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Seismic fragility of non-ductile and limited ductile reinforced concrete and masonry walls subjected to in-plane loading

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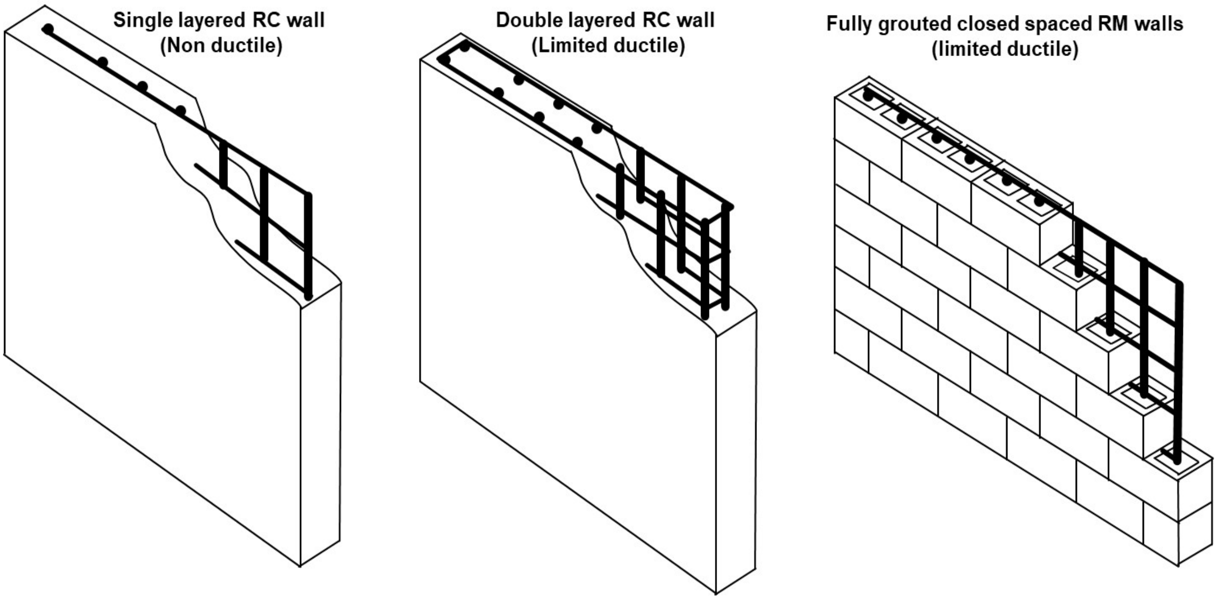
Abstract

Following the 2010/2011 New Zealand earthquakes, the provisions related to the design of reinforced concrete (RC) walls have been revised in the Australian and New Zealand standards (AS 3600 and NZS 3101). The new provisions consider RC walls with centrally placed single layer of reinforcement as non-ductile walls, whereas walls with double layers of reinforcement without special detailing or boundary elements are considered as limited ductile walls. Although these revisions were based on research conducted on RC walls under seismic loading, the updates prompted the current study to investigate the relevance to close-spaced reinforced masonry (RM) walls. RM walls are conventionally designed with centrally placed single layer of reinforcement and are considered as limited ductile walls in AS 3700. In this research, a systematic investigation through available experimental datasets was conducted to assess the damage states and the seismic fragility of RC and RM walls. The experimental studies involved in-plane cyclic testing of six walls (RC and RM) and interpreting similar experimental datasets from the literature. The outcomes indicate that closely spaced RM walls with a centrally placed single layer of reinforcement exhibit better performance at severe damage levels compared to single layer RC walls and achieve performance comparable to double layer RC walls at higher drift levels, without special detailing.

Keywords: Reinforced concrete walls; Reinforced masonry walls; Ductility; Seismic fragility

1 Introduction

Reinforced concrete (RC) and reinforced masonry (RM) walls are integral components in buildings due to their established structural efficiency and cost-effectiveness in moderate and high seismic regions. “Non-ductile” and “limited-ductile” are two classes of RC shear walls that are defined in Standards Australia (AS 3600, 2018) with a single-layer and a double-layer of reinforcement, respectively. In contrast, “limited ductile” is a class of RM walls that requires only a single layer of closely spaced vertical reinforcement. These walls are made of grout-filled hollow concrete blocks, and bed-joint reinforcement is added to create a monolithic section (Zahra et al. 2021; Ghaseminia et al., 2024). This construction method enables RM walls to exhibit structural behaviour comparable to limited ductile RC walls (El-Sokkary et al., 2020) despite having only one layer of reinforcement. However, the seismic vulnerabilities of buildings utilising RC and RM shear walls have become a concern following the recent earthquakes, such as the 2010/2011 Canterbury and the 2010 Chile earthquakes. These events highlighted the limitations in the ductility of these walls to withstand both lateral and axial seismic forces, particularly in the absence of specialised seismic boundary element (BE) detailing (Kam et al., 2010; Westenenk et al., 2013). Furthermore, experimental studies have demonstrated that a lack of confinement detailing at critical sections, such as the toe and heel of RC walls, along with the level of axial load, can lead to instability and failure during seismic events (Almeida et al., 2017; Blandon et al., 2018). Figure 1 illustrates the typical detailing configurations for non-ductile and limited ductile RC walls, as well as limited ductile RM walls, highlighting differences in reinforcement layers and spacing.



(a) (b) (c)

Figure 1. Typical cross-sectional diagrams of (a) non-ductile RC and (b) limited ductile RC and (c) limited ductile RM wall configurations.

These findings led to some revisions in reinforcement detailing and the ductility factors for non-ductile and limited-ductile RC walls in AS3600 (2018). Subsequently, these recent changes eventually created an inconsistency between Australian Standards for Masonry (AS3700, 2018) and Concrete (AS3600, 2018). While AS3700 allows close-spaced single layer of reinforcement in limited-ductile RM walls, AS3600 requires two reinforcement layers for RC walls to achieve the same classification. Past studies revealed that the RM shear walls with single-reinforcement layer resist seismic actions comparable to RC walls with double reinforcement layer (El-Dakhakhni et al., 2017; Robazza et al., 2020; Ghaseminia et al., 2024). However, the seismic vulnerability of RC and RM walls, especially within the framework of performance-based design methodologies, has not been extensively investigated.

Despite similarities in construction forms, comparative studies specifically addressing the seismic performances of these two wall types remain limited. The literature lacks detailed investigations into how non-ductile and limited ductile RC and limited ductile RM walls perform under varying seismic demands. This aspect can be studied by a more precise evaluation of damage states for each wall system.

Therefore, this research aims to address the critical gaps in the existing literature by an evaluation of in-plane lateral drift capacities followed by creating seismic fragility functions. This work is done utilising available experimental datasets and has the novelty that it includes parallel development of fragility functions for both RC and RM walls. This approach is expected to enhance the understanding of performance-based design and vulnerability assessments of buildings with these types of walls configurations.

2 In-plane behaviour of RC and RM Shear walls

Over the past decades, extensive research efforts have been conducted to evaluate the seismic performance of RC and RM shear walls separately, with a particular focus on their in-plane lateral behaviour (Shing et al., 1989; Voon and Ingham, 2006). Only two studies have been found to have compared RC and RM walls of similar material properties and reinforcement configuration in El-Azizy et al., (2023). Table 1 provides details of these walls, along with those tested by the authors, while Table 2 summarises their in-plane behaviour properties.

El-Azizy et al., (2023) tested six RC (limited ductile and ductile) and three RM (limited ductile and ductile) walls. The ductile RC and RM shear walls employed similar boundary elements at the toe and heel, which provided comparable resistance under analogous loading conditions. In contrast, the limited ductile shear walls were constructed with either a rectangular cross-section or flanges at the toe and heel ends. Furthermore, Ghaseminia et al. (2023, 2024) conducted an experimental investigation including two non-ductile RC walls, two limited ductile RC walls, and four limited ductile RM walls with comparable cross-section, boundary conditions at the toe and heel, and loading conditions. In Table 2, the yield limit is defined as the point at which the wall reaches 90% of its peak load (maximum lateral capacity) in the pre-peak zone, and the ultimate drift is defined as the point at which a 20% reduction from the peak load occurs in the post-peak zone. The findings from El-Azizy et al., (2023) revealed that the rectangular RM and RC walls with similar vertical reinforcement ratios exhibited comparable shear capacities. However, RM1 wall demonstrated a higher ductility ratio compared to RC1 wall as shown in Table 2. Ghaseminia et al., (2023; 2024) concluded that regardless of the reinforcement detailing, all tested RC and RM walls exhibited a flexural-shear failure mode. The comparison of non-ductile RC-SL and limited ductile RM-SL walls, each featuring a single layer of vertical and horizontal reinforcement, indicated that RC walls exhibited higher initial stiffness and greater yield and peak capacities. However, their drift capacities were similar, with ductility ratios of 2.71 and 2.72 for RC and RM walls, respectively. Additionally, RM walls with a single vertical and double horizontal reinforcement layer did not show enhanced lateral load capacities compared to RM walls with a single layer of reinforcement; however, they exhibited slightly reduced drift capacities, with a ductility ratio of 2.66. Similarly, comparisons of RM walls with double layers of reinforcement demonstrated higher initial stiffness, but lower load capacities than double-layered RC walls. In terms of drift limits, RC-DL wall exhibited a ductility ratio of 3.0, while RM-DL walls showed a drift ratio of 2.9 at an average.

Table 1. Summary of cross sectional and reinforcement detailing of RC and RM walls.

Reference	Wall ID	Config	H (mm)	H/L	H/t	Axial Load MPa	ρ_v (%)	ρ_{BE} (%)	ρ_h (%)
El-Azizy et al., 2023	RC1	R	3990	2.2	44	1.09	1.17	-	0.64
	RC2	F				0.89	0.37	0.29	0.53
	RC3	BE					0.45	0.24	0.53
	RC4	R				1.09	2.80	-	1.28
	RC5	F				0.89	0.58	1.00	1.05
	RC6	BE					0.72	0.91	1.05
	RM1	R				1.09	1.17	-	0.30
	RM2	F				0.89	0.30	0.25	0.30
	RM3	BE					0.41	0.14	0.30
Ghaseminia et al., 2023	RC-SL	R	1600	1	8.4	0.3	0.53	-	0.29
	RC-DL	R					0.58	-	0.33
Ghaseminia et al., 2024	RM-SL	R					0.53	-	0.29
	RM-SL*	R					0.53	-	0.33
	RM-DL	R					0.58	-	0.33
	RM-DL	R`					0.58	-	0.33

R: Rectangular; F: Flanged; BE: Boundary Element, ρ_v, ρ_h, ρ_{BE}: vertical, horizontal, and BE reinforcement ratios

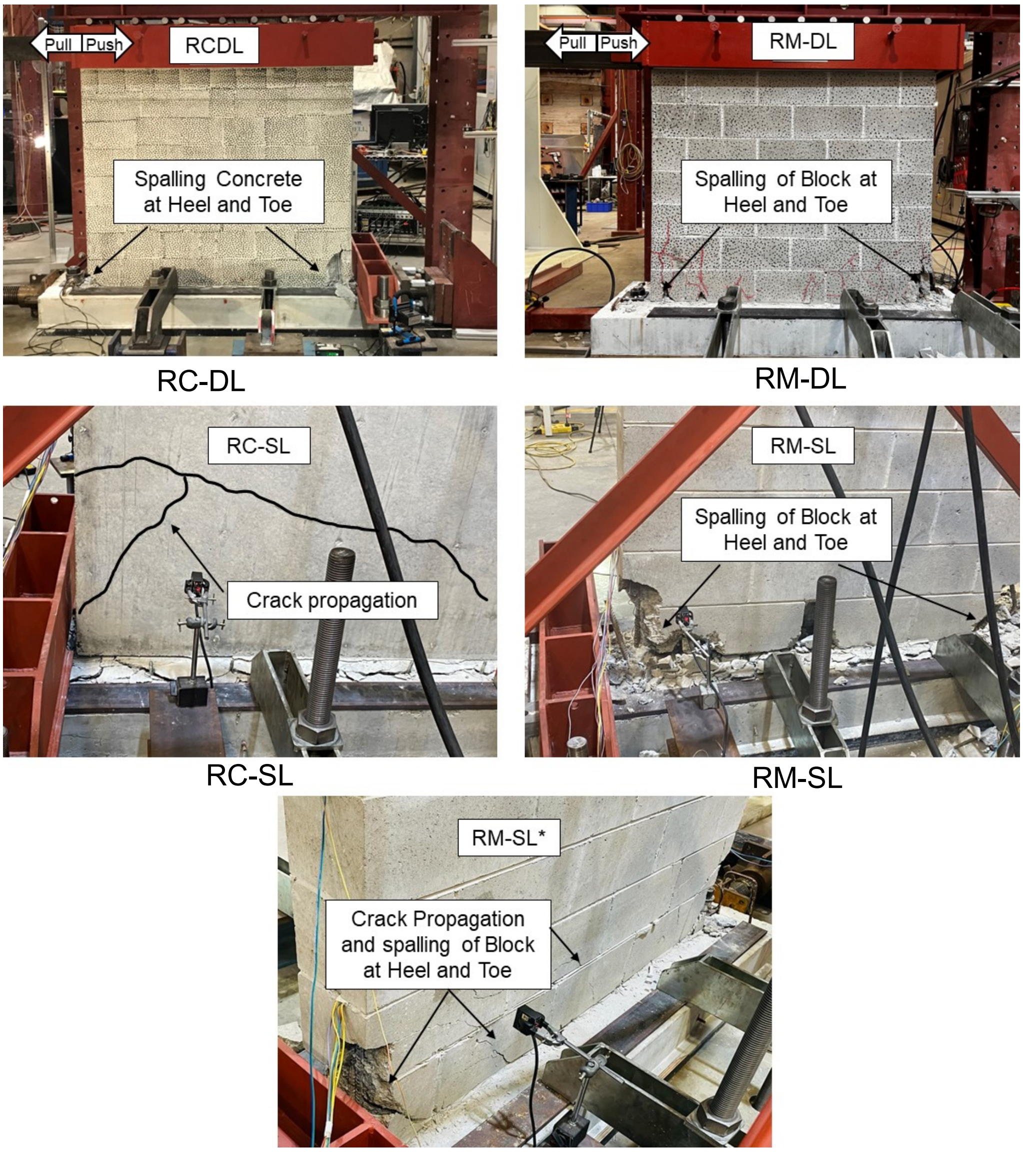
Table 2. Lateral behaviour of RC and RM shear walls.

Wall ID	Initial stiffness (kN/mm)	Yield limit		Peak limit		Ultimate drift (%)	Ductility
		Load (kN)	Drift (%)	Load (kN)	Drift (%)		μ
RC1	N.A	137.5	0.21	201.0	0.50	0.89	2.95
RC2	N.A	166.5	0.22	185.0	0.49	0.82	3.48
RC3	N.A	160.0	0.21	176.5	0.43	0.93	4.05
RC4	N.A	208.5	0.27	345.5	0.79	1.18	2.63
RC5	N.A	245.0	0.23	317.5	0.85	1.30	4.91
RC6	N.A	218.0	0.26	323.5	0.79	1.58	4.05
RM1	N.A	105.5	0.21	178.5	0.62	1.16	3.55
RM2	N.A	122.0	0.26	152.5	0.79	1.73	5.25
RM3	N.A	135.5	0.23	149.5	0.91	2.35	7.42
RC-SL	78.2	240.3	0.58	322.8	0.97	1.58	2.71
RC-DL	95.5	315.3	0.56	420.3	0.97	1.66	2.96
RM-SL	62.2	206.3	0.58	275.0	0.99	1.57	2.72
RM-SL*	61.5	183.2	0.60	244.2	0.92	1.57	2.61
RM-DL	97.2	243.1	0.51	324.4	0.84	1.47	2.88
RM-DL	96.5	257.0	0.49	342.6	0.95	1.44	2.93

RM-SL*: Configured with single layer of vertical and double layers of horizontal reinforcement.
N.A: Not Available

Figure 2 depicts the typical failure patterns of singly and doubly reinforced RM and RC walls at peak load, where initial cracking occurred at the lower boundaries (toe and heel) and propagated upwards with increased lateral cyclic displacement, indicating a combined flexural-shear failure mode (Ghaseminia et al., 2023; 2024). On comparing, RM-SL showed more distributed cracking as compared to RC-SL, which was similar to RC-DL. Al-Azizy et al., (2023) also reported that the rectangular RM wall (RM1 in Table 2) depicted more distributed crack pattern, leading to more ductile behaviour than RC 1 wall (as shown with high ductility in Table 2).

With only few comparable studies, it can be understood that the limited ductile RM and RC walls could depict similar in-plane behaviour, however this must be further verified through detailed investigations. To this end, past experimental studies on comparable RC and RM walls were collected to thoroughly examine the vulnerability of these structures through fragility assessments.



RC-DL RM-DL

RC-SL RM-SL

RM-SL*

Figure 2. Typical failure pattern observed on single and double layered RC and RM shear walls Ghaseminia et al. (2023; 2024).

3 Development of in-plane fragility curves

Comparative research on limited ductile RC and RM shear walls under in-plane lateral loading conditions with similar geometrical and reinforcement properties is limited in literature. To address this gap, datasets for RC and RM walls have been created using past experimental studies, filtered to incorporate limitations set by AS3600 (2018) and AS3700 (2018), in terms of configuration and detailing of reinforcement. Subsequently, these comprehensive datasets that incorporate standardised damage states (DS) were used in seismic vulnerability assessment of RC and RM walls. The performance metrics that relate to the outcomes derived from fragility assessments, such as the probability of exceeding certain DS is critical for accurately comparing the vulnerability of RC and RM walling systems. This approach allows for a more precise evaluation of how non-ductile and limited ductile RC and RM structures respond to seismic events. Furthermore, the establishment of standardised DSs and performance metrics ensures that the seismic performance assessments are based on robust and comparable data, thereby enhancing the clarity and reliability of comparisons between RC and RM wall systems.

3.1 Damage states of shear walls

The damage states of shear walls under in-plane loading conditions are defined to appropriately develop fragility curves for comparison. Three generalised damage states (DS1, DS2, and DS3) are proposed for RC and RM walls, derived from in-plane damage sequences observed in prior experimental research and consistent with the methodology of Rezaei et al. (2023). These damage states provide quantifiable performance limits for assessing structural degradation in RC and RM walls, specifically aligned with cyclic load-displacement behaviour. In contrast, the European Macroseismic Scale (EMS-98) is primarily designed for macroseismic assessments based on observational data. Table 3 provides a detailed overview of the damage states (DS1, DS2, and DS3) for RC and RM walls subjected to lateral loading conditions.

Table 3. Characteristics of Damage States (DS1, DS2, and DS3) for RC and RM Walls

Damage states	Terminology	Performance Level	Criteria
DS1	Onset of cracking at approximately 50% of peak load	Immediate occupancy	Minimal repairs required
DS2	Wider cracks at maximum load	Life safety	Structural integrity maintained; repairs needed
DS3	Extensive damage with boundary region crushing and significant concrete spalling	Severe damage	Repairs unfeasible; near complete structural failure

Figure 3 presents a typical cyclic load-displacement response for RC and RM walls subjected to in-plane loading, with the corresponding DS1, DS2, and DS3 indicated schematically on the backbone curve.

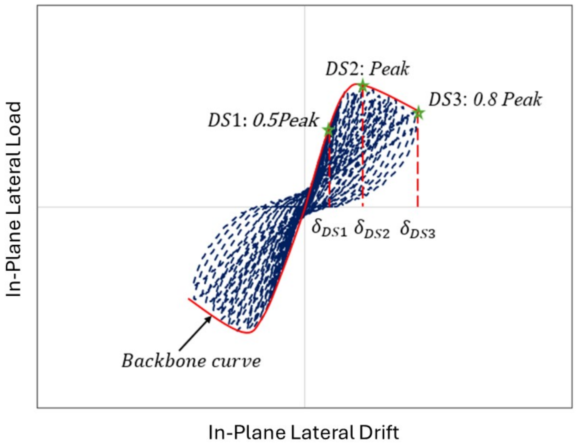


Figure 3. Typical in-plane lateral cyclic load displacement/drift response of shear walls.

3.2 Experimental datasets

Comprehensive experimental datasets were established to assess the seismic vulnerability of reinforced concrete (RC) and reinforced masonry (RM) walls. These datasets enabled an in-depth examination of drift levels in relation to predefined damage states (DS). It encompasses data from 47 non-ductile RC walls, 49 limited ductile RC walls, and 152 limited ductile RM walls tested under in-plane loading conditions. Key parameters include wall geometries such as height (h), length (l), and aspect ratio (h/l) as well as axial load capacities, with corresponding drift limits specified for each DS. Notably, axial load levels represent a critical factor in wall stability and potential failure mechanisms, including buckling and spalling of concrete and masonry block at the toe and heel regions, where this phenomenon influences the cyclic load-displacement behaviour and, consequently, the backbone curve.

The backbone curves were derived from cyclic load-displacement plots of the collected studies from the literature using an open-source software WebPlotDigitizer (Rohatgi, 2014) to precisely determine the numerical data points for DS1, DS2 and DS3. The summary of established datasets for non-ductile and limited ductile RC and limited RM walls are given in *Ghaseminia (2024)*. The collected RC and RM wall cases were divided into two groups, (1) $h/l < 1$ and (2) $h/l > 1$, corresponding to short and slender walls respectively. It is well known that the shear walls with aspect ratios below 1.0 predominantly exhibit shear failures, a phenomenon attributed to exceeding their defined shear capacities. Whereas the walls with aspect ratios exceeding 1.0 are more prone to flexural failures, characterised by the development of plastic hinges at the base of the analysed wall sections. The specific drift levels extracted for the three designated damage states (DS1, DS2, and DS3) were used to develop fragility functions of these groups of RC and RM walls.

4 Fragility Curves Development of RC and RM shear walls

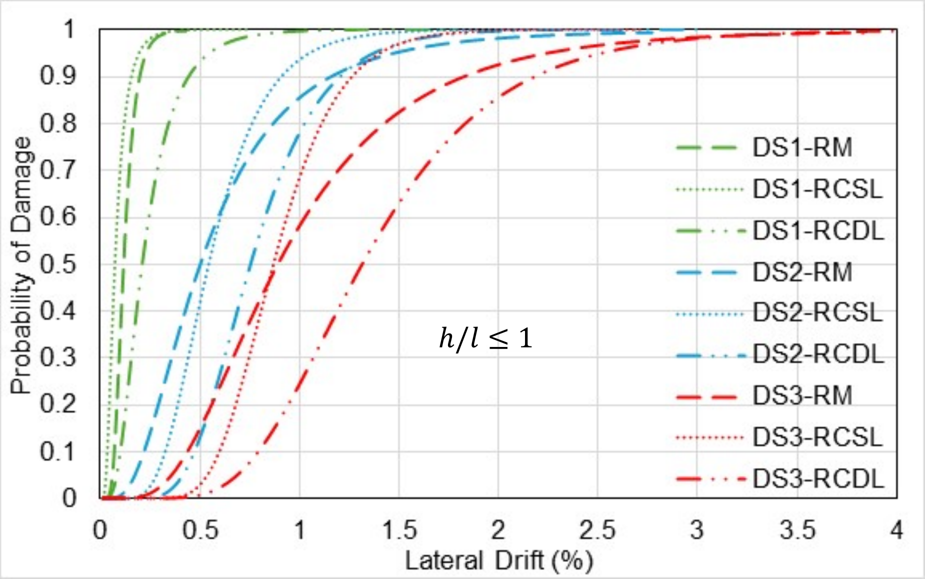
The methodology outlined in FEMA P-58 (2012) was employed to develop fragility functions for each damage state of RC and RM walls, specifically for non-ductile and limited ductile RC walls as well as limited ductile RM walls, as described in Section 3. These functions are based on a lognormal distribution, as shown in Equation (1), where $F_p(\delta)$ represents the conditional probability that a structural component will reach a specified damage state (DS) given the in-plane drift demand. In this equation, Φ is the standard normal cumulative distribution function, θ_d is the median of the probability distribution, and β_d is the logarithmic standard deviation.

$$F_p(\delta) = \Phi\left(\frac{\ln(\delta/\theta_d)}{\beta_d}\right) \tag{1}$$

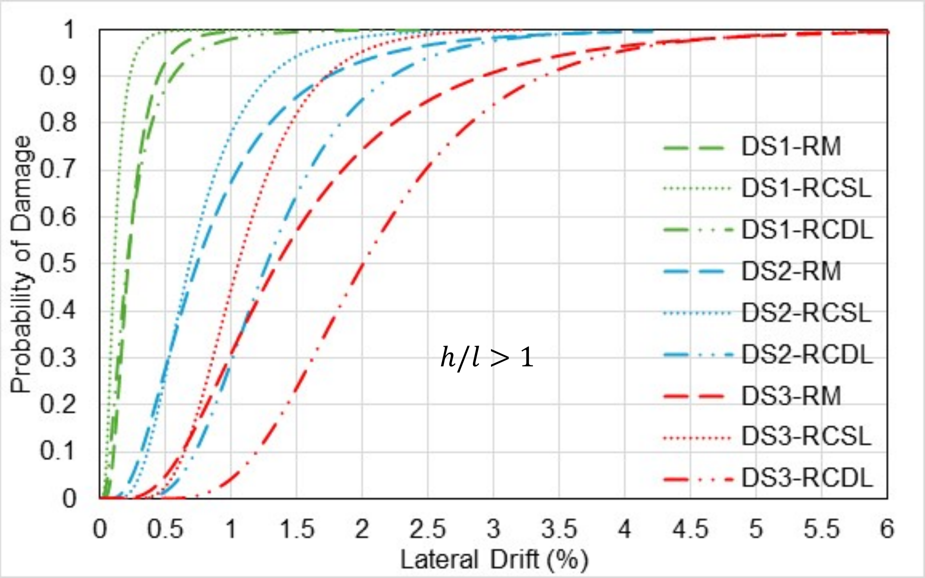
Subsequently, the fragility curves for RC and RM walls subjected to in-plane loading were developed to explain the probabilistic relationship between engineering demand parameters i.e. drift and predefined damage states. These curves were systematically categorised according to wall type based on their aspect ratios $h/l \leq 1$ for shear-dominated walls and $h/l > 1$ for flexural-dominated walls. This categorisation aligns with the corresponding failure modes as outlined in AS3600 (2018) to determine the ultimate shear capacity of concrete walls, ensuring that the fragility functions accurately reflect the structural behaviour under seismic loading. For each category, the fragility curves separately present the experimental data for both types of walls. The analysis reveals that walls with in-plane flexural dominance have a lower probability of exceedance compared to those with in-plane shear characteristics, given the same damage state and drift level. This trend was consistently observed across both RC and RM walls with varying aspect ratios.

The fragility curves for non and limited ductile RC and RM shear walls with an aspect ratio of $h/l \leq 1$ (shear dominated) and $h/l > 1$ (flexural dominated) are illustrated in Figure 4(a) and (b) respectively. In Figure 4(a), the probability of damage increases with escalating in-plane drift ratios, progressing through damage states DS1 to DS3. Conversely, Figure 4(b) shows that flexural-dominated walls demonstrate greater tolerance for in-plane drift before reaching comparable damage probabilities. Further analysis of Figure 4(a) reveals that at 50% probability of damage for DS1, the lateral drift is 0.07%, 0.12%, and 0.21% for non-ductile RC (RCSL), limited ductile RM (RM), and limited ductile RC (RCDL) walls, respectively. For DS2, representing moderate damage, RCSL walls have a higher probability of damage, reaching 93% at around 1% lateral drift. In comparison, RM walls have a slightly lower probability of 85%, and RCDL walls are even lower at about 78%. This pattern continues across all three wall types in all damage states.

Figure 4(b) illustrates a greater resistance to damage in flexural-dominated walls at lower in-plane drift ratios. For DS1, the lateral drift at a 50% probability of damage in RCSL walls is approximately 91% less than in RM walls. Notably, RM and RCDL walls exhibit the same level of drift, indicating comparable performance in DS1. For DS2, the lateral drift at a 50% probability of damage is about 10% higher for RM walls compared to RCSL walls, yet 41% lower compared to limited ductile RC walls. This suggests that RM walls perform better than RCSL walls but are outperformed by RCDL walls in moderate damage conditions. In DS3, at a 3.5% drift level, RM walls show 2% higher damage probability than RCDL walls, while RCSL walls reach 100% damage at a drift level of 2.57%. This highlights the increased vulnerability of RCSL walls compared to RM and RCDL walls, particularly from immediate occupancy through severe damage conditions. Additionally, it underscores the comparability of RM and RCDL walls at higher lateral drift levels, indicating that RM walls can achieve reasonable resilience but slightly lower than RCDL walls in severe damage states.



(a)



(b)

Figure 4. Fragility curves of (a) shear dominated, (b) flexural dominated RC and RM walls.

5 Summary and Conclusions

This study systematically examined the seismic fragility of 47 non-ductile and 49 limited ductile RC and 152 limited ductile RM walls, focusing on their behaviour under in-plane loading conditions with different aspect ratios, specifically those dominated by shear $(h/l \leq 1)$ and those dominated by flexure $(h/l > 1)$. The study evaluated the probability of damage as a function of in-plane drift ratios, progressing through various damage states (DS1 to DS3). In shear-dominated walls, the probability of damage increases with rising drift ratios. Non-ductile RC walls demonstrate the highest probability of damage at lower drift levels, particularly in the severe damage state (DS3), compared to limited ductile RM and RC walls.

Conversely, flexural-dominated walls exhibit greater tolerance to in-plane drift before significant damage probabilities are reached. The data indicate that limited ductile RC walls require higher drift ratios to reach the same probability of damage as compared to non-ductile RC and limited ductile RM walls. As the severity of damage increased from DS1 to DS3, the differences in drift tolerance between the wall types became more pronounced, with limited ductile RC walls generally showing the highest resistance to damage, followed by limited ductile RM walls and non-ductile RC walls showed the lowest resistance.

Furthermore, the results demonstrate that limited ductile RM walls consistently outperform non ductile RC walls across all evaluated damage states (DS1, DS2, and DS3) by exhibiting greater resistance to damage, withstanding higher drift capacities before reaching equivalent damage probabilities. This highlights the characteristic resilience of limited ductile RM walls, particularly in the contexts of maintaining immediate occupancy and mitigating severe damage are critical considerations.

A comparative analysis between the limited ductile RM and non-ductile RC walls reveals a significant degree of equivalence in the immediate occupancy state (DS1), where both wall types display similar drift levels at a 50% probability of damage. Even under more severe conditions (DS3), RM walls achieve higher drift levels at same damage probabilities than those of RCSL walls, demonstrating that RM walls can deliver seismic performance comparable to limited ductile RC walls, despite their single-layer reinforcement configurations.

Overall, the fragility functions developed in this study, based on a systematic analysis of experimental datasets, emphasise the necessity for further experimental research on limited ductile RM and RC shear walls. These wall types are common in construction but are underrepresented in current datasets due to the absence of comparable and parallel studies.

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