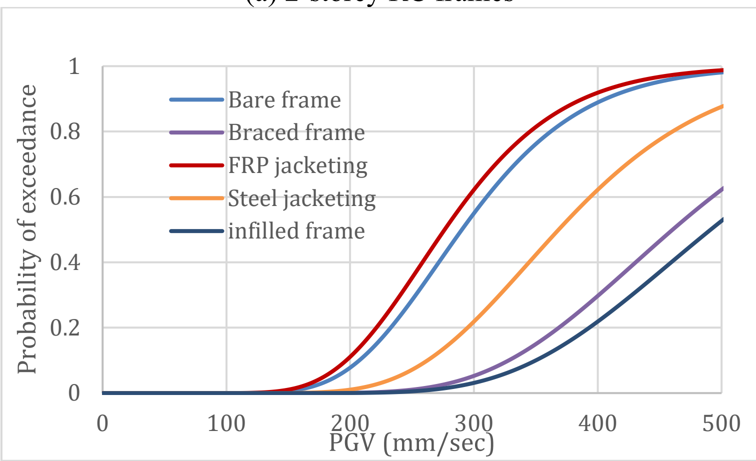


(c) 9-storey RC frames

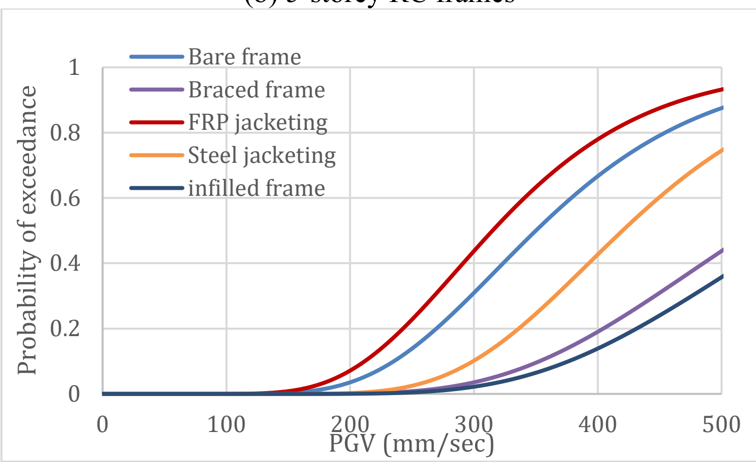
FIGURE 6 FRAGILITY CURVES FOR RETROFITTED RC FRAMES, MODERATE DAMAGE [2]



(a) 2-storey RC frames



(b) 5-storey RC frames



(c) 9-storey RC frames

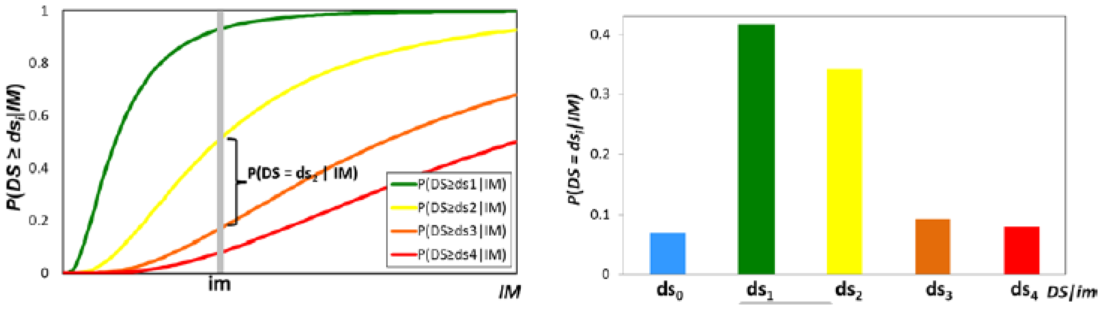
FIGURE 7 FRAGILITY CURVES FOR RETROFITTED RC FRAMES, EXTENSIVE DAMAGE [2]

VULNERABILITY ASSESSMENT

The mean vulnerability curves can be constructed out of the fragility curves presented in the previous section using the following equation [12]:

$$E(C|im) = \sum_{i=0}^{n} E(C|ds_i).P(ds_i|im) \quad (1)$$

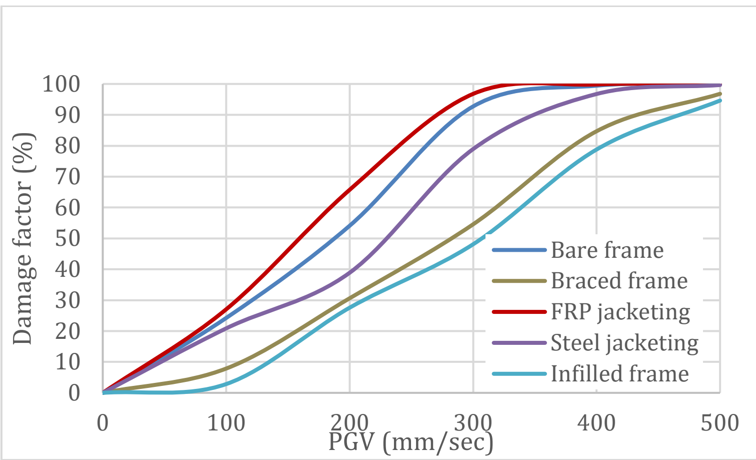
where, $E(C|im)$ is the mean of the vulnerability curves, $E(C|ds_i)$ is the cost (loss) for a given damage state ds_i (the cost is presented in terms of damage index, which is the repair to replacement ratio), and $P(ds_i|im)$ is the probability of a building sustaining damage state ds_i. The damage probability $P(ds_i|im)$ is defined as the distance between two successive fragility curves as illustrated in Figure 8.



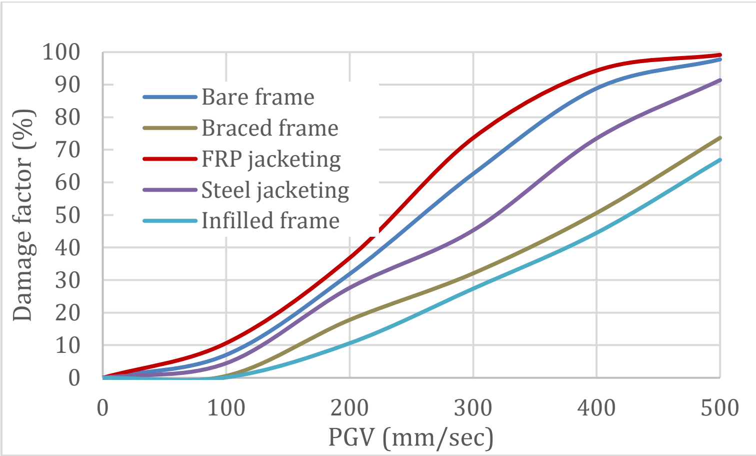
(a) Fragility curves corresponding to 4 damage states (b) damage probability for intensity im

FIGURE 8 CALCULATION OF DAMAGE PROBABILITIES FROM FRAGILITY CURVES [12]

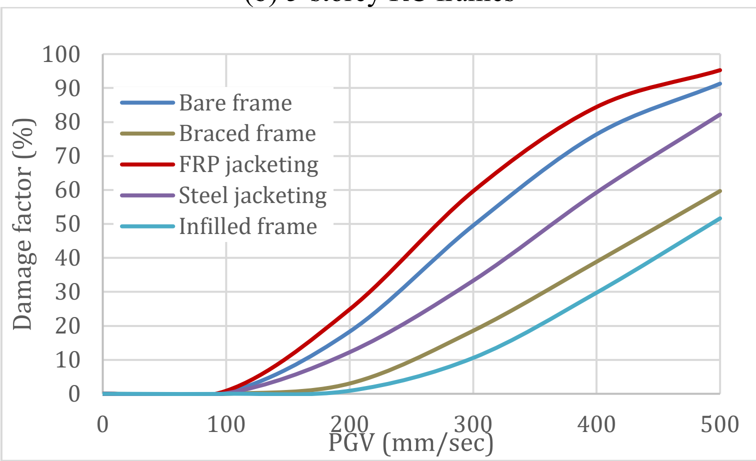
Vulnerability curves were constructed for two damage states, moderate and extensive damage, based on fragility curves presented in Figures 6 and 7. The values of cost, in terms of damage index, were 30% and 100%, for moderate and extensive damage, respectively. These values were adopted from a previous study conducted by the authors [13]. The vulnerability curves are presented in Figure 9.



(a) 2-storey RC frames



(b) 5-storey RC frames



(c) 9-storey RC frames

FIGURE 9 VULNERABILITY CURVES FOR RETROFITTED RC FRAMES

CONCLUDING REMARKS

This report presents vulnerability curves of as built and retrofitted limited ductile reinforced concrete buildings. Four retrofitting techniques have been evaluated: i) addition of bracing system; ii) addition of infill walls; iii) fibre reinforced polymer (FRP) jacketing; and iv) steel jacketing. The vulnerability curves have been constructed based on fragility curves that have been presented in the previous BNH CRC report. Retrofitting by addition of infill walls was found to provide the greatest benefit followed by retrofitting by addition of bracing systems. This is cause by the additional stiffness provided by the infill walls and bracing systems, which in turn delay the onset of failure of the reinforced concrete frames. On the other hand, the addition of FRP and steel jacketing was found to have less impact on the seismic performance of the limited ductile RC buildings.

REFERENCES

1 Lumantarna, E., Goldsworthy, H., Lam, N., Tsang, HH, Gad, E, Wilson, J (2018). Report on fragility curves for limited ductile reinforced concrete buildings, BNH CRC report.
2 Tsang, HH, Gad, E, Wilson, J, Lumantarna, E, Lam, N (2019). Report on fragility curves of retrofitted limited ductile reinforced concrete frames, BNH CRC report.
3 Chakrabarti, A., Menon, D., & Sengupta, A. K. (2008). *Handbook on seismic retrofit of buildings*: Oxford : Alpha Science International, c2008.
4 Kiyoji, T., Kyoya, T., Toshiaki, S., Asao, S., & Yoshiteru, O. (2013). Seismic retrofit of reinforced concrete buildings in Japan using external precast, prestressed concrete frames. PCI Journal, 58(3), 41.
5 Liel, A. B., & Deierlein, G. G. (2013). Cost-benefit evaluation of seismic risk mitigation alternatives for older concrete frame buildings. *Earthquake spectra, 29*(4), 1391-1411. doi:10.1193/030911EQS040M
6 Dere, Y. (2017). Assessing a Retrofitting Method for Existing RC Buildings with Low Seismic Capacity in Turkey. Journal of Performance of Constructed Facilities, 31(2), 1-17. doi:10.1061/(ASCE)CF.1943-5509.0000969
7 Moretti, ML 2015, 'Seismic Design of Masonry and Reinforced Concrete Infilled Frames: A Comprehensive Overview', *American Journal of Engineering and Applied Sciences,* vol. 8, no. 4, pp. 748.
8 Holmes, M 1961, 'Steel Frames with Brickwork and Concrete Infilling', *Proceedings of the Institution of Civil Engineers,* vol. 19, no. 4, pp. 473-478.
9 Truong, G. T., Kim, J.-C., & Choi, K.-K. (2017). Seismic performance of reinforced concrete columns retrofitted by various methods. Engineering Structures, 134, 217-235. doi:10.1016/j.engstruct.2016.12.046
10 Choi, S. W., Park, S. W., & Park, H. S. (2017). Multi-objective design model for retrofit of reinforced concrete frames with infilled walls using FRP bracings, 454.
11 ACI 440.2R-02. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. ACI Committee 440, American Concrete Institute. Farmington Mills, MI; 2002. p. 45.
12 D'ayala, D., Meslem, A., Vamvastikos, D., Porter, K., Rossetto, T., Crowley, H., & Silva, V. (2014). Guidelines for analytical vulnerability assessment of low/mid-rise Buildings—Methodology. Vulnerability Global Component project.
13 Menegon, S. J., Tsang, H. H., Lumantarna, E., Lam, N. T. K., Wilson, J. L., & Gad, E. F. (2019). Framework for seismic vulnerability assessment of reinforced concrete buildings in Australia. *Australian Journal of Structural Engineering*, *20*(2), 143-158.