

PARAMETRIC STUDY AND FRAGILITY CURVES FOR EXISTING RC FRAME BUILDINGS RETROFITTED WITH RC INFILL WALLS

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Abstract

This research investigates the performance of existing reinforced concrete (RC) frame buildings retrofitted with RC infill walls under different earthquake inputs at various acceleration levels. The seismic retrofitting of existing multi-bay RC frame buildings by converting selected bays into new RC infill walls, was studied experimentally on a full-scale specimen within the SERFIN project. A series of experiments were conducted at the European Laboratory of Structural Assessment (ELSA) of the Joint Research Centre (JRC). The aim of the experiments was to assess the efficiency of the retrofitting method and to examine the optimal amount of RC wall web reinforcement, as well as the connection details between the new walls and the bounding frame. To complement the experimental findings and further study the interaction between the RC infills and the bounding frame both at the global and local levels, a parametric study was conducted by reducing the number of dowels, starting from a spacing of 100mm (monolithic) to no dowels. The parametric study was performed by incremental dynamic analyses on a two-dimensional (2D) finite element (FE) model, that was calibrated using the experimental results obtained from the full-scale experiment. Seismic inputs and levels impact on the performance of this retrofitting method were evaluated, with the aim of examining earthquake input's effects on fragility curves. Fragility curves were computed for RC frames infilled with RC infill walls using the results obtained from each simulation study to investigate the effect of reducing the dowels. The results of the performance-based numerical analysis, as well as the fragility curves for the examined earthquake inputs at various acceleration levels, are presented, along with the conclusions drawn from the study.

Keywords: RC infill walls, Finite element model, Fragility curves, Parametric study, Seismic strengthening, Nonlinear response-history analysis.

1 INTRODUCTION

The seismic safety of existing reinforced concrete (RC) buildings remains a critical issue, particularly in regions with moderate to high seismic hazard such as southern and eastern Europe. A significant proportion of the European building stock was constructed over 30 years ago, often without adherence to modern seismic design standards. These older structures are especially vulnerable to earthquake-induced damage, posing a considerable risk to life safety and leading to substantial economic losses. Given the widespread vulnerability of low- to mid-rise RC buildings, the development of effective and economically viable retrofitting strategies has become increasingly important.

Among the various retrofitting methods, global strengthening techniques—such as enhancing the overall stiffness and reducing seismic deformations—have proven more efficient and cost-effective than local interventions (Fardis 2009; Kaplan et al. 2011; Moehle et al. 2000; Sonuvar et al. 2004). One of the most practical and widely adopted solutions involves infilling selected frame bays, particularly at the perimeter, with reinforced concrete (RC) infill walls (Chrysostomou et al. 2013; Fardis et al. 2013; Turk et al. 2006). This technique significantly improves the global strength, stiffness, and ductility of the structure.

Current design codes, such as Eurocode 8 Part 3 (CEN 2010) and national guidelines (KANEPE 2017), recommend monolithic integration between the new RC infills and the existing frame elements. This is typically achieved by constructing infill walls with thicker webs and placing reinforcement outside the original members to ensure strong interaction. However, this often leads to over strengthened walls, which can introduce new challenges such as foundation incompatibilities (Fardis et al. 2013). A more balanced approach, involving RC infill walls with thicknesses equal to the bounding frame members, has emerged as a promising alternative—offering adequate performance while minimizing intervention cost and complexity.

Despite the growing use of RC infills for seismic strengthening, current codes do not quantitatively address their contribution, including Eurocode 8 Part 3. This omission is largely due to limited understanding of the interaction between infill walls and existing frames, especially in cases where non-monolithic behavior is present. Key design aspects—such as the degree of connection, detailing of reinforcement, and overall structural contribution of the infill walls—remain insufficiently studied and regulated. In particular, the lack of standardized methods to quantify engineering properties such as effective stiffness, moment and shear resistance, yield deformation, and cyclic capacity limits the use of performance-based seismic design for retrofitted RC frames (Strepelias et al. 2012).

To address these gaps, the performance of RC frames retrofitted with RC infill walls was experimentally investigated within the SERFIN project (“Seismic Retrofitting of RC Frames with RC Infilling”). Full-scale pseudo-dynamic tests were carried out to evaluate the effectiveness of this retrofitting strategy (Chrysostomou et al. 2013, 2014, 2016; Kyriakides et al. 2015; Georgiou 2021; Poljansek et al. 2014). A numerical finite element (FE) model of the tested specimen was developed and calibrated using experimental data (Georgiou et al. 2018; Georgiou et al. 2022b), providing a validated platform for extensive parametric studies.

These studies examined the influence of connection detailing by systematically reducing the number of dowels—from fully doweled (monolithic response) to undoweled configurations—followed by nonlinear response-history analyses. The results highlighted the interaction mechanisms between RC infills and existing frames under varying levels of seismic input, leading to design recommendations on connection details and performance metrics (Georgiou et al. 2021; Georgiou et al. 2022a). Further analyses focused on evaluating non-monolithic RC infill walls at different earthquake intensity levels ($PGA = 0.15g, 0.20g, \text{ and } 0.25g$), based on seismic zonation for Cyprus per Eurocode 8 (EN 2009), to derive practical design guidelines (Georgiou et al. 2022c; Georgiou et al. 2023).

In this paper, we extend this research by examining the seismic performance of existing RC frame buildings retrofitted with RC infill walls subjected to varying earthquake input levels. The objective is to investigate how different levels of seismic excitation affect structural performance and fragility. Ground motions recorded on rock (soil type A) were selected and propagated to the surface using one-dimensional site response analysis. These surface motions were used in nonlinear dynamic analyses to assess frame behavior under increasing intensity. Structural responses were then correlated with interstorey drift damage states to develop fragility functions and derive vulnerability and loss curves. The outcomes of this performance-based evaluation offer new insights into optimizing RC infill retrofitting techniques and contribute to the development of quantitative guidelines for seismic strengthening of RC buildings.

2 EXPERIMENTAL CASE STUDY

The SERFIN project ("Seismic Retrofitting of RC Frames with RC Infilling") focused on the seismic upgrading of multi-storey, multi-bay RC frame buildings through the conversion of selected bays into RC infill walls. The primary objective of the experimental campaign was to evaluate the effectiveness of this retrofitting technique, particularly in terms of wall reinforcement, connection detailing between the new infill walls and existing frame members, and the overall seismic performance of the retrofitted system.

To this end, a full-scale specimen comprising two parallel planar frames was constructed and tested using unidirectional pseudo-dynamic loading. In this section, a brief overview of the specimen geometry, design characteristics, and key experimental results is provided. A detailed account of the experimental setup, design process, and test results is available in Kyriakides et al. (2015), Chrysostomou et al. (2013, 2014), and Poljanšek et al. (2014).

2.1 Specimen geometry and design

The experimental specimen was a full-scale prototype structure designed to simulate two external three-bay RC frames from a typical residential building constructed in Cyprus during the late 1970s to early 1980s. At that time, no seismic design provisions were in place, and structures were typically designed for gravity loads only. For this reason, the mock-up structure was designed using BS8110, the code in force during that period.

The specimen had a centerline length of 8.5 m, a storey height of 3.0 m, and a total height of 12.0 m (excluding foundations). The RC infill walls were placed in the central bays of both frames—identified as the North and South frames in Figure 1—and had a thickness of 0.25 m,

matching the thickness of the surrounding beams and columns. The loading direction during testing was oriented from East to West.

The structural elements were cast using concrete class C20/25, with a unit weight of 25 kN/m³ and a modulus of elasticity of 30 GPa. To evaluate the influence of different reinforcement arrangements on wall behaviour, the North and South infills were designed with varying reinforcement layouts, with the North wall being the more heavily reinforced of the two.

The South frame was selected for detailed numerical modeling and calibration in later stages of the project, and its results are the basis of the validated finite element simulations presented in this study.



Figure 1: Elevation of the specimen in the laboratory.

3 NUMERICAL SIMULATION

To complement the experimental investigation, a detailed finite element (FE) model of the South frame from the SERFIN experiment was developed using DIANA FEA software (Georgiou et al. 2022a). The model geometry replicated that of the physical specimen, and a 2D continuum approach was adopted to accurately capture the in-plane behaviour of the RC frame-infill system (see Figure 2).

Rigid foundations were assumed for the model, with pinned supports at the base. The self-weight of the structural elements, along with additional dead load contributions from the slab and transverse beams, was applied to the 16 nodes of the frame using mass point elements. The wall-to-frame connection was modelled using interface elements that allowed relative separation under tension, thus simulating realistic interaction. Dowels connecting the infill wall to the surrounding beams and columns were explicitly modelled and allowed to resist both axial and shear forces, as observed in the physical specimen. A total of 24 dowels connected the wall to the columns, while 20 dowels connected it to the beams—matching the test configuration.

Dead and live loads were applied as edge pressure loads on the beams. Earthquake excitation was introduced via base acceleration using a nonlinear transient analysis, with input ground motion represented by a scaled Herzeg Novi (Montenegro 1979) accelerogram adjust-

ed to a peak ground acceleration (PGA) of 0.25g. This scenario corresponded to the most severe shaking level considered in the study.

Additional parametric studies were conducted to assess the influence of varying connection detailing. Eight different dowel configurations were simulated, ranging from the original set-up (representing monolithic behaviour) to cases with no dowels at all. All scenarios used the same ground motion input and followed an identical analysis procedure. Full details of the modelling approach, element types, and material models are provided in Georgiou (2021) and Georgiou et al. (2022b).

Furthermore, additional analyses were performed under reduced PGAs of 0.20g and 0.15g, corresponding to seismic hazard levels defined in the Cyprus National Annex to Eurocode 8 (EN 2009). These cases were evaluated to understand the response of the retrofitted frames across a range of seismic intensities and to develop preliminary design recommendations for EC8-3 (Georgiou et al. 2022c; Georgiou et al. 2023).

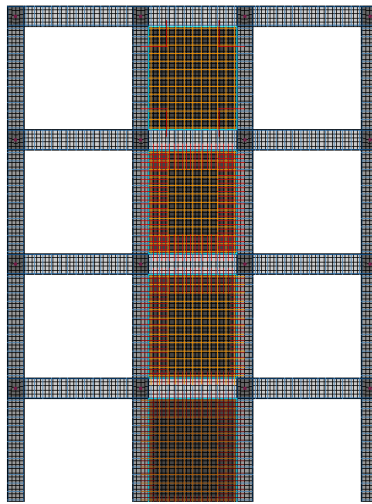


Figure 2: Finite element model of the South frame of SERFIN experiment.

4 PERFORMANCE-BASED ANALYSIS AT VARIOUS EARTHQUAKE INPUTS AND LEVELS

Performance-based seismic analysis allows for a detailed assessment of a structure's response to earthquake loading, extending beyond the prescriptive requirements of building codes. This methodology aims to evaluate the seismic performance of buildings by simulating their behaviour under different levels of ground motion, thereby supporting the development of resilient and cost-effective retrofitting strategies.

In this study, a series of numerical simulations was performed using a validated finite element (FE) model of a retrofitted RC frame to evaluate its performance under varying seismic inputs. The selected earthquake records were originally recorded on bedrock with typical spectral accelerations around 0.1g. These inputs were scaled from 0.05g to 1.0g to perform a comprehensive performance-based analysis across a wide range of intensities.

4.1 Ground motions

Five actual ground motion records were selected for the incremental dynamic analyses (IDA), sourced from rock sites to eliminate site amplification effects and ensure spectral compatibility with Eurocode 8 (EC8) soil type A. All selected earthquakes had moment mag-

nitudes (M_w) above 5.5, with spectral characteristics aligning closely with both the EC8 Type 1 and ASCE-16 rock spectra.

Table 1 summarizes the key parameters of the selected ground motions, including PGA, magnitude, and fault mechanism, while Figure 3 presents their corresponding response spectra (adapted from Ptilakis and Petridis, 2022). These records represent realistic earthquake scenarios that may affect Cyprus and similar Mediterranean seismic regions.

Date	Location	Code	Repi (km)	M_w	PGA (m/s^2)	$V_{s,30}$ (m/s)	Mechanism
09/09/1998	Appennino Lucano, Italy	ITACA_614	9.80	5.60	1.62	1024.00	Normal
16/01/1995	Kobe, Japan	NGA_1108	25.40	6.90	2.85	1043.00	Strike-slip
18/10/1989	Loma Prieta, USA	NGA_3548	20.35	6.93	4.12	1070.34	Reverse-oblique
10/01/1987	Whittier Narrows, USA	NGA_680	13.85	5.99	1.10	969.07	Reverse-oblique
10/06/2000	Western Tottori, Japan	KIK-Net_3775	31.37	6.60	1.55	967.27	Strike-slip

Table 1: Selected ground motion records for dynamic analysis (Ptilakis and Petridis 2022).

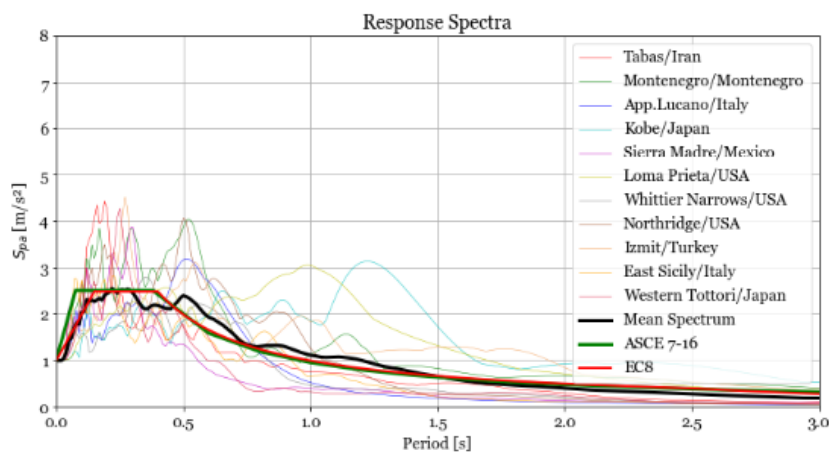


Figure 3: Response spectra including the selected ground motions, the mean response spectrum (in solid black line), and the EC8/ASCE-16 response spectra for soil type A. (Ptilakis and Petridis 2022).

4.2 Incremental dynamic analyses and fragility evaluation

Incremental dynamic analysis (IDA) was performed by applying each earthquake record at increasing intensity levels, from 0.0g to 1.0g PGA. Although spectral acceleration is often a more precise intensity measure (IM), peak ground acceleration (PGA) was selected here due to its practicality and compatibility with large-scale parametric studies.

The engineering demand parameter (EDP) selected for this study was the maximum interstorey drift ratio (ISDR), a widely accepted measure of global structural performance and damage potential. IDA enabled the generation of PGA–ISDR pairs for each scenario.

To define structural damage states (DS), drift-based thresholds were adopted based on calibrated limits from Rossetto & Elnashai (2003), Ghobarah (2004), and Kappos et al. (2006), as summarized in Table 2.

Damage State	Description
Slight (SD)	Onset of inelastic behavior
Moderate (MD)	Beyond peak lateral strength; initiation of degradation
Extensive (ED)	High ductility demand; structure retains gravity load
Complete (CD)	Near-collapse or collapse condition

Table 2: Damage state definitions based on maximum ISDR.

5 RESULTS

This section presents and analyzes the results of performance-based numerical simulations, focusing on frame response across various earthquake records and intensity levels. Fragility curves were developed to describe the probability of exceeding each damage state under increasing seismic input.

5.1 Structural response to ground motion inputs

The nonlinear dynamic analysis results are summarized in Figures 4 and 5, which present the earthquake time histories and corresponding maximum ISDR values for each ground motion and intensity level.

For PGA values below 0.35g, the ISDR remained consistently under 0.2% across all cases, with approximately linear behaviour observed. However, for higher PGA values, structural response became nonlinear, with significant increases in ISDR. Notably, the Loma Prieta record produced the most pronounced drift at higher intensities, while the Western Tottori record—despite having one of the highest PGAs—resulted in the lowest ISDR, due to its delayed peak acceleration.

This suggests that not only PGA but also time-history characteristics (e.g., energy content and duration) significantly influence structural damage. Early peaks in ground motion tend to correlate with higher damage levels.

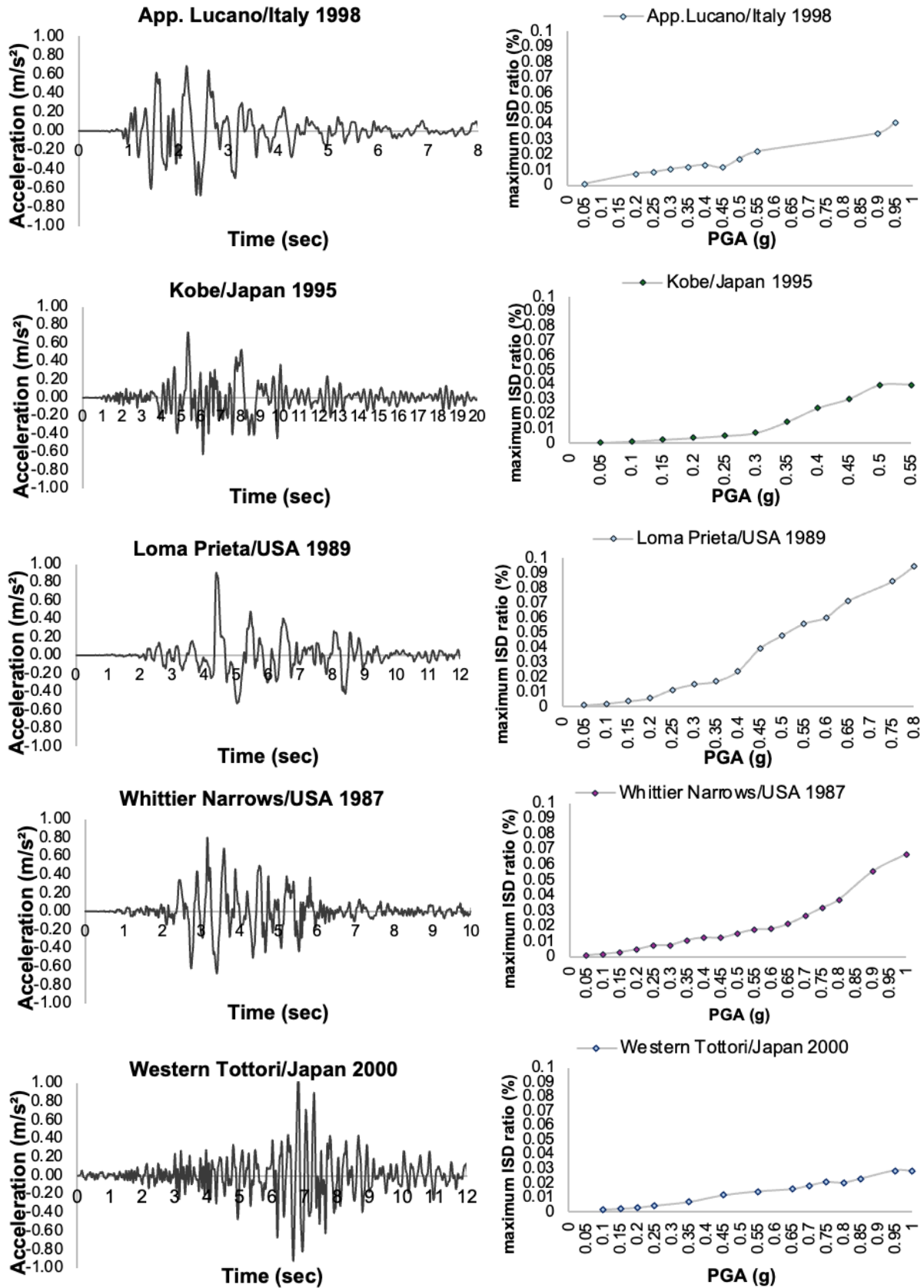


Figure 4: Earthquake time-histories and corresponding maximum ISDR.

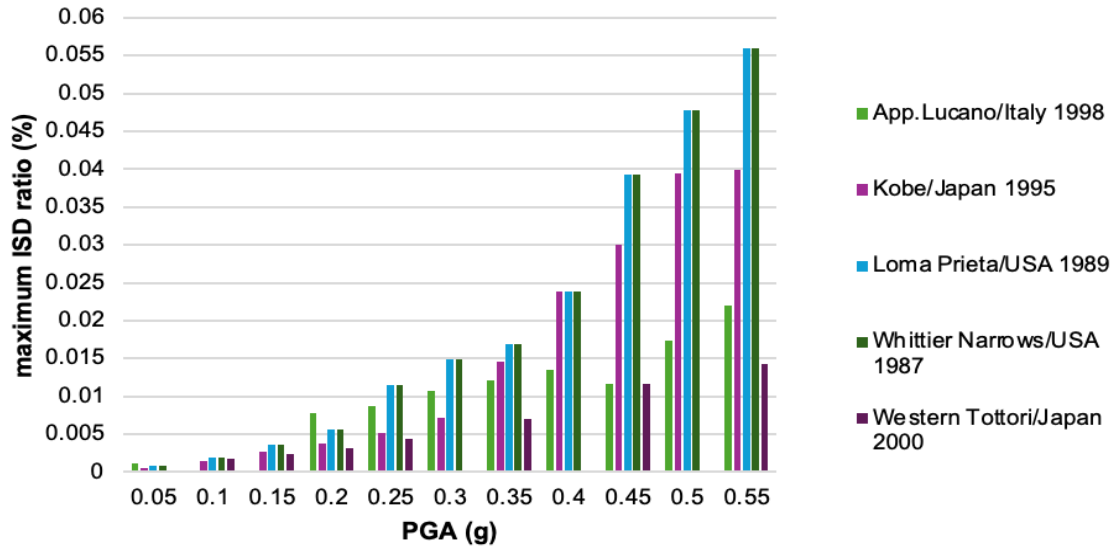


Figure 5: Maximum ISDR for each earthquake record across intensity levels.

5.2 Fragility assessment of the retrofitted frame

Fragility curves were constructed using the IM–EDP pairs derived from IDA and follow the methodology outlined by Pitilakis and Petridis (2022). Figure 6 illustrates the probability of exceeding each damage state as a function of PGA.

For PGA levels below 0.2g, the probability of exceeding slight and moderate damage states exceeds 60% and 40%, respectively, while extensive and complete damage remain below 20% and 10%. As PGA increases beyond 0.5g, the likelihood of extensive and complete damage rises sharply, exceeding 60% and 40%, respectively.

These fragility curves offer essential insights into the vulnerability of RC frames retrofitted with RC infill walls. They represent a probabilistic relationship between seismic intensity and structural damage, supporting risk-informed design decisions and retrofitting strategies.

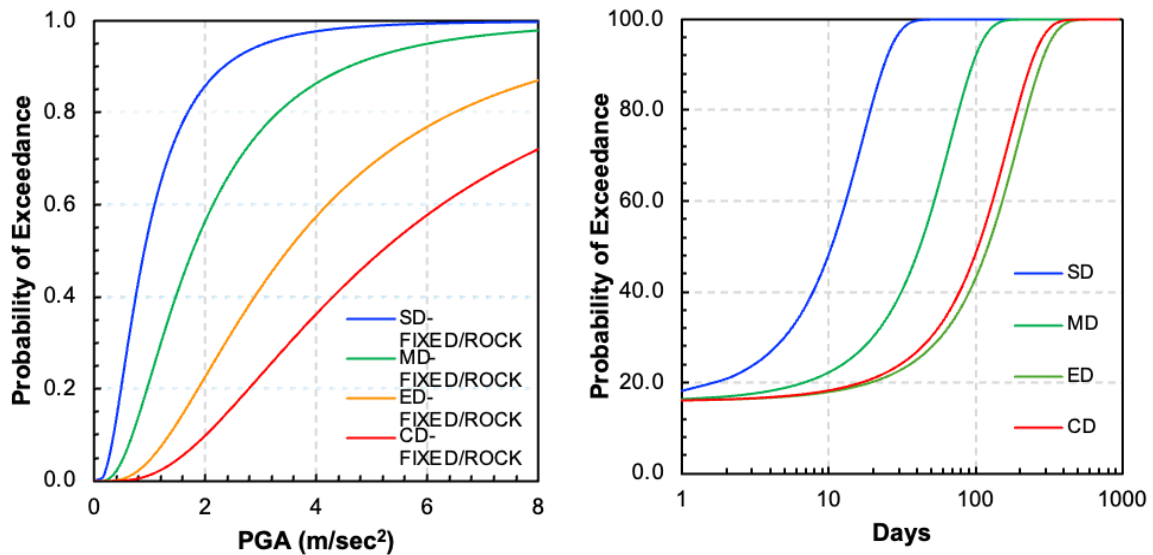


Figure 6: Fragility (graph on the left) and Rehabilitation (graph on the right) curves for RC-frames retrofitted with RC infill walls (bedrock site conditions).

6 CONCLUSIONS

This study investigated the seismic performance of existing RC frame buildings retrofitted with RC infill walls, emphasizing a cost-effective alternative to traditional over-strengthening methods. A novel retrofitting configuration—using infills with the same thickness as bounding frame members—was experimentally and numerically evaluated.

A full-scale experimental campaign from the SERFIN project provided the basis for the development and calibration of a detailed FE model. Parametric simulations under multiple dowel configurations and various earthquake scenarios demonstrated the significant impact of connection detailing on global behaviour.

Performance-based analysis using incremental dynamic analysis (IDA) was carried out with real ground motion records scaled across a wide range of intensities. PGA was selected as the intensity measure, and maximum interstorey drift ratio (ISDR) served as the engineering demand parameter. The selection of rock-site records avoided soil amplification effects and ensured spectral compatibility with EC8.

Fragility curves were derived based on the numerical results, offering a probabilistic understanding of structural performance under seismic loading. The curves revealed that while the retrofitted frames performed well at low-to-moderate PGA levels, higher intensities introduced considerable risk of extensive or complete damage.

Overall, the study contributes to the advancement of performance-based seismic design for retrofitted RC frames. The results support the viability of using RC infill walls with compatible thickness and proper connection detailing, offering a balanced solution between performance and constructability. These findings can inform future updates to Eurocode 8 and national guidelines and serve as a reference for risk-based retrofit decision-making.

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