CHALLENGES IN DAMAGE PROGNOSIS FOR REINFORCED CONCRETE STRUCTURES CONCERNING THE LEVEL OF EARTHQUAKE-RESISTANT DESIGN

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Abstract: *The prediction of damage in buildings under severe shaking has been the subject of numerous studies over the years. Buildings designed and built to resist earthquakes can exhibit varying dynamic characteristics, depending on the regional code development and the ductility, strength, and stiffness requirements. Due to the lack of damage observations for buildings with earthquake-resistant design (ERD), analyses based on reliable structural models and experimental tests are used to evaluate their responses and assess their performance under varying shaking intensities. One of the challenges when using structural analyses results is establishing a link between global damage grades and the estimated response at the element level and the corresponding local damage grade. Reinforced Concrete (RC) buildings with ERD are generally - but not always - designed for ductility and have high plastic deformation capacity and cumulative energy dissipation capacity. Complex behaviour in the energy dissipation zones within structural elements needs to be accurately modelled, as it influences the assignment of local and, consequently, global damage grades. This study focuses on the evaluation of the quality and suitability of fragility functions derived for RC framed and walled buildings designed with different levels of ERD. It underscores the need for elements and structural models representing the intended level of ERD, while taking into account the detailing of reinforcement according to the corresponding ductility classes. The paper refers to the development of Eurocode 8 in its first generation, assuming that its basic principles were adopted in national codes and engineering practice.*

1 Introduction

Despite the advancements in understanding the seismic behavior of reinforced concrete (RC) structures and the adaptation of seismic design procedures, severe earthquakes in seismically active regions continue to cause substantial damage, including collapses. Local brittle and undesired failure modes in the structural elements have occurred in buildings designed to resist earthquakes. Notable examples are events with an earthquake with a return period exceeding the 500-year return period like the Canterbury Earthquake Sequence of 2010/2011 (Shegay et al., 2020). The damage is not limited to structural elements as non-structural elements may also dominate the damage assignment due to the interaction with a ductile structural system of a building as seen in recent observations from the Northwestern Albania earthquake in 2019 (Abrahamczyk et al., 2021; 2022).

Buildings designed to resist earthquakes therefore could be thought of as engineered structures with varying seismic vulnerability according to many parameters, most importantly the seismicity level of the region, the development, and enforcement of seismic codes in the region among other factors. Those buildings could be described as having some level of Earthquake-resistant design (ERD) (borrowing the term from the EMS-98 (Grünthal et al. 1998)). Other terms seen in the literature include code-compliant, buildings with anti-seismic design, engineered buildings, and buildings with a certain level of ductility (e.g., high ductility building [x]). Although these terms may describe this building type to some extent, it is seen that the term ERD with a certain level (e.g., moderate level of ERD) implies that the building is engineered and compliant with a seismic code of some level without explicit reference to a ductility level associated with that level.

The description of seismic vulnerability of buildings with ERD may be described using empirical or analytical methods. On the one hand, empirical methods, developed from post-earthquake observations, are commonly considered to be reflective of the actual response of the building stock, as they implicitly account for the complex interaction between building components and ground shaking. In addition, the limited damage observations for buildings with ERD make this method less applicable. On the other hand, analytical methods, which are based on numerical simulations may be of interest to assess the seismic vulnerability of a building with ERD, keeping in mind the need for good quality numerical models, with some kind of calibration is needed. The analytical methods are useful in cases where damage observations are limited for a building type or for measuring the increased vulnerability due to retrofitting interventions.

The seismic vulnerability of buildings with ERD is relevant in the exposure modelling for a seismic hazard assessment, in addition to a better understanding of the implications of developing seismic codes and their rules. In addition, understanding their responses to earthquakes is relevant for macroseismic intensity following earthquakes.

This paper is an attempt to identify the challenges related to the seismic vulnerability of this building type, by reviewing the seismic code developments (section 2) and identifying major changes and their influence. In the same section with insights from the seismic code development, the existing classification schemes (building typologies). Section 3 discusses the expected behavior of RC buildings with some level of ERD at different excitation levels and discusses the influence of secondary elements on the general behavior of this building type. Section 4 discusses the current state of exposure modelling for this building type, particularly numerically based studies, and examines them in terms of quality and relevance. Section 5 then summarizes the challenges identified in the previous sections and suggests resolutions to bridge the gaps and improve the exposure modelling of this building type.

2 Seismic codes development

2.1 Evolution of seismic codes

Substantial research has been conducted on the evolution of seismic codes, reflecting the lessons learned by ancient civilizations from significant earthquakes. These lessons influenced construction practices in earthquake-prone areas. However, in regions where earthquakes are less frequent yet destructive, there tends to be a relaxation of adherence to these codes over time, until a new seismic event occurs, as observed in countries like Turkey and Morocco. Over time, with increased awareness and in more stable socio-economic conditions, the implementation and enforcement of building codes become more standardized. The development and adaptation of seismic codes are influenced by various factors, including: (1) Direct experience with seismic events. (2) The influence of neighboring, more developed countries. (3) Increased national wealth and a corresponding decrease in risk tolerance. (4) Ongoing advancements in research related to seismicity. (5) Historical colonial influences.

Seismic codes may be categorized into several levels, with regard to only basic design principles and ductility/energy dissipation considerations.

Level 1 Basic Seismic Consideration: At this level, seismic designs are applied without considerations for ductility or energy dissipation. It represents the initial steps towards acknowledging seismic forces in structural design. This is similar to the outdated New Zealand seismic codes NZSS 1900, issued in 1965 or still in place Libyan seismic code.

Level 2 Static Force Adaptation: This level introduces a static force-based method, employing a ductility factor (e.g. R or q) to reduce the seismic action. This level is also characterized by the introduction of the ultimate strength method and limit state design.

Level 3a Capacity Design Principles: This level is a step forward from force-based designs with detailed rules for capacity design, ensuring critical structural elements remain elastic during quakes. It introduces elements of displacement-based design, marking a shift towards more resilient seismic strategies. (A set of requirements are provided for ensuring ductile behavior in potential plastic regions).

Level 3b Improved displacement-based design: This advanced stage fully embraces displacement-based design and performance-based principles, with an increased focus on nonlinear behavior. The new generation of Eurocode 8 and the performance-based design developed by the Pacific Earthquake Engineering Research Center (PEER 2016) are an example of this level.

Figure 1 is an initial attempt to go through the seismic codes in different regions and classify them based on their principles and requirements using results from international students of the master course Natural Hazards and Risks in Structural Engineering (NHRE) in Bauhaus-Universität Weimar and ongoing studies. The figure indicates that the seismic codes of certain regions with moderate to high seismicity (e.g., around the Mediterranean Sea and along the South Pacific coast) need to be examined with regard to their design principles and detailing requirements.

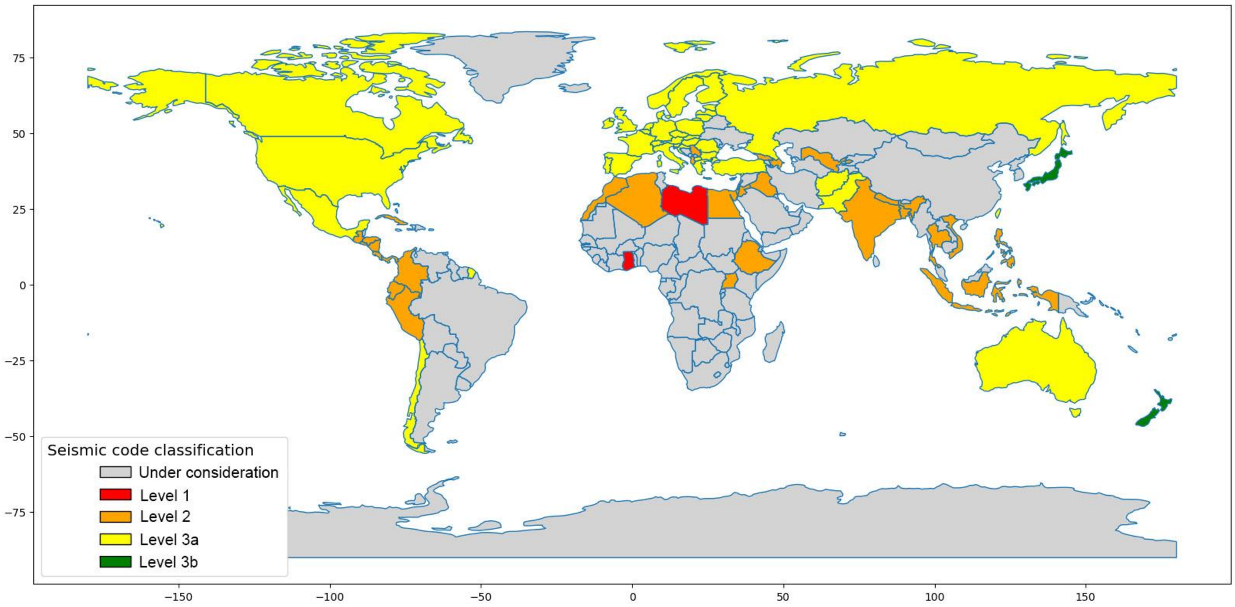


Figure 1. Initial attempt to classify seismic codes (not finalized).

Changes in seismic codes, particularly regarding ductility requirements, have significant implications for building vulnerability. The evolution of Eurocode 8's ductility classes, for example, reflects a shift in understanding and approach to seismic design, with potential impacts on exposure modeling and risk assessment.

Table 1. Changes of ductility classes for reinforced concrete structures.

Eurocode generation	**Ductility classes**				
EC8, 1998 (Draft)		DCL		DCM	DCH
EC8, 2004 (First Generation)				DCM	DCH
EC8 (Second generation, 2023)			DC2	DC3	
EC2, 2004	*q*=1.5*				

* Following dimensioning and detailing rules specified in EC2 for non-seismic actions member

2.2 Classification schemes for buildings with ERD

The establishment of a classification scheme to describe buildings with ERD is the first step in assessing their seismic vulnerability. At both the European and international levels, attempts have been made to establish suitable terms for describing buildings with ERD, based on local and global conditions. Those terms are often influenced by the code development in the region of interest and local practices.

The European Macroseismic Scale (EMS) in its first version (EMS-92) (Grünthal et al., 1993) provided a classification of engineered buildings using different qualitative parameters as shown in Table 2. The current version of the EMS, EMS-98 (Grünthal et al., 1998), uses the term ERD-i. Here, 'i' represents the macroseismic intensity of the design earthquake, as well as the level of earthquake-resistant design. Three levels of ERD are identified, namely: low or minimum, moderate, and high.

These levels are expected to be relatively uniform within any region according to the seismic zoning and are commonly assigned for buildings designed for an intensity of VII, VIII and IX respectively. The EMS-98 clearly distinguish the terms ductility, which is the building's ability to withstand lateral loading in a post-elastic range and the levels of ERD. In principle, a building with a high-level of ERD is expected to have ductile behavior to provide larger safety margins against higher damage grades. However, it is realized that the choice of ductility level affects the lateral strength (i.e., more ductile buildings are designed to provide lower lateral strength in favor of deformation capacity).

Good examples of associated those levels with a certain code generation can be seen for New Zealand in Charleson et al. (2024). The authors associate Level 1 with pre-1935 buildings lacking earthquake resistance design. Buildings constructed between 1935 and 1980 (Level 2) had minimum lateral load requirements, while those built post-1980 (Level 3) adhered to more advanced design standards, incorporating displacement ductility and limit state design methods.

As part of developing European exposure models in the SERA project (Crowley et al., 2018), a building taxonomy is adopted where buildings are classified to different code levels with associated hazard and assumed ductility levels. Pre-code and low-code levels are before the implementation of a seismic code or an application of a code without seismic provisions. Moderate and high code levels are related to code implementations preceding codes with capacity design principles (e.g., EC8 (CEN 2004)).

Similarly, Kappos et al. (2006) classified buildings in Greece into four subclasses (pre-code, low-code, moderate-code, and high-code) with similar descriptions of these subclasses to the SERA project description without reference to ductility levels. In FEMA/NIBS (HAZUS) methodology (FEMA, 1991), the 1994 Uniform Building Code (IC80, 1994) establishes differences in seismic design levels, where buildings are graded to be of high (seismic zones 4), moderate (seismic zones 2B) or low (seismic zones I) seismic performance.

Table 2. Classification of engineered structures according to the EMS-92 and EMS-98.

EMS-92		**EMS-98**	**Level of code generation**	**Remarks**
Engineered buildings classification	**Sub-classification**	**ERD classification**		
Engineered buildings without anti-seismic design	EASD		(Pre-code)	In the EMS-98, buildings in this group are implemented in one group together with ERD-L
Buildings with anti-seismic design (ASD)	ASD$_7$	ERD-L	Level 1 (Low-code)	Early developments
	ASD$_8$	ERD-M	Level 2 (Moderate-code)	
	ASD$_9$	ERD-H	Levels 3a/3b (High-code)	
Buildings with special anti-seismic measures				Not used in the macroseismic intensity assignment.

Explanations:
ASD$_7$: Minimum level of anti-seismic design with no special measures of detailing (designed for intensity 7, with a base shear coefficient of 3-4% of g).
ASD$_8$: Engineered building incorporating a moderate (improved) level of antiseismic design (designed for an intensity of 8 or a base shear coefficient of 5-6% of g).
ASD$_9$: Engineered buildings incorporating a high (qualified) level of antiseismic design (designed for an intensity of 9 or a base shear of about 8-12% of g).
EASD: Engineered buildings incorporating a limited or equivalent level of antiseismic design.
ERD-L, ERD-M, and ERD-H: Similar definitions to ASD$_7$, ASD$_8$, and ASD$_9$.

When examining these classification schemes, the following open questions may be raised:

(1) Is it reasonable to establish a link between the level of code development and the level of ductility that could be achieved?

Note: This is particularly pertinent knowing that codes like EC8, in its current adapted version, do not require certain ductility levels for different seismicity levels, unless specified by a national annex.

(2) Should the quality and influence of secondary elements' interaction with primary lateral load-resisting system elements be described when categorizing these building types?

(3) How does the further development of code rules and limitations affect future classifications?

Note: For instance, the second generation of Eurocode 8, which is still in draft form, has removed the high-ductility design option DCH and introduced a new intermediate ductility level between the previously adopted DCL and DCM.

(4) Is the current description of buildings' vulnerability, used for seismic hazard assessment, consistent with established definitions?

3 Damage progression in buildings with ERD

The progression of damage for RC buildings with ERD design is influenced by varies factors including the system type, ductility level, and the interaction with non-structural elements (e.g., infills). Moment-resisting frames are characterized by a flexible response and increased ductility. However, damage to non-structural elements may influence the global damage grade assignment, and the strength of the infills could affect the behaviour of the structure, as shown in Figure *2*, extracted from experimental tests (Abrahamczyk et al. 2019; Abrahamczyk 2021).

Results from numerical simulations by Al Hanoun (2021), shown in Figure *3*, demonstrates that more often than not, the damage to weak infills (secondary system) influences the damage in both scenarios: when there are weak and strong frame systems (primary system). In the case of strong infills and a strong frame, damage to the infills can still impact the overall damage to a building. The terms 'Strong Frame' and 'Weak Frame' should still be reinterpreted with relation to design seismicity level and ductility. In addition, modelling of the interaction in the mentioned publication still misses nonlinear shear modelling which plays an important role in frame-infill interaction.

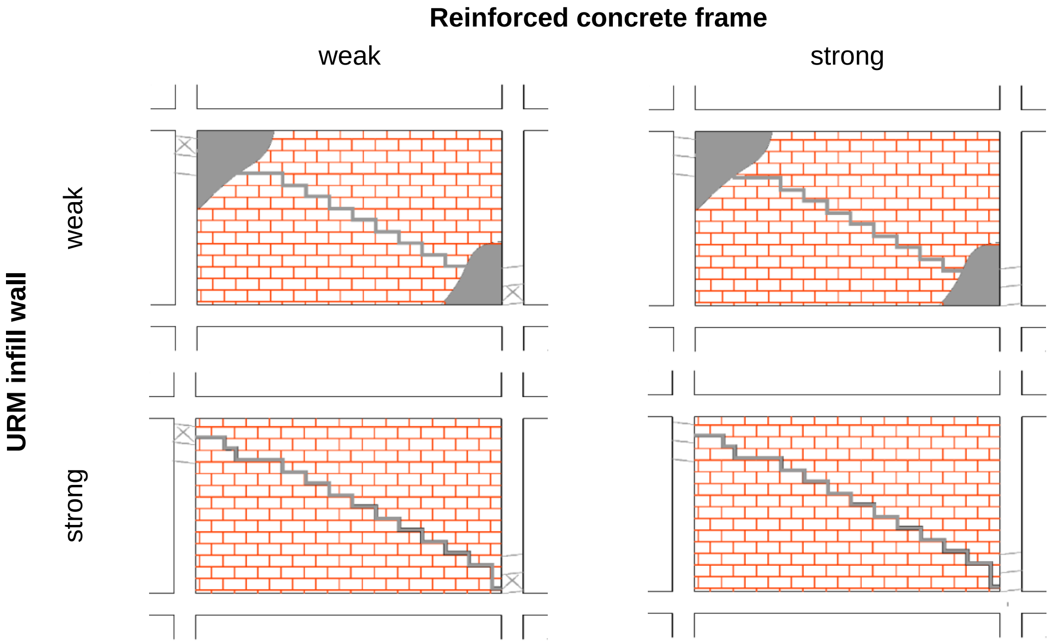


Figure 2. Typical, schematized damage patterns for reinforced concrete frames with masonry infills, depending on the quality of the material, design levels, and deformability (Abrahamczyk et al., 2019).

Systems with RC structural walls are stiffer than frames, which limits deformations and reduces damage in non-structural elements. However, the concentration of energy dissipation in walls can result in undesirable modes of failure, including end region (i.e., boundary elements), crushing and longitudinal reinforcement buckling, diagonal crushing of the web concrete region, and out-of-plane response (Shegay et al., 2020).

Dual systems are characterized by the interaction between frame elements and RC walls, where increased deformations are expected at the upper stories due to increased rotations at the top part of the cantilever wall. Coupled structural wall systems possess even higher stiffness, but the connecting beams (i.e., coupling beams) need to be carefully designed and detailed.

In buildings designed using capacity design principles, it is expected that reduced stiffness due to reduced design seismic action will result in slight damage occurring earlier. However, under increased seismic action, buildings designed conventionally are expected to have a higher probability of partial and complete collapse - in other words, a reduced life safety threshold. The difference in damage progression between conventionally designed buildings and those designed for ductility is significant in multiple aspects, including seismic hazard assessment and the assignment of macroseismic intensities following an earthquake.

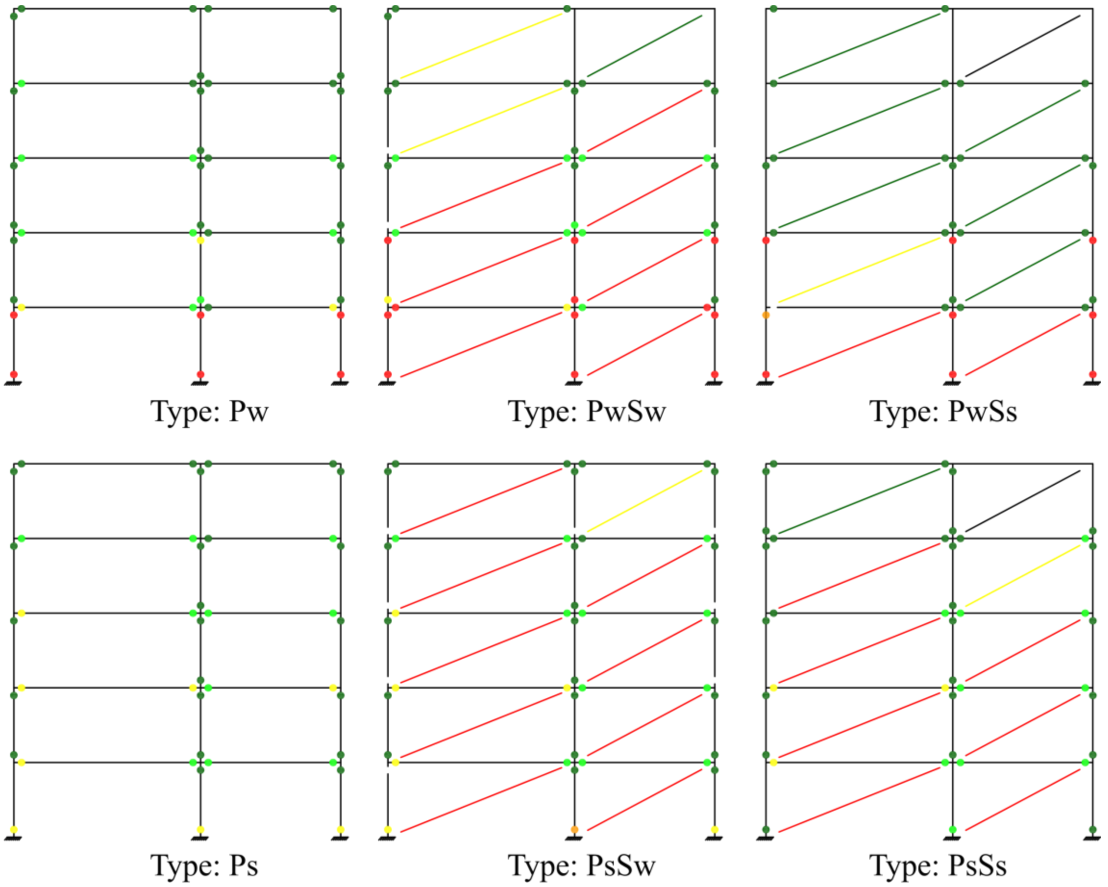


Figure 3. Plastic hinges formation with corresponding local damage grades for frame hinges and infills at an excitation level of 0.35g (from Al Hanoun (2021); colors for damage grades are modified according to Schwarz et al. (2021).

<u>Explanations</u>:
Local damage grade: Primary system (Moment-resisting frame): ●LDG1, ●LDG2, ●LDG3, ●LDG4, ●LDG5.
Secondary system (Infills): / LDG1, / LDG2, / LDG3 (limited to in-plane response).

4 Current state of exposure modelling

4.1 Trends and assumptions in fragility functions for RC building types

Overview of considered functions:

Fragility functions are commonly used to assess the vulnerability of a building type and estimate the level of ground shaking required to reach a certain damage grade or state. A set of fragility functions, derived numerically, has been compiled and investigated as part of the EU-funded TURNkey project (D'Ayala et al., 2021). From the compiled set, publications featuring functions with certain aspects of ERD (e.g., high code, high ductility, with ERD) derived for Europe and worldwide are listed in Table 3. The variation in ERD description, damage description, and intensity measure shows the challenge in comparing the consequences of using different functions where correlation across these aspects is necessary. General trends regarding ERD level, height class, and building type are estimated from the functions presented in these publications, as shown in Figures 3 and 4.

Table 3. Selected functions from the literature for Europe with ERD.

Aspects	Considered publications				
	Kappos et al. (2006)	Kyriakides et al. (2015)	Martins & Silva (2021)	Milutinovic & Trendafiloski (Ed.) (2003)	Tsionis & Papailia (2011)
Region	Greece	Cyprus	Worldwide	Europe	Euro-Mediterranean
RC building types	LFM, LFINF, LDUAL	LFM	LFM, LFINF, LWAL, LDUAL	LFM, LWAL, LDUAL	LFM, LFINF, LWAL, LDUAL
Height classes	(1-3), (4-7) (8-19)	LR, MR	Separate heights from 1 to 12	LR, MR, HR	LR, MR, HR
ERD description	Low-code, High-code	Without ERD, With ERD	DUL, DUM, DUH	Pre-code, Low-code, Moderate-code, High-code	Old-code-ND Low-code-ND Moderate-code-D High-code-D
Damage description	DG1, DG2, DG3, DG4, DG5	DL, SD, NC, C	Slight, Moderate, Extensive, Complete	Slight, Moderate, Extensive, Complete	Yielding, Collapse
IM	PGA	PGA	Sa, PGA (1 story)	Sd	PGA

Explanations: LFM: Moment-resisting frame. LFINF: Frame with infills. LDUAL: Wall-frame dual system. LWAL: Structural wall system. IM: Intensity measure. ND: Non-ductile. D: Ductile. DG: Damage grade. DL: Damage limitation. SD: Significant damage. NC: Near collapse. C: Building collapse. NLS: Nonlinear static analysis. NLD: Nonlinear dynamic analysis. PGA: Peak ground acceleration. Sa: Spectral acceleration. Sd: Spectral displacement. Functions from the highlighted publications are used in Figure 6.

Lateral strength and ductility with regards to ERD level:

Figure 4(a) shows the typical trend in fragility functions where an increase in ERD level corresponds to a combined increase in lateral strength and ductility. This can be observed through a slight shift to the right in the fragility curves for lower damage grades (i.e., a lower probability of exceedance for a damage grade at a given intensity), and a substantial shift for higher damage grades.

Figure 4(b) shows the scenario where an increase in ERD level is achieved by increasing the ductility of the building. This results in a higher probability of occurrence for lower damage grades and a reduced probability for higher damage grades. It is important to note that new versions of seismic codes often increase the design hazard levels, which could explain the trend in many of the fragility functions.

Influence of height class and structural system type:

Figure 4(a) and (b) show that in the case of low-code, low-rise buildings are less vulnerable than mid-rise buildings. However, in the case of high-code, mid-rise buildings have a lower probability of collapse compared to low-rise buildings. This could be due to the increased redundancy of energy-absorbing elements in high-code mid-rise buildings.

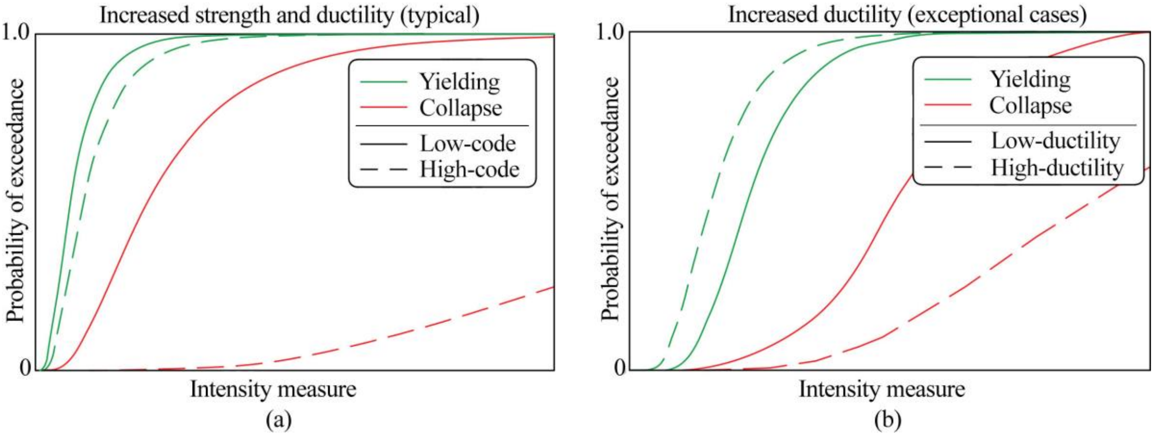


Figure 4. Typical trends in fragility: (a) for the code level and (b) for the change in ductility level.

Explanations: Legend: The color indicates the limit states, and the line type indicates the types of buildings.

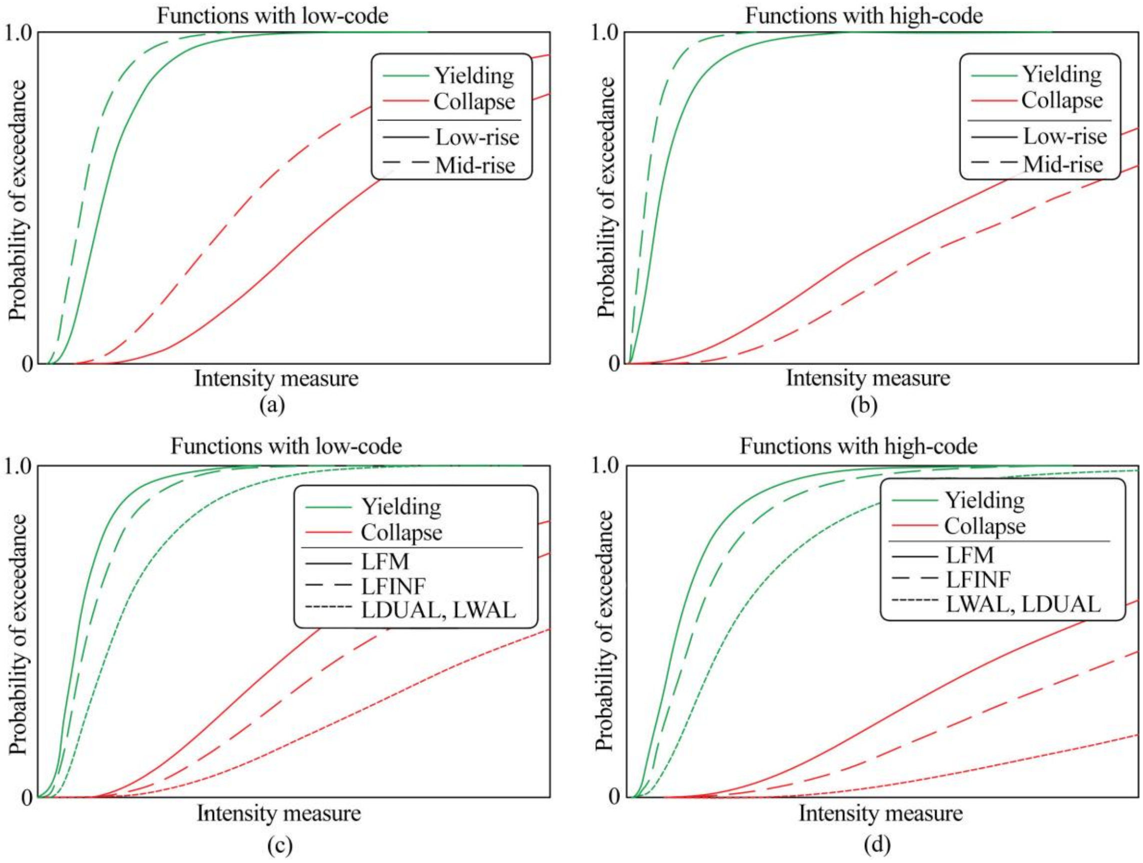


Figure 5. Impact of parameters on fragility curves: (a, b) Change of height class, (c, d) Change of system type.

Explanations: Legend: The color indicates the limit states, and the line type indicates the types of buildings.

LFM: Moment-resisting frame. LFINF: Frame with infills. LDUAL: Wall-frame dual system. LWAL: Structural wall system.

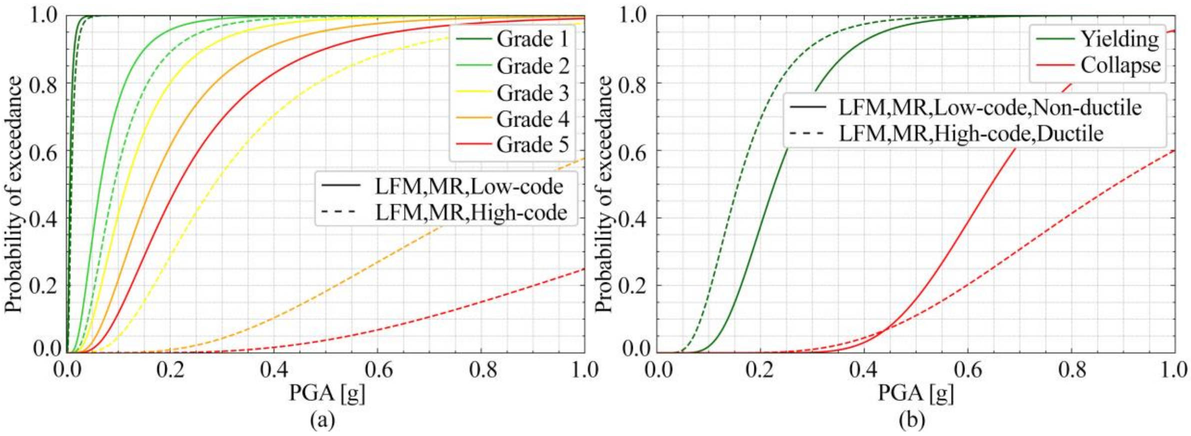
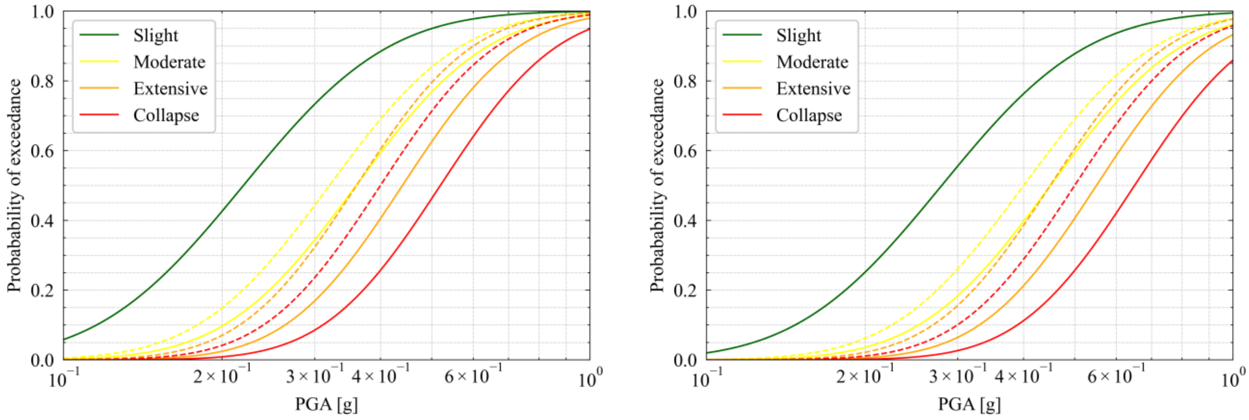


Figure 6. Fragility function samples for earthquake-resisting and non-resisting building types. (a) functions from Kappos et al. (2006) derived for Greece (b) functions from Tsionis & Papailia (2011) derived for Euro-Mediterranean Regions.

Figures 5(c) and (d) show that when considering building types and keeping the code level constant, moment-resisting frames are typically perceived as the most vulnerable. This level of vulnerability is also shared by infilled frames with a soft story. However, the inclusion of infills into the frame is hypothesized to enhance the building's resilience, especially when it is uniformly distributed. Structures with structural walls or wall-frame dual systems show improved performance. Examples of fragility functions for earthquake-resisting and non-resisting building types are shown in Figure 6.

4.2 Insights on precast systems

The adaptation of RC precast systems is widely used for commercial and industrial buildings, and understanding their seismic vulnerability is important in comparison to cast-in-situ systems. The need to treat them separately in the EMS-98 vulnerability table seems to be necessary. The following includes some readings on fragility functions derived for cast-in-situ and precast systems to try to understand their relative seismic vulnerability. The results from this reading are shown by Schwarz et al. (2024). Figure 7 and Figure 8 indicate that precast systems for the same ERD level are more vulnerable than cast-in-situ systems. This is particularly apparent for higher damage grades. This could be associated to the reduced ability to dissipate energy in joints in precast systems.

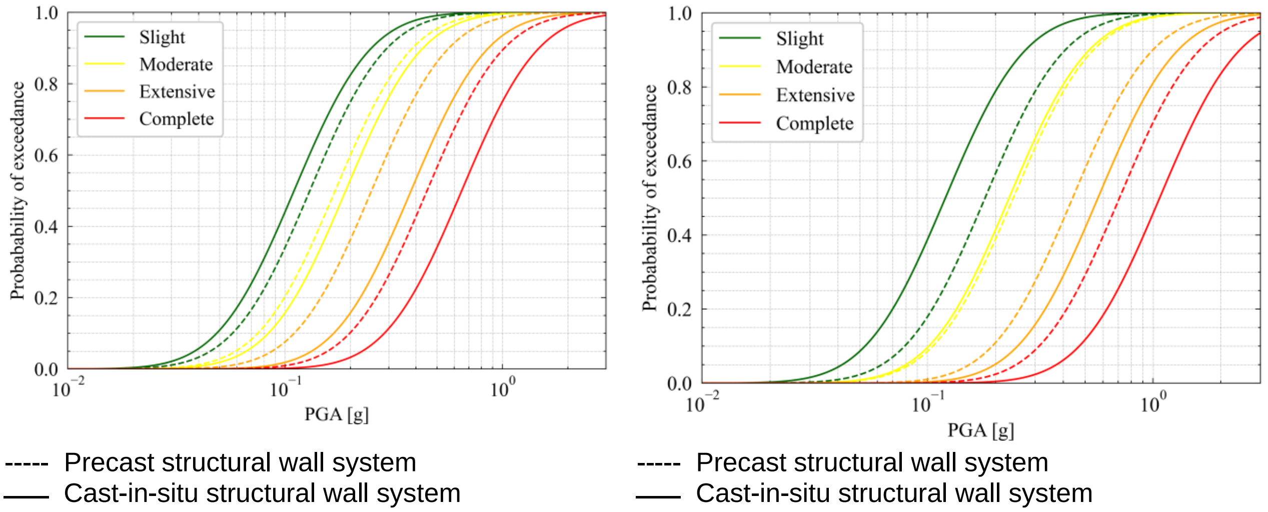


----- Precast moment-resisting frame
—— Cast-in-situ moment-resisting frame

----- Precast moment-resisting frame
—— Cast-in-situ moment-resisting frame

a) Low-code *b) Moderate-code*

Figure 7. RC precast versus cast-in-situ moment-resisting frame (Functions source: Liao et al 2006).



a) Low-code *b) Moderate-code*

Figure 8. RC precast versus cast-in-situ structural wall system (Functions source: FEMA 1999).

5 Challenges with Earthquake-Resistant Design

With reference to the previous sections, the following challenges are identified with regard to the seismic vulnerability of buildings with ERD.

Challenge 1: The scarcity of empirical data

The lack of empirical data to support the understanding of the seismic vulnerability of buildings with ERD is realized. Experimental data and well-described observations in different regions with different seismic code requirements would help in better understanding the behavior of this building type increase the reliability and improve the calibration of numerically-based studies.

Challenge 2: Impact of seismic code development

The changes in seismic code requirements that influence design parameters (e.g., base shear, ductility level, and deformation requirements) result in increased difficulty in modeling seismic vulnerability. It is realized that, in most cases, newer generations of codes impose stricter rules. However, changes in ductility requirements, as seen in the newer generation of Eurocode 8, need to be carefully addressed.

Challenge 3: The (open) reliability of Fragility Functions

Fragility functions used in seismic hazard assessment need to be evaluated in terms of their relevance to the intended application. An example of a classification scheme for suitability (Most Suitable, Still Suitable, Less or Not Suitable) according to building class, used damage grades/classes, and used intensity measures can be seen in the works of Schwarz et al. (2021). Additionally, quality assessment criteria are needed with regard to the derivation background of those functions, particularly those relevant to buildings with ERD, addressing the nonlinear behavior of the models used.

Challenge 4: Nonlinear behavior and the outcome of analytical studies

The energy dissipation behavior expected in buildings equipped with ERDs requires a thorough understanding of the nonlinear behavior of the structural system's materials. The use of simplified numerical models (e.g., bilinear stiffness modelling) may compromise the quality of assessments conducted with these models.

Challenge 5: Influence of secondary elements

The influence of secondary elements (e.g., infill walls) on the structural system (e.g., structural frame) can be complex, as it is affected by the quality of those secondary elements and the need to incorporate other modes of failure (e.g., out-of-plane failure), in addition to introducing nonlinear shear behavior in the frame elements. Although numerical models that account for such behavior exist in the literature, their implementation in numerical studies to derive fragility functions remains limited.

Challenge 6: Damage prognoses and interpretation of (future) observations

Visually identifying buildings with ERD in a region following seismic events, although theoretically possible, can be challenging based on the building's configuration. Additional information regarding detailing, along with design documents, is typically required. Assigning damage grades to these buildings can also be challenging because energy dissipation in plastic zones may not be readily visible. As a result, using these observations to assign macroseismic intensity following a seismic event remains a challenge.

6 Conclusions

The seismic vulnerability assessment of RC buildings with varying levels of ERD is crucial in seismic risk studies. The existing literature has primarily focused on buildings with limited or no ERD.

When examining the evolution of seismic codes, these codes can be categorized into several levels concerning basic design principles and ductility/energy dissipation considerations. These levels are then compared with the well-established classification of engineered structures according to EMS-92 and EMS-98. The damage progression and influence of secondary elements with varying qualities and levels of ERD are then reviewed. To explore the trends and assumptions associated with this building type, the current state of exposure modeling is reviewed by examining a set of publications with analytically based fragility functions for buildings with some level of ERD.

Limitations are identified, including the varying definitions used for buildings with ERD, and the limited distinction between lateral strength and ductility. The separation between ductility levels and lateral strength, as originally suggested in EMS-98, appears necessary with current design codes and practices. The publications also reveal a lack of consideration for the influence of non-structural elements. Functions that include infills are characterized by increased lateral strength without considering the quality of the infills. Challenges related to this building type are listed to guide future research and enhance the understanding of the difficulties encountered when dealing with this building type.

7 Acknowledgement

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