Damage-State Threshold Definitions in Analytical Fragility Assessment of Non-Ductile and Code-Deficient RC Buildings: A Systematic Review of Framework Origins, Inter-Study Divergence, and Transferability

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Abstract

Damage-state thresholds are the primary numerical input governing fragility curve position, yet their definition receives substantially less methodological scrutiny than ground-motion selection or structural modelling in seismic fragility assessment. This review systematically examines how damage-state thresholds are sourced, applied, and justified in analytical fragility studies of non-ductile and code-deficient reinforced concrete buildings. Five major threshold frameworks, HAZUS, EMS-98, ASCE 41, Eurocode 8 Part 3, and FEMA P-58, are classified by calibration basis and embedded structural assumptions; none was developed for a non-ductile, gravity-load-designed, or pre-code population as its primary target. Reported values for nominally equivalent damage states diverge substantially across structural classes, with the spread appearing to increase as damage severity increases. Transfer of thresholds from an external framework occurs in the majority of reviewed studies, yet full structural justification accompanies fewer than a third of these transfers. Controlled comparisons in which authorship and archetype basis are held constant demonstrate that divergence of comparable magnitude can arise from methodological choice alone. Detailing quality, governing failure mechanism, and demand-parameter compatibility are identified as the variables that determine whether a transferred threshold retains its physical validity. The evidence establishes that damage-state threshold definition functions as a primary determinant of fragility predictions and that current practice does not treat it accordingly, with direct consequences for seismic risk assessment of the non-ductile building stock that dominates seismically active regions worldwide.

Keywords: seismic fragility; damage-state thresholds; non-ductile reinforced concrete buildings; threshold transferability; interstorey drift ratio; performance-based earthquake engineering

1. Introduction

Cornell (1968) established the probabilistic foundation on which nearly all subsequent seismic risk assessment rests, expressing seismic hazard not as a single design value but as a relationship between ground-motion intensity and its average return period, derived transparently from explicit assumptions about source location, magnitude-frequency behaviour, and attenuation. This framework solved the hazard side of the seismic risk problem: it specifies, with disclosed and testable assumptions, how often a given level of shaking can be expected at a site. It does not, and was never intended to, address the second half of the risk chain: how a given level of structural response is classified as having reached a particular state of damage. That second step, the definition of the damage-state threshold against which an engineering demand parameter is compared, is the subject of this review, and no comparable standard of transparency exists for threshold transfer across structurally distinct populations, which is what the evidence assembled in this review directly addresses.

The gap is consequential because the building population most exposed to seismic risk in many regions is not the ductile, capacity-designed reinforced concrete construction for which most modern fragility frameworks were calibrated. Non-ductile reinforced concrete buildings, lacking the transverse reinforcement, weak-beam–strong-column proportioning, and continuous detailing that capacity design requires, remain widespread wherever construction predates the enforcement of modern seismic provisions or where enforcement has historically been inconsistent. Liel et al. (2011) document that, despite long-standing concern about pre-1970s non-ductile reinforced concrete frames in California, data sufficient to quantify their collapse risk relative to modern construction were lacking for an extended period, a gap that motivated a substantial body of subsequent fragility research. Celik and Ellingwood (2008, 2010) extend this concern to gravity-load-designed frames more broadly, showing that beam-column joint shear and bond-slip behaviour, mechanisms largely absent from ductile-frame fragility models, govern much of this population's vulnerability and require explicit representation that many fragility analyses do not provide. Opabola et al. (2021) identify a further mechanism, bond-critical lap-splice failure, that existing assessment guidance has historically grouped with shear-critical behaviour despite evidence that the two exhibit materially different collapse potential.

Against this structurally distinct population, the threshold values used to define damage states in the literature are drawn from frameworks whose calibration basis varies widely and whose mutual compatibility is rarely demonstrated. Rossetto and Elnashai (2005) report slight-damage and collapse thresholds for infilled reinforced concrete frames, derived from a macroseismic-informed displacement scale, that sit substantially below the equivalent values found in HAZUS- or ASCE 41-type drift tables, a divergence the authors attribute in part to the broader inconsistency in analysis technique, structural idealisation, and damage characterisation that has long characterised vulnerability-curve development for this building class. Parizat et al. (2024) provide a documented instance of the practical consequence of this inconsistency: applying generic HAZUS fragility curves, calibrated on a different structural population, to pre-code reinforced concrete apartment buildings in Israel produced a resilience estimate the authors themselves found to overestimate the building's actual seismic performance once locally calibrated curves were developed. The problem is not confined to moment-frame or infilled-frame typologies. Dede et al. (2025) report that no bespoke damage scale existed for tunnel-form construction prior to their own work, with prior studies in that field deriving thresholds from literature developed for unrelated structural systems, and Ghanem et al. (2024) show that even nominally regular reinforced concrete frames can require different threshold treatment once post-construction changes in occupancy alter their effective mass distribution. Opabola et al. (2024) demonstrate that uncertainty in which failure mechanism governs a given component, rather than uncertainty in ground motion or modelling assumptions alone, can shift median collapse fragility by more than twenty percent, indicating that the mechanism a threshold is implicitly calibrated to represent is itself a substantial source of variability that is rarely made explicit in the studies that adopt it.

Taken together, this body of evidence indicates that damage-state threshold definition for non-ductile reinforced concrete buildings remains fragmented across framework origin, engineering demand parameter selection, and threshold transfer practice. Although probabilistic seismic hazard analysis has long been built on transparent assumptions regarding source activity, ground-motion intensity, and return period, the subsequent step of assigning structural response to damage states is often less explicit. This lack of transparency is particularly consequential for non-ductile reinforced concrete buildings, where drift capacity, damage progression, and collapse potential depend strongly on detailing quality, governing failure mechanism, and structural system type. The central contribution of this review is therefore to examine damage-state thresholds not as fixed numerical inputs, but as transferable assumptions whose validity depends on their calibration basis and compatibility with the building population under assessment.

This review addresses four objectives:

1. To classify the damage-state frameworks used in reinforced concrete fragility studies according to their origin, calibration basis, and embedded structural assumptions.
2. To examine how frequently damage-state thresholds are transferred from external frameworks or prior studies, and how transparently this transfer is justified.
3. To document the extent of inter-study divergence in reported threshold values across structural classes, engineering demand parameters, and framework families.
4. To identify the structural and contextual conditions under which threshold transfer to non-ductile reinforced concrete buildings is defensible.

The paper proceeds by first describing the systematic review methodology, followed by an examination of damage-state framework origins, non-ductile building characteristics, engineering demand parameter selection, inter-study threshold divergence, and threshold transferability. The review then synthesises these findings to clarify the limitations of current practice and to identify directions for more transparent, mechanism-aware fragility assessment of non-ductile reinforced concrete buildings.

2. Review Methodology

A systematic review of analytical fragility studies addressing reinforced concrete buildings was conducted following PRISMA 2020 reporting conventions (Page et al. 2021). No protocol was pre-registered prior to the review. Records were retrieved from Dimensions, used as the primary database, supplemented by Google Scholar for framework documents and literature not indexed elsewhere. Dimensions was selected as the primary source because it indexes peer-reviewed literature, supports Boolean search operators and document-type filtering, and produces reproducible results, properties not reliably available through Google Scholar alone. Search strings combined terms for damage-state thresholds, fragility curves, non-ductile or gravity-load-designed reinforced concrete construction, and interstorey drift ratio, including combinations such as ("non-ductile" OR "gravity load designed" OR "pre-code" OR "code deficient") AND ("reinforced concrete" OR "RC frame") AND (fragility OR vulnerability) AND ("damage state" OR "damage threshold"), together with framework-specific strings incorporating HAZUS, FEMA P-58, ASCE 41, and Eurocode 8. More than twenty such strings were applied across both databases in April 2026, with results restricted to publications from 1985 onwards, a lower bound that encompasses the emergence of modern analytical seismic vulnerability assessment methodology, through to the search date. The complete search strategies used for each database are provided in Online Resource 1.

Title and abstract screening retained records addressing reinforced concrete buildings as the primary structural subject, addressing seismic performance, vulnerability, or damage assessment, and published as a peer-reviewed journal article or primary framework document; records addressing non-reinforced-concrete structural systems, non-seismic hazards, or non-journal sources such as conference papers, theses, or technical reports were excluded. This stage reduced an initial pool of 250 records, after the removal of 15 duplicates, to 235 screened records, of which 73 were excluded, yielding 162 records carried forward to full-text assessment.

Full-text screening applied stricter criteria, requiring that each study explicitly define a non-ductile, gravity-load-designed, pre-code, or otherwise code-deficient reinforced concrete structural system, employ an analytical fragility methodology rather than a purely empirical or observational one, and report sufficient information to identify the threshold source framework adopted. Records were excluded at this stage for the following reasons: no numerical threshold values reported and no threshold source identifiable, structural population limited to ductile or modern code-designed systems only, purely empirical or observational methodology without analytical threshold definition, or full text unavailable after reasonable retrieval effort. A two-tier approach was applied to avoid the bias that would result from excluding studies that cite a threshold framework without reporting the underlying numerical values, since such studies are themselves directly relevant evidence of undisclosed threshold transfer. Studies reporting full or partial numerical threshold values were retained for the comparative analysis of inter-study divergence; studies adopting a threshold framework by citation alone were retained separately and contribute to the analysis of transfer prevalence and transparency. This screening stage reduced the 162 full-text-assessed records to 62 included studies. The full screening process is summarised in Fig. a. The completed PRISMA 2020 checklist is provided in Online Resource 2.

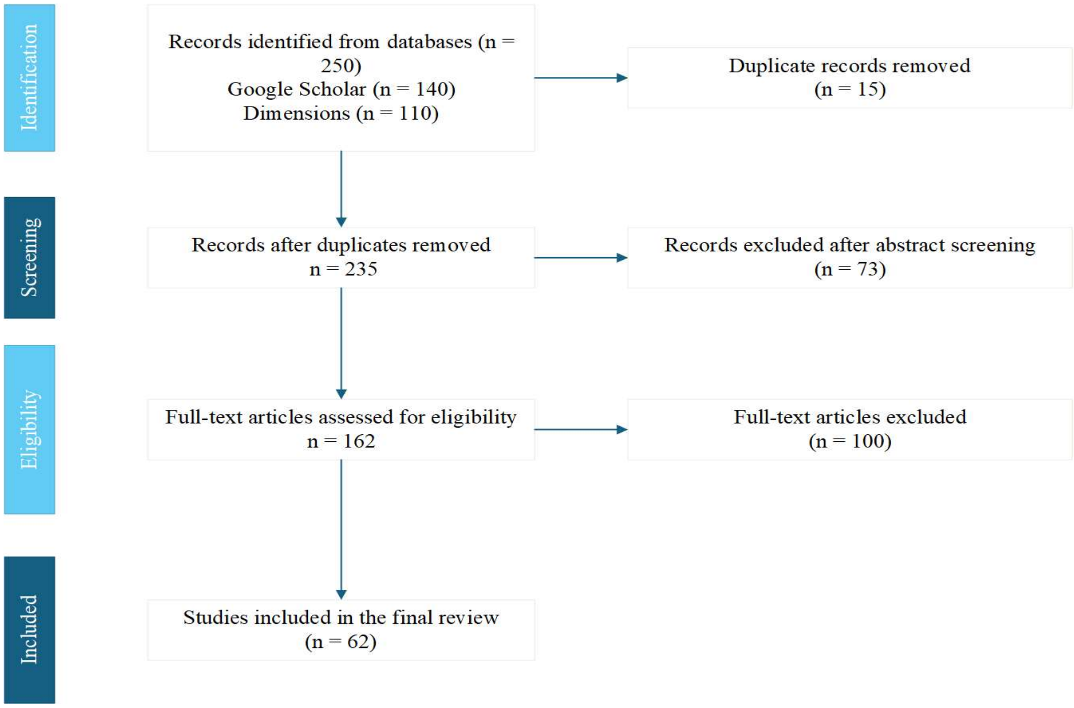

Fig. a. PRISMA flow diagram of the three-stage systematic review process, from initial record identification through to the 62 studies included in the final review.

For each included study, data were extracted on country or region, structural system, design era, number of storeys, seismic design level, analysis method and software, intensity measure, primary engineering demand parameter, threshold source framework, reported damage-state threshold values, and the presence and nature of any justification provided for threshold transfer. Threshold justification was coded into three categories: full justification, where the study explicitly discusses structural reasoning for why the transferred value is appropriate to the population under assessment; partial justification, where a citation to the source framework is accompanied by a brief structural rationale without demonstrated equivalence; and no justification, where the threshold source is cited with no accompanying argument. Screening and data extraction were performed by the lead author, with a second author independently reviewing a proportion of records at each stage to verify consistency. Structural systems described in the original studies using heterogeneous terminology were consolidated into six standardised classes, Non-Ductile RC Moment Frame, Gravity-Load-Designed RC Frame, Pre-Code RC Frame, RC Infilled Frame, RC Shear Wall or Core-Wall, and Mixed or Other RC, to enable grouped comparison across studies addressing structurally comparable populations. Five framework documents, HAZUS, FEMA P-58, ASCE/SEI 41-17, Eurocode 8 Part 3, and EMS-98, were included directly as primary sources, identified as the threshold sources most frequently cited across the included studies, and are examined in detail in the discussion of framework origins that follows. No formal quality-scoring instrument was applied to the included studies; instead, study quality is addressed through the systematic assessment of reporting completeness and threshold-justification transparency, which forms a substantive part of the analysis itself rather than a separate screening criterion.

3. Damage-State Frameworks: Origins and Structural Assumptions

3.1 Expert-Judgment and Macroseismic Frameworks

Damage-state threshold values in the reviewed literature are drawn from a wide range of sources, including HAZUS, EMS-98, ASCE 41, Eurocode 8 Part 3, FEMA P-58, the Japan Structural Consultants Association methodology, the Italian NTC 2018 code, the Park-Ang damage index family, and numerous study-specific or hybrid derivations developed by individual authors for a particular building population. Among these, HAZUS, EMS-98, ASCE 41, Eurocode 8 Part 3, and FEMA P-58 are examined individually in this section because they represent the major framework families observed in the reviewed literature and the principal calibration philosophies — expert consensus, field observation, code-based performance levels, and component-level experimental fragility — from which threshold values are subsequently adapted, combined, or departed from Fig. b. The remaining sources, including the substantial share of studies that develop thresholds independently of any single named framework, are addressed later in this discussion.

HAZUS and the European Macroseismic Scale are among the most widely used threshold sources in the reviewed literature, and they arrive at damage classification through largely incompatible routes. HAZUS assigns interstorey drift thresholds to each damage state as a function of building type and seismic design level, ranging from high-code through pre-code (Federal Emergency Management Agency 2012a). For a low-rise concrete moment frame under the high-code design level, the methodology specifies drift thresholds of 0.005, 0.010, 0.030, and 0.080 at the slight, moderate, extensive, and complete damage states respectively; the moderate-code values for the same building type are lower at every state (Federal Emergency Management Agency 2012a). These values originate from a structured expert-elicitation process applied to a generic building class rather than from analysis of a specific structural model, and the classification distinguishes design era without distinguishing ductility detailing within an era — a non-ductile gravity-load-designed frame and a capacity-designed ductile frame built under the same code generation are assigned the same threshold set whenever both fall into the same HAZUS building class (Federal Emergency Management Agency 2012a).

The European Macroseismic Scale takes a markedly different approach, defining five damage grades for reinforced concrete buildings entirely through field-observable criteria, with no engineering demand parameter specified at all (Grünthal 1998). Grade 3 describes cracking in columns and beam-column joints accompanied by spalling of the concrete cover and buckling of longitudinal reinforcement; Grade 4 describes compression failure of concrete with fracture of reinforcing bars and bond failure at lap splices, alongside collapse of a few columns or an upper storey (Grünthal 1998). Compared against HAZUS, the two frameworks can be understood as addressing complementary rather than equivalent needs: HAZUS provides a numerical demand value without a documented structural basis specific to any one building, while EMS-98 provides a physically specific description of failure mechanism without an attached demand measure (Grünthal 1998; Federal Emergency Management Agency 2012a). A study adopting EMS-98 as a threshold source must therefore introduce an additional translation step, assigning a drift, rotation, or displacement value to a descriptive grade, and this step is not always reported with the same transparency as the rest of the study's methodology.

3.2 Performance-Level and Code-Based Frameworks

ASCE/SEI 41-17 and Eurocode 8 Part 3 both move away from the building-class logic of HAZUS and EMS-98 by defining damage through deformation capacity at the level of the individual structural component. ASCE 41 defines Immediate Occupancy as the postearthquake state in which a structure essentially retains its preearthquake strength and stiffness, Life Safety as the state in which damaged components retain a margin of safety against partial or total collapse, and Collapse Prevention as the state in which the structure continues to support gravity loads but retains no margin against collapse (American Society of Civil Engineers 2017). These definitions describe structural condition narratively; the numerical acceptance criteria that operationalise them are tabulated separately by component type and detailing condition, so the performance level itself reads as generic while the threshold value behind it is component-specific (American Society of Civil Engineers 2017).

Eurocode 8 Part 3 extends this component-level logic by deriving deformation capacity directly from a mechanics-based chord-rotation expression rather than a lookup table indexed to component type (European Committee for Standardization 2005). The ultimate chord rotation capacity of a concrete member is computed as a function of concrete and reinforcement strength, axial load ratio, shear span, and confinement effectiveness, and the standard reduces this capacity by a factor of 1.2 for members lacking detailing for earthquake resistance, by a further factor for smooth or lap-spliced longitudinal bars, and by an additional factor of 1.6 for cold-worked brittle reinforcement (European Committee for Standardization 2005). Among the five frameworks considered here, Eurocode 8 Part 3 is the only one in which detailing enters through a continuous mechanics-based reduction factor applied directly to the computed deformation capacity; ASCE 41 incorporates detailing through discrete component classifications, differentiating conforming from non-conforming members in its tabulated acceptance criteria, rather than through a continuously varying capacity reduction (American Society of Civil Engineers 2017). HAZUS addresses detailing only implicitly through its building-classification scheme (Federal Emergency

Management Agency 2012a), while EMS-98 leaves detailing quality undefined in its damage descriptions (Grünthal 1998). A further detail is relevant to any comparison across frameworks: the Eurocode 8 Part 3 commentary notes that its own Near Collapse state is defined closer to the physical collapse of the structure than the nominally similar "no collapse" requirement of Eurocode 8 Part 1, and that the Part 1 state corresponds more closely to what Part 3 separately defines as Significant Damage (European Committee for Standardization 2005). If two damage states bearing similar names within a single code family are not interchangeable, the same caution applies, with greater force, to comparisons between frameworks developed independently of one another, such as HAZUS and Eurocode 8.

3.3 Experimental, Component-Based, and Hybrid Frameworks

FEMA P-58 shares the component-level logic of ASCE 41 and Eurocode 8 Part 3 but differs from both in how its threshold values are obtained. Rather than computing deformation capacity from a mechanics-based expression or assigning it from a code-based table, the methodology derives fragility functions for individual structural and nonstructural components from laboratory testing, post-earthquake field observation, analytical calculation, or expert judgement, with explicit testing protocols specified for the experimental case (Federal Emergency Management Agency 2012b). The probability that a component has reached a given damage state is combined across all components in the building through an explicit damage logic to produce a building-level outcome, rather than that outcome being read directly from a single global drift value as in HAZUS (Federal Emergency Management Agency 2012a, b). A FEMA P-58 threshold is therefore only as representative of a given structural population as the specimens from which it was experimentally derived. Cardone and Perrone (2017) make this limitation explicit: applying the FEMA P-58 methodology to pre-1970 Italian reinforced concrete frames, they found the published component library insufficiently representative of that population's deficient detailing and developed study-specific experimental fragilities rather than applying the standard library directly (Cardone and Perrone 2017). This documented departure illustrates, in an unusually transparent form, a substitution that the present review finds occurring elsewhere in the literature with less explicit disclosure.

This pattern of substitution is, in fact, the most frequent outcome rather than the exception. Across the studies reviewed, the largest single category of threshold source is not any one named framework but a combination of hybrid, modified, and study-specific derivations, accounting for 28 of the 62 included studies (45.2%), as established by the present review's extraction as shown in Fig. b — a larger share than HAZUS/ATC-40-based, ASCE 41/FEMA 356/273-based, EMS-98-based, FEMA P-58-based, and Eurocode 8-based sources individually, each of which appears as the named source in between four and ten studies as shown in Fig. b. This distribution indicates that authors working on non-ductile or otherwise atypical reinforced concrete populations frequently regard the established frameworks as a starting point requiring adaptation rather than a directly applicable source of threshold values, even where one of the five frameworks is cited as the nominal basis.

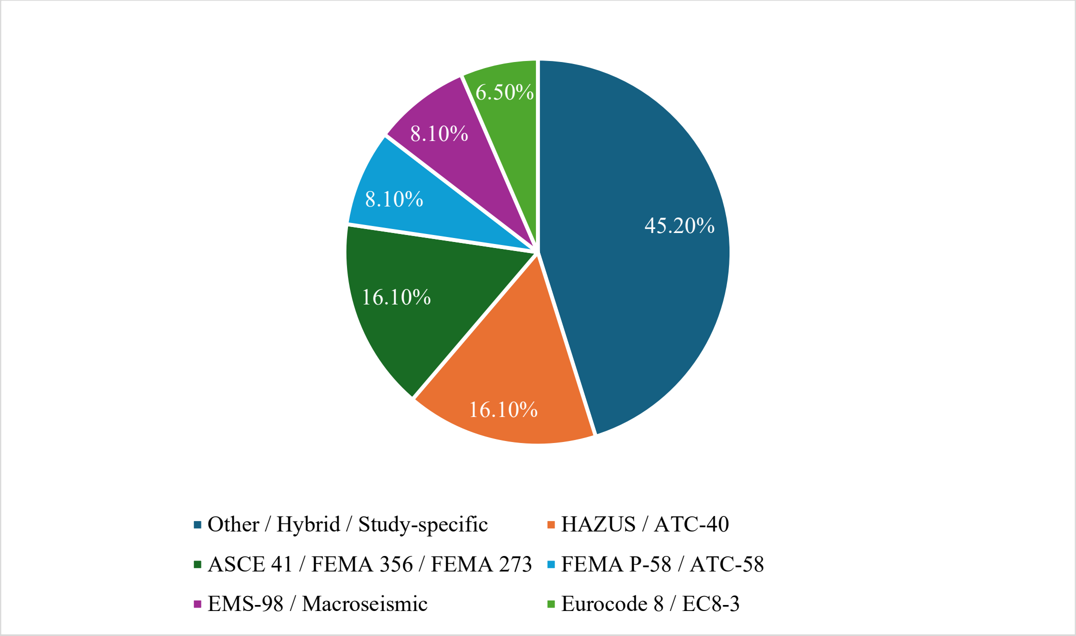

Fig. b. Distribution of damage-state threshold sources by framework family across the 62 reviewed studies.

As Fig. b shows, no single framework accounts for a majority of the reviewed studies; instead, hybrid, modified, and study-specific approaches collectively form the largest category.

3.4 Summary of Embedded Structural Assumptions

The five named frameworks examined above differ in calibration basis, unit of analysis, and treatment of detailing quality, but they share a limitation relevant to this review: their stated calibration procedures do not explicitly identify non-ductile, gravity-load-designed, or code-deficient reinforced concrete buildings as the primary target population (Grünthal 1998; European Committee for Standardization 2005; Federal Emergency Management Agency 2012a, b; American Society of Civil Engineers 2017). HAZUS and EMS-98 classify by design era and material rather than by detailing quality, so a non-ductile frame inherits whichever threshold is assigned to its broader code-era class, regardless of whether its detailing matches the construction practice that informed the original consensus or observational basis (Grünthal 1998; Federal Emergency Management Agency 2012a). ASCE 41 and Eurocode 8 Part 3 are the only two frameworks that incorporate a detailing distinction directly into the threshold computation, but the distinction is binary — detailed for earthquake resistance or not — rather than calibrated to the specific failure mechanisms, such as joint shear failure or lap-splice bond degradation under low transverse reinforcement ratios, that govern non-ductile response (European Committee for Standardization 2005; American Society of Civil Engineers 2017). FEMA P-58 addresses the building-classification problem in principle by deriving thresholds from tested specimens, but its applicability still depends on whether the specimens tested are representative of the population being assessed, a condition its documentation requires without independently guaranteeing (Federal Emergency Management Agency 2012b), as the departure documented by Cardone and Perrone (2017) demonstrates.

The frequency with which the reviewed studies depart from these five frameworks, whether through partial adoption, combination, or independent derivation, is itself evidence of this limitation in practice rather than only in principle. Where a study does adopt a named framework, the adoption is frequently selective: Adom-Asamoah and Osei (2018) retain HAZUS's slight-damage threshold of 0.5% interstorey drift without modification but report extensive- and complete-damage thresholds of 2.0% and 5.0%, both below HAZUS's own high-code values of 3.0% and 8.0% for the same building class (Federal Emergency Management Agency 2012a), without stating which design level the modified values are intended to represent. A threshold framework, in other words, is rarely adopted or rejected as a complete set; individual damage states within it are more often retained, modified, or replaced according to criteria that the adopting study does not always disclose.

Given that HAZUS, EMS-98, ASCE 41, Eurocode 8 Part 3, and FEMA P-58 differ in calibration basis, unit of analysis, and treatment of detailing quality, and given that nearly half of the reviewed studies depart from any single framework altogether, the numerical threshold values reported across the literature would be expected to diverge accordingly, even among studies addressing structurally similar non-ductile populations. The extent and pattern of this divergence, and its relationship to the demand parameters and statistical fitting methods examined subsequently, is the focus of the comparative analysis that follows.

4. Non-Ductile RC Buildings: Characteristics and Damage Mechanisms

4.1 Classification and Regional Prevalence

The term non-ductile reinforced concrete building, as used throughout this review, designates a structural population defined by what its design and construction process omitted rather than by a single code provision (Liel and Deierlein 2012). The defining omission is capacity design: the deliberate hierarchy by which a structure is proportioned to yield in flexure at predetermined locations before any brittle mechanism can govern. Buildings outside this hierarchy fall into several overlapping categories that recur across the reviewed literature. These include gravity-load-designed frames proportioned for vertical loads with seismic demand addressed only incidentally or not at all (Celik and Ellingwood 2008, 2010), pre-code buildings constructed before the jurisdiction's first seismic provisions were enforced (Tesfamariam and Goda 2015; Cardone and Perrone 2017), and buildings nominally subject to an earlier seismic code whose detailing requirements fall well short of current capacity-design practice (Amirsardari et al. 2019, 2022). What unites these categories structurally, despite differing regulatory histories, is the absence of three specific provisions: adequate transverse reinforcement in beam-column joints and potential plastic hinge regions, a weak-beam–strong-column proportioning rule enforced through design, and continuous, properly developed longitudinal reinforcement rather than lap splices terminating at floor level without confinement. The term code-deficient is used in this review as an umbrella designation encompassing all three categories — gravity-load-designed, pre-code, and non-ductile — where the distinction between them is not critical to the point under discussion.

Among the structural classes identified across the reviewed studies, non-ductile moment frames form the largest single category at 30.65% of the included sample, followed by gravity-load-designed frames and infilled frames, each at 16.13%, pre-code frames at 14.52%, mixed or other reinforced concrete configurations at 12.90%, and shear-wall or core-wall systems at 9.68% as shown in Fig. c.

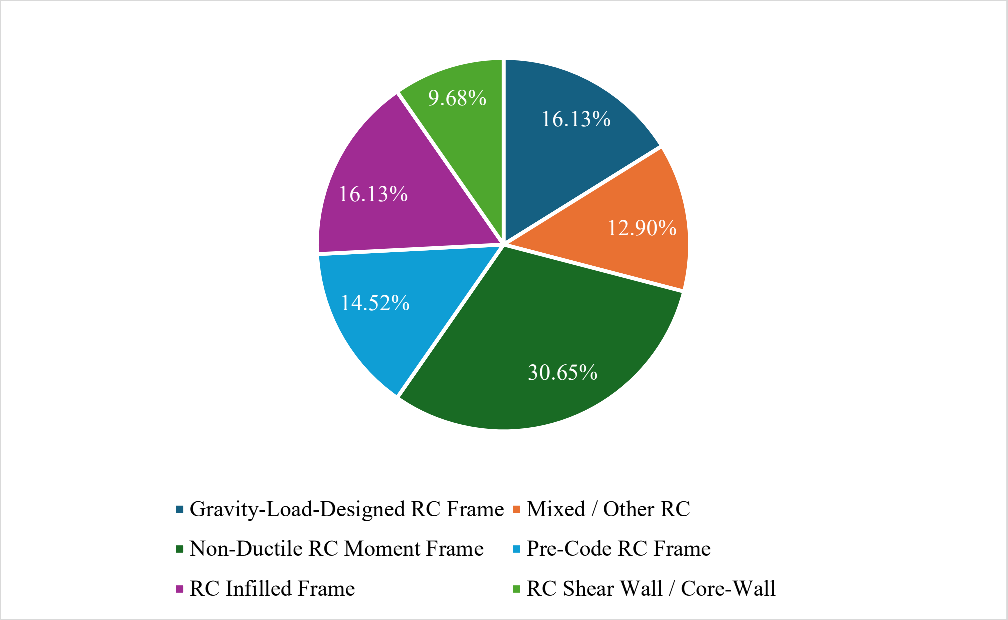

Fig. c. Structural-class distribution of the reviewed RC fragility studies.

This distribution carries two implications beyond simple frequency. First, the predominance of non-ductile moment frames over shear-wall systems is consistent with the failure-mechanism literature reviewed below: moment frames lacking capacity design are disproportionately vulnerable to the storey-mechanism and joint-failure modes that have motivated the bulk of non-ductile fragility research, whereas shear-wall systems, even when lightly reinforced, tend to retain a more distributed deformation capacity that has attracted comparatively less targeted study. Second, the near-equal representation of gravity-load-designed and infilled frames suggests that the literature treats two structurally distinct deficiency types as comparably important research targets: the first arising from the absence of seismic design intent altogether, the second from the unintended stiffness and strength contribution of a non-structural component. Both produce non-ductile response, but through different mechanisms, a distinction with direct consequences for which engineering demand parameter is appropriate to each, as discussed later in this review.

These deficiencies are frequently compounded by construction-quality characteristics that do not appear in design drawings. Such characteristics are therefore only identifiable through field investigation or experimental testing. Ahmad (2019) reports shake-table testing of substandard reinforced concrete frames built with low-strength concrete, smooth reinforcing bars, and inadequate joint confinement, representative of informal construction practice rather than any particular code provision. The presence of smooth, rather than deformed, longitudinal bars is itself structurally significant. Smooth bars rely on end hooks and friction rather than surface deformation for anchorage, producing a bond-slip behaviour distinct from that of the deformed bars on which most contemporary deformation-capacity expressions were calibrated, including those underlying the code-based frameworks discussed previously.

The reviewed studies are also distributed across a wide geographic range rather than concentrated in a single seismic region. Europe and the Mediterranean account for 27.40% of the sample, Asia and the Middle East for

25.80%, North America for 19.40%, international or generic case studies for 8.10%, and Africa, Latin America, and Oceania each for 6.50% as shown in Fig. d.

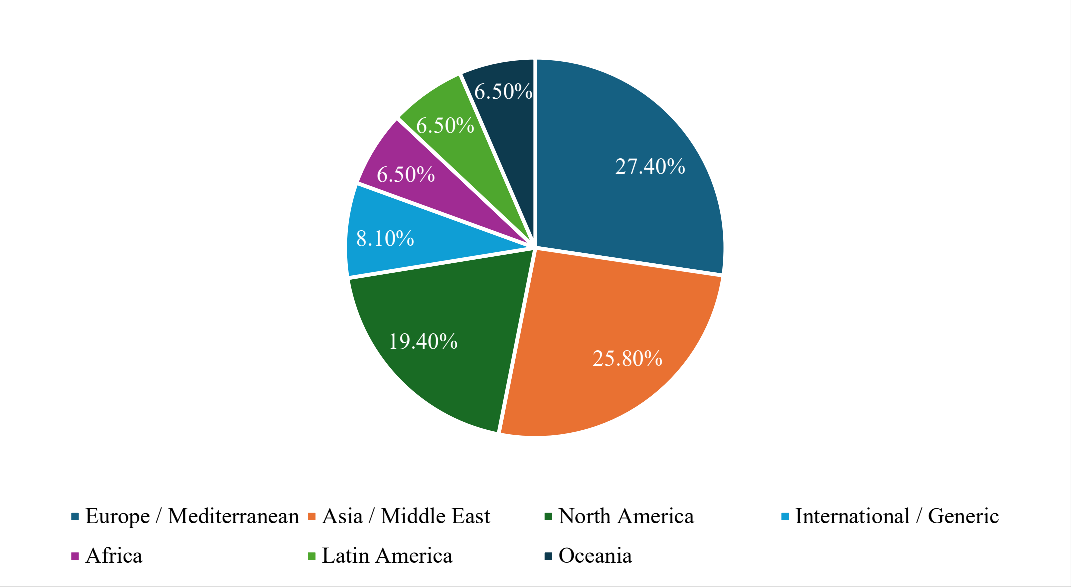

Fig. d. Regional distribution of the reviewed RC fragility studies.

This distribution is informative beyond the geographic spread itself. The concentration of studies in Europe/Mediterranean and Asia/Middle East regions corresponds to areas where pre-code and pre-1970s gravity-load-designed construction remains in active use and coincides with documented high seismic hazard, which together create the practical motivation for non-ductile fragility assessment as a research priority. The comparatively smaller shares from Africa, Latin America, and Oceania do not necessarily indicate that non-ductile construction is less prevalent in those regions; they more plausibly reflect a lower volume of published fragility research relative to construction stock, since several of the included studies from these regions explicitly motivate their work by noting the absence of prior locally calibrated assessment. Within this geographic range, studies in the present review document non-ductile or code-deficient reinforced concrete construction in Pakistan (Ahmad et al. 2014; Ahmad 2019; Rasheed et al. 2022; Khan and Rizwan 2024, 2025), Türkiye (Akkar et al. 2005; Nemutlu et al. 2023), Ghana (Adom-Asamoah 2012; Adom-Asamoah and Osei 2018), Cyprus (Hedayat and Yalciner 2010), Afghanistan (Sharafi and Saito 2024), and Australia (Amirsardari et al. 2019, 2022). These sit alongside the gravity-load-designed and pre-code populations of the central and eastern United States and Italy referenced above. This geographic range spans countries with no seismic code history at the time of construction and countries whose codes lacked enforced capacity-design provisions until comparatively recently. It also includes countries where enforcement of an existing code was inconsistent despite its formal existence. At the same time, this geographic distribution is not methodologically neutral with respect to threshold-source selection: European and Mediterranean studies in the reviewed literature disproportionately cite Eurocode 8 Part 3 and study-specific experimental frameworks, while North American studies predominantly reference HAZUS and FEMA-family documents, meaning that a portion of the inter-study divergence documented in this review reflects differences in regional methodological tradition alongside genuine structural population differences.

The structural consequence is the same in each case regardless of the regulatory pathway that produced it. The result is a building population whose seismic deformation capacity was not the governing design consideration, assessed today using fragility frameworks whose threshold values were derived, as established in the preceding discussion of framework origins, from building classes or component populations that did not share this characteristic.

4.2 Failure Modes and Damage Progression

The absence of capacity design does not simply lower the deformation capacity of non-ductile reinforced concrete buildings relative to ductile counterparts. It changes which mechanism governs failure and therefore which physical quantity a damage-state threshold should be measuring. Jeon et al. (2015) demonstrate this directly by analysing a single non-ductile archetype under three alternative governing mechanisms — flexural yielding, column shear failure, and joint shear failure combined with bar-anchorage failure — and showing that each mechanism produces a distinct deformation capacity at nominally the same damage state. Where a ductile frame is expected to develop a stable flexural hinge with a sustained yield plateau, a non-ductile frame lacking adequate transverse reinforcement in the column or joint region is liable to lose lateral strength through diagonal shear cracking before flexural yielding is reached. This eliminates the yield plateau that conventional drift-based damage-state definitions implicitly assume.

This mechanism dependency compounds at the system level. Liel and Deierlein (2012) and Baradaran Shoraka et al. (2013) characterise collapse in non-ductile moment frames as a two-stage process in which an individual column first loses shear capacity and then loses axial load-carrying capacity. This triggers redistribution to adjacent columns and potential progressive collapse, a sequence that does not correspond to any single global drift value but to a structural-state condition evaluated at the component level. Gaetani d'Aragona et al. (2017) extend this characterisation to aftershock scenarios, in which a structure already weakened by shear or axial damage during a mainshock exhibits a further reduced collapse capacity that a drift threshold calibrated on undamaged response cannot represent. A further source of mechanism-specific behaviour arises at lap splices, where longitudinal bars are spliced with inadequate length and no confining transverse reinforcement at the critical end region. Opabola et al. (2021) show that bond-critical columns subject to splice failure exhibit a deformation capacity and failure sequence distinct from shear-critical columns governed by transverse reinforcement alone. This means that even within the broad category of non-ductile construction, the governing failure mechanism is not uniform across structural elements within the same building.

The practical consequence of this mechanism diversity is that the engineering demand parameter best suited to describing damage is itself mechanism-dependent. A flexure-governed element's condition is reasonably summarised by a single global or storey-level drift value, since deformation is distributed continuously along the member length up to the point of yielding. A shear- or bond-governed element behaves differently: its capacity is exhausted abruptly once diagonal cracking or bar slip initiates, and the global drift recorded at that instant reflects the structure's overall flexibility as much as it reflects the condition of the failing element. Two storeys at the same recorded drift can therefore be in materially different physical states if one is approaching a stable flexural hinge and the other has just exceeded its shear or bond capacity. A single drift-based threshold cannot resolve this distinction without separately tracking which mechanism is active.

The combined effect of these mechanisms is that damage in non-ductile reinforced concrete buildings tends to initiate earlier, in deformation terms, than in ductile construction, and to concentrate in a smaller number of elements rather than distributing across the structure through sequential hinge formation (Liel and Deierlein 2012; Jeon et al. 2015). A storey governed by column shear failure can lose a substantial fraction of its lateral and vertical capacity at a drift level well below what a flexure-governed storey of comparable height and stiffness would sustain. The transition from local component failure to storey-level or building-level collapse can occur over a narrower deformation range than the multi-stage degradation sequence that global drift-based damage-state frameworks were generally formulated to describe (Baradaran Shoraka et al. 2013; Gaetani d'Aragona et al. 2017). Because the studies reviewed here examine governing mechanisms that range from flexural yielding to column shear, joint shear, and lap-splice bond failure, often within the same broad structural class, the drift thresholds reported for nominally similar non-ductile buildings should be expected to vary according to which mechanism the underlying analysis actually captures, independently of any difference in the threshold framework adopted.

5. Engineering Demand Parameters in Threshold Definition

5.1 Drift-Based and Deformation-Based Parameters

The reviewed studies define damage-state thresholds on seven distinguishable categories of engineering demand parameter. Storey or interstorey drift-based parameters are the most common, used in 21 of 62 studies (33.9%), followed by multi-parameter definitions that combine interstorey drift with a second indicator, used in 16 studies (25.8%). Spectral or structural displacement-based parameters account for 9 studies (14.5%), for example O'Reilly and Sullivan (2018), Pammi et al. (2026), Karimzadeh et al. (2018), Romero-Sanchez et al. (2020), and Remki et al. (2018), roof or global drift-based parameters and Park-Ang or other energy-based damage indices each account for 5 studies (8.1%), component-level rotation or capacity-based parameters account for 4 studies (6.5%), and other physical or cumulative indicators, including the multi-criteria qualitative approach adopted by Schwarz et al. (2015) within an EMS-98-based assessment, account for the remaining 2 studies (3.2%). Interstorey drift therefore appears, in some form, in the majority of the reviewed literature, but the diversity of the remaining categories indicates that no single parameter has been treated as a sufficient descriptor of damage across the full range of structural systems and failure mechanisms considered in this review.

The practical advantage of interstorey drift is that it is a natural output of any storey-level structural model, linear or nonlinear, and is directly comparable across buildings of different height once normalised by storey height. The structural assumption underlying its use, less frequently acknowledged, is that interstorey drift serves as a reliable proxy for the physical state of the structural components within that storey. This assumption holds when deformation is distributed across a yielding mechanism, but it becomes increasingly questionable when a single component within the storey has failed in shear or bond while adjacent components remain elastic, a condition discussed in the preceding section as characteristic of non-ductile response.

Even within the broad category of drift-based thresholds, the reviewed studies do not measure the same quantity. Maximum interstorey drift ratio captures the peak demand at the critical storey and is therefore sensitive to soft-storey formation, the failure mode most characteristic of non-ductile moment frames. Roof drift ratio, used as the primary parameter in studies including Ahmad (2019), Akkar et al. (2005), Hedayat and Yalciner (2010), and Uprety and Paudel (2025), normalises roof displacement by total building height and therefore averages over the height of the structure, smoothing out the storey-level concentration of demand that defines non-ductile collapse. Global drift ratio, applied by Rasheed et al. (2022) among others, functions similarly. A threshold expressed as 2% roof drift and a threshold expressed as 2% maximum interstorey drift describe two different physical states for many non-ductile moment frames, since a non-uniform drift profile over height is common wherever a weak storey governs the response. These two threshold values are not directly comparable even when their numerical magnitude is identical, because they are measured on different physical quantities; comparing maximum interstorey drift to a height-averaged roof drift confounds peak-demand and mean-demand quantities, since the two measures are not interchangeable even when their numerical values coincide. This distinction is not always made explicit in the literature: studies that cite a drift-based threshold from a prior source do not always state whether the source's drift parameter is the same quantity as the one computed in the adopting study's own analysis.

5.2 Local, Cumulative, and Energy-Based Parameters

The limitations of a single global drift parameter have motivated a subset of studies to define thresholds at the component level, using chord rotation, plastic hinge rotation, or demand-to-capacity ratio as the engineering demand parameter. This component-level parameter appears in seven studies as a co-primary measure alongside interstorey drift, including Liel and Deierlein (2012), Baradaran Shoraka et al. (2013), and Elmorsy and Vamvatsikos (2025), rather than as a replacement for it. This dual-parameter approach implicitly acknowledges that global and local response can diverge: two buildings at the same interstorey drift can exhibit materially different chord rotations at the critical column end section if their member stiffness distributions, axial load ratios, or joint deformability differ. The component-level parameter captures this divergence; the global drift parameter does not.

Five studies adopt the Park-Ang damage index or a modification of it, either as the sole parameter or alongside interstorey drift, including Sengupta and Li (2016), El-Kholy et al. (2012), Badal and Sinha (2024), Adom-Asamoah (2012), and Carrillo et al. (2019). The Park-Ang index combines peak deformation with cumulative dissipated energy, accounting for loading history rather than only instantaneous demand. This is structurally significant for non-ductile members whose degradation is progressive: a column that has cycled through several moderate-amplitude displacement reversals may be in a worse physical state than one subjected to a single reversal of equal peak amplitude, a distinction invisible to any instantaneous drift-based threshold. The energy term, however, introduces a calibration parameter, the weighting factor between deformation and energy contributions, whose value is itself uncertain and varies with detailing quality. The Park-Ang index is therefore both more physically complete and more difficult to assign a universally applicable threshold to than a single deformation-based parameter.

A related but distinct local parameter is illustrated by Carrillo and Avila (2017), who define damage progression in lightly reinforced shear walls through the fractal dimension of the observed cracking pattern rather than through any deformation quantity directly. This measure shares the cumulative, history-dependent character of the Park-Ang index, since the cracking pattern at a given load step reflects the accumulated damage from all preceding cycles rather than only the instantaneous peak demand, but it substitutes a geometric description of physical damage for an energy-based one. Its use, alongside Carrillo et al.'s (2019) Park-Ang application to a structurally similar wall population, indicates that lightly reinforced shear walls have prompted a search for parameters beyond drift more consistently than most other structural classes considered in this review.

These local and energy-based parameters do not emerge arbitrarily; they emerge because different structural systems and failure mechanisms make a single global parameter insufficient. A component-level rotation parameter responds to the same need identified for shear- or joint-governed elements in the preceding section, while an energy-based or geometric damage index responds to the cumulative, history-dependent degradation that a single peak-demand measure cannot represent. The choice among these parameter types is therefore not a matter of methodological preference but a response to which physical process the analyst judges to govern the structure under study.

5.3 EDP–Structural System Compatibility

The choice of engineering demand parameter is not independent of the structural system being assessed. Among the six shear-wall studies identified in this review, only two use interstorey drift ratio as the sole parameter; the remaining four employ in-plane drift ratio, structural displacement, a Park-Ang or fractal-dimension-based index, or a demand-to-capacity ratio, a degree of EDP diversity not observed to the same extent in any other structural class. Ghaseminia et al. (2025) illustrate this diversity in its most pronounced form, reporting specimen-specific response without committing to a fixed threshold value transferable across wall configurations, on the grounds that the deformation capacity of lightly reinforced or limited-ductility walls is too sensitive to individual reinforcement layout to support a single generalised limit. This pattern is structurally coherent: a shear wall's deformation profile is governed by flexural and shear interaction over its full height rather than by discrete hinge formation at storey level, making interstorey drift a less natural descriptor of its damage state than it is for a moment frame.

Infilled frames present a related but distinct problem. The majority of infilled-frame studies in this review use interstorey drift as the primary parameter, yet the relationship between drift and component damage in an infilled frame differs from that in a bare frame. An infill panel that has cracked diagonally at a low drift level alters the stiffness and strength distribution of the storey, and a drift value recorded after infill failure reflects a structural system that is no longer the system to which the threshold was originally assigned. A subset of infilled-frame studies responds to this by adding or substituting a second parameter: Sattar and Liel (2016) define damage through a storey lateral-capacity ratio rather than drift alone, Requena-Garcia-Cruz et al. (2022) adopt chord rotation alongside drift to capture soil-structure interaction effects on local member demand, and Celarec et al. (2012) define their damage-limitation state through top displacement rather than storey-level drift. Each of these responses implicitly recognises that a single global parameter cannot distinguish between a storey whose infill is intact at a given drift and one whose infill has failed at the same drift.

Non-ductile moment frames show a comparable pattern: 6 of the 19 studies in this structural class (31.6%) define thresholds on interstorey drift combined with a second, mechanism-specific parameter, including Liel and Deierlein (2012), Baradaran Shoraka et al. (2013), Badal and Sinha (2024), Adom-Asamoah (2012), Unal et al. (2026), and Elmorsy and Vamvatsikos (2025). This proportion is consistent with the mechanism diversity established previously for this structural class, in which flexural, shear, joint, and bond failure can each govern the same nominal building type.

The pattern across the full set of reviewed studies is consistent: the more mechanism-dependent the structural system, the more likely a study is to supplement or replace interstorey drift with a component-level or cumulative parameter. This indicates that the engineering demand parameter and the damage-state threshold defined on it are not separable decisions. A threshold defined on maximum interstorey drift carries one set of physical assumptions about how damage accumulates and distributes through a structure; a threshold defined on chord rotation, a Park-Ang index, a fractal cracking measure, or a roof drift carries a different set. Reported variability in damage-state threshold values across the literature is therefore not attributable to differences in numerical threshold value alone. It also reflects differences in the underlying engineering demand parameter, the choice of which is itself shaped by framework origin, structural system, and governing failure mechanism, and which compounds with the divergence already documented across framework philosophy and structural classification to produce the wide variability in reported thresholds examined in the remainder of this review.

6. Inter-Study Divergence in Threshold Values

6.1 Comparative Analysis of Extracted Threshold Values

Among the 62 studies included in this review, 32 report a numerical damage-state threshold expressed on storey or interstorey drift ratio, the only parameter common enough across structural classes to support direct numerical comparison.

Table 1. Storey/interstorey drift ratio thresholds used in reviewed studies (†Collapse-only mechanistic criterion, no graded scale.)

Study	Country	Framework	DS1 (%)	DS2 (%)	DS3 (%)	DS4 (%)
Mixed / Other RC						
Yin et al. (2022)	Malaysia	HAZUS	0.5	1	1.5	2
Harati & van de Lindt (2024)	USA	HAZUS/archetype	0.40–0.80	1.00–2.00	2.50–5.00	—
Aljawhari et al. (2021)	Mediterranean	Study-specific	0.16–0.26	1.47–1.75	2.38–2.62	—
Pitilakis et al. (2014)	Greece	HAZUS/IDA	0.5	2.25–2.80	—	—
Carobeno et al. (2025)	Brazil	HAZUS/ATC-40	0.27–0.33	0.43–0.58	1.07–1.56	2.67–4.00
Pre-Code RC Frame						
Amirsardari et al. (2022)	Australia	ASCE 41/FEMA P-58	0.4	0.8	1.5	2
Tesfamariam & Goda (2015)	Canada	FEMA 356/P-58/Vision 2000	0.4	0.9	2.5	4.5
Cardone & Perrone (2017)	Italy	FEMA P-58	0.55–0.75	1.25–1.75	2.00–3.00	3.20–5.00
Rashid et al. (2024)	Kazakhstan	FEMA 356/HAZUS	0.44–0.46	1.43–1.53	2.30–2.47	3.45–3.72
Harati & van de Lindt (2025)	USA	HAZUS 2020	0.45–0.90	1.15–2.30	3.00–6.00	—
Kyaw & Mon (2025)	Myanmar	FEMA 356	0.5	1	1.5	2
RC Infilled Frame						
Fikri & Ingham (2022)	New Zealand	Cardone & Perrone / Elwood & Moehle	0.15	0.4	1	1.75

Rossetto & Elnashai (2005)	Italy/Europe	HRC scale	0.05	0.08	0.3	1.15
Radman Ahmed et al. (2025)	Yemen	FEMA 356	1	2	4	—
Nafeh & O'Reilly (2024)	Italy	NTC 2018/study-specific	0.16	0.29	—	—
Mucedero et al. (2022)	Italy	Study-specific	—	—	—	5
Ahmad et al. (2014) [a] — bare	Pakistan	Rossetto & Elnashai (2003)	0.44	0.8	1.16	2.05
Ahmad et al. (2014) [a] — infilled	Pakistan	Rossetto & Elnashai (2003)	0.08	0.24	0.57	1.39
RC Shear Wall / Core-Wall						
Amirsardari et al. (2019)	Australia	ASCE 41/FEMA P-58	0.4	0.8	1.5	2
Sengupta & Li (2016)	Singapore	Study-specific	0.124–0.133	0.311–0.333	0.497–0.533	1.243–1.334
Non-Ductile RC Moment Frame						
Liel & Deierlein (2012) [b]	USA	Study-specific	—	—	—	3.00–6.00
Adom-Asamoah & Osei (2018)	Ghana	HAZUS	0.5	0.8	2	5
Baradaran Shoraka et al. (2013)	USA	ATC-58-informed	2.80–3.40	4.20–4.80	5.30–8.90	—
Jeon et al. (2015)	USA	HAZUS-informed	0.5	0.90–1.00	2.00–3.50	4.50–6.00
Khan & Rizwan (2024)	Pakistan	ATC/FEMA 273/HAZUS	0.5	1.26	1.88	2.5
Elmorsy & Vamvatsikos (2025)	Generic	FEMA 356/ASCE 41	1	2	4	—
Sharafi & Saito (2024)	Afghanistan	JSCA	0.33	0.67	1	1.33
Gravity-Load-Designed RC Frame						
Celik & Ellingwood (2008)	USA	MAE Centre	0.25	2	4	—
Celik & Ellingwood (2010)	USA	MAE Centre	0.20–0.30	2	3.60–5.00	—
El-Kholy et al. (2012)	Egypt	FEMA 356/Park-Ang	1	2	4	—
Rajeev & Tesfamariam (2012)	Europe	Prior GLD study	0.50–0.75	2.5	3.60–5.00	—
Ellingwood et al. (2007)	USA	Study-specific/HAZUS	0.25	2	4.00–4.80	—
Zucconi et al. (2022)	Italy	HAZUS/Borzi	0.4	0.6	1.6	1.6
Yu et al. (2024)	China	Study-specific/FEMA P-58	0.41–0.57	0.73–0.97	1.04–1.35	1.31–1.63

[a] The bare-frame and infilled-frame configurations of Ahmad et al. (2014) are presented as separate rows reflecting structurally distinct response characteristics; both rows correspond to a single study in the reviewed literature total of 62.

[b] Liel and Deierlein (2012) define collapse through a mechanistic criterion rather than a graded damage scale and contribute only to the final-state divergence analysis.

A further four studies define thresholds on roof or global drift ratio, a related but physically distinct quantity that is reported separately to avoid conflating two measures that respond differently to a non-uniform deformation profile over building height.

Table 2. Roof/global drift ratio thresholds reported in reviewed studies.

Study	Class	Country	Framework	DS1	DS2	DS3	DS4
Ahmad (2019)	Non-Ductile RC MF	Pakistan	FEMA/experimental	0.78%	1.30%	2.50%	3.70%
Akkar et al. (2005)	Non-Ductile RC MF	Türkiye	Study-specific	0.11–0.12%	0.68–0.90%	0.90–1.20%	—
Hedayat & Yalciner (2010)	Non-Ductile RC MF	Cyprus	FEMA 356/Yakut	0.48%	1.34%	2.00%	—
Rasheed et al. (2022)	Pre-Code RC Frame	Pakistan	Zain et al. (2019)	0.35%	0.66%	0.89%	—

The remaining studies define thresholds on spectral displacement, chord rotation, the Park-Ang damage index, plastic-hinge percentage, or other parameters that cannot be placed on the same numerical axis as drift without an additional, generally unstated, conversion assumption, and are accordingly treated qualitatively rather than tabulated alongside the drift-based set. Studies reporting fewer than four damage states contribute to the divergence analysis only at the states they define; Mucedero et al. (2022) and Liel and Deierlein (2012) each report a single collapse-adjacent threshold and therefore appear only in the final-state analysis. Of the six shear-wall studies in the reviewed literature, four define thresholds on parameters other than storey or interstorey drift ratio and do not appear in Table 1; the drift-based divergence analysis for this structural class consequently rests on two studies only.

DS1 divergence. The slight-damage threshold, illustrated in Fig. e, varies markedly by structural class. Infilled frames produce the widest spread among the six classes, with values ranging from a fraction of a percent of interstorey drift in studies calibrated on the early onset of infill cracking to roughly an order of magnitude higher in studies addressing bare-frame or less infill-sensitive populations. Non-ductile moment frames show a narrower but still substantial range, with most reported values clustering at the lower end and a small number of outlying studies reporting slight-damage thresholds several times higher than this cluster. Gravity-load-designed and pre-code frames show comparatively tighter clustering at this damage state than infilled frames or non-ductile moment frames, a pattern consistent with the narrower range of threshold sources typically applied to these two classes.

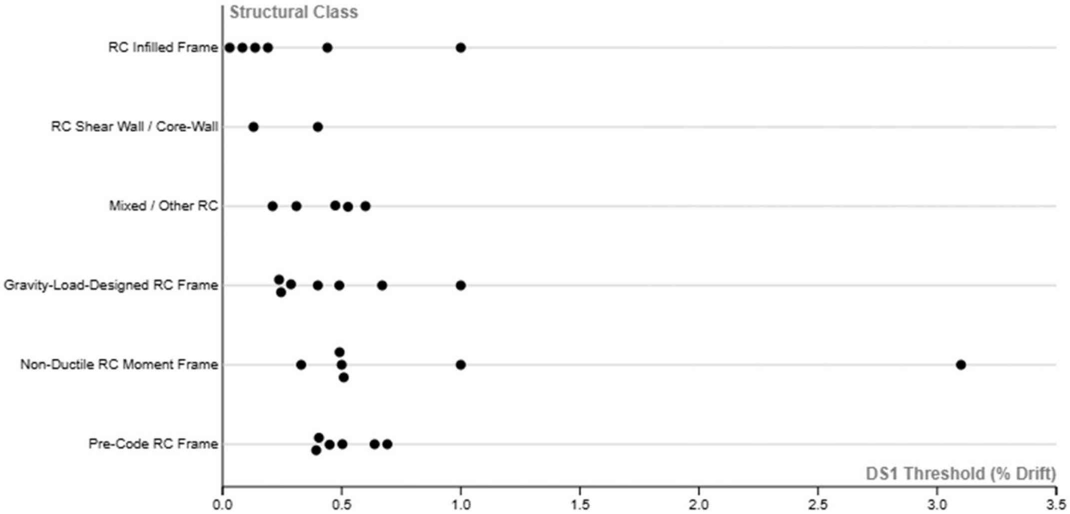

Fig. e. Distribution of DS1 drift thresholds by structural class. Reported ranges were represented by midpoint values for visualisation; original ranges are preserved in Table 1.

The clustering visible in Fig. e is not simply a matter of dispersion around a population mean; it reflects a pattern suggesting two apparent sub-groups within each structural class, one anchored to a code-based or expert-consensus threshold and one derived independently through study-specific calibration, that happen to share the same axis but do not necessarily describe the same physical onset of damage.

Final-state divergence. The pattern at the highest reported damage state, shown in Fig. f, is structurally similar but proportionally larger. Infilled frames again show the widest spread of any class, spanning from studies that define their highest reported state at a comparatively low drift value to others that extend their scale to a collapse-adjacent threshold several times larger. Non-ductile moment frames show a comparable pattern, with the upper bound of the reported range driven by a small number of studies that define damage progression through to near-collapse conditions rather than stopping at a moderate or extensive damage state. Gravity-load-designed and pre-code frames again cluster more tightly than the infilled-frame and non-ductile classes, though the absolute spread at this damage state is larger in every class than the corresponding spread at the slight-damage state.

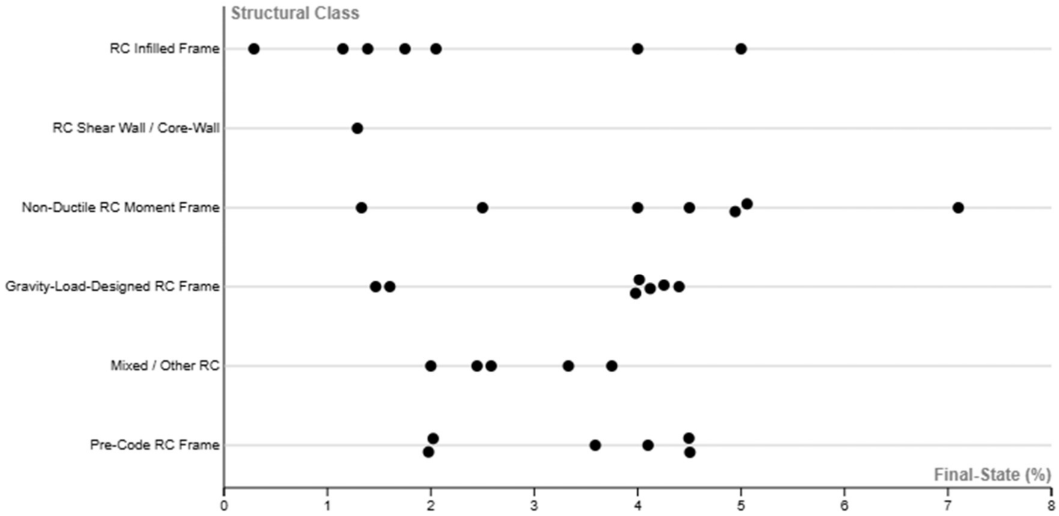

Fig. f. Distribution of final-state drift thresholds by structural class. Final-state thresholds correspond to the highest drift-based damage state reported by each study; reported ranges were represented by midpoint values for visualisation, with original ranges preserved in Table 1.

Figures e and f together suggest that the spread in reported threshold values increases from slight to final damage states across most structural classes, though a formal quantitative comparison is constrained by the unequal number of drift-based studies per class per damage state. If divergence at the slight-damage state reflected only differences in initial cracking criteria, the spread might be expected to narrow at the more severe states, where physical damage is more visibly defined; the visual pattern in both figures is instead consistent with the choice of threshold framework and engineering demand parameter exerting a growing rather than diminishing influence as the damage state approaches collapse.

Framework and EDP explanation. This pattern is not randomly distributed across the reviewed literature; it tracks the framework origin and engineering demand parameter distinctions established earlier in this review. Studies whose threshold source is named as HAZUS or a HAZUS-derived archetype, including Adom-Asamoah and Osei (2018), Jeon et al. (2015), and Khan and Rizwan (2024), cluster tightly around the slight-damage value HAZUS assigns to a generic moment-frame building class, a value that does not distinguish detailing quality within that class (Federal Emergency Management Agency 2012a). Studies whose threshold is derived through FEMA P-58 component logic, including Cardone and Perrone (2017), report a noticeably higher slight-damage value, reflecting a different unit of analysis rather than a different physical population (Federal Emergency Management Agency 2012b). Rossetto and Elnashai's (2005) outlying low value originates from a displacement-based vulnerability procedure calibrated on a population of older, low-rise infilled frames using a macroseismic-derived scale rather than a HAZUS- or ASCE 41-type drift table, illustrating directly that the position of a threshold within Table 1's range is frequently explained by which framework supplied it rather than by a documented structural difference between the buildings under study.

The width of these ranges carries a specific consequence for fragility curve construction. A fragility function is defined by the probability of exceeding a threshold as a function of intensity measure, and the median of that function is anchored directly to the threshold value adopted. The spread documented in Table 1, even before any difference in ground-motion suite, analysis method, or statistical fitting procedure is introduced, implies that two analysts assessing structurally similar buildings could report substantially different exceedance probabilities at a common intensity level, purely as a function of which threshold value each adopted from the literature.

6.2 Controlled Comparisons: Threshold Effects on Fragility Predictions

The comparisons of greatest diagnostic value are those in which the structural population, and frequently the authorship, are held constant while the threshold framework or its application evolves. Two such pairs exist within the reviewed literature, one fully controlled and one near-controlled.

Celik and Ellingwood published fragility assessments of gravity-load-designed reinforced concrete frames in (2008) and again in (2010), using the same MAE Centre archetype basis on both occasions. The (2008) study reports a fixed extensive-damage threshold, corresponding to DS3 in Table 1; the (2010) study, which explicitly separates aleatoric and epistemic uncertainty sources and introduces height-dependent treatment of the same archetype population, reports the equivalent threshold as a range of 3.60–5.00%, spanning roughly one-third of its midpoint value (Table 1). Only the moderate-damage threshold remains fixed between the two studies at 2.00% drift in both cases; the slight-damage threshold shifts from a fixed 0.25% in 2008 to a range of 0.20–0.30% in (2010), indicating that height-dependent uncertainty was introduced at this state as well. The divergence at the extensive-damage state is therefore attributable to a methodological refinement — the explicit decomposition of uncertainty and the introduction of height-dependence — rather than to any re-assessment of the underlying structural population. This pair demonstrates that threshold divergence can arise even in the complete absence of disagreement about the structure being assessed, making it the clearest available evidence in this review that threshold divergence is, at least in part, a reflection of methodological sensitivity rather than purely of genuine population diversity.

Harati and van de Lindt produced two further fragility studies, in (2024) and (2025), addressing related populations of reinforced concrete frame archetypes under successive seismic and hazard sequences. The threshold values reported in the later study are systematically higher than those in the earlier study at both the slight- and extensive-damage states (Table 1), and the (2025) study, addressing a more narrowly defined pre-code population using a machine-learning-based fragility-surface approach, also classifies its archetype population differently from the earlier paper, with the earlier study's frames recorded as a mixed or generically defined reinforced concrete class and the later study's as specifically pre-code. Because the structural classification itself shifts between the two papers, this pair is better described as a near-controlled rather than a fully controlled comparison: part of the threshold difference may reflect a genuine narrowing of the population under study rather than a methodological change alone. Even allowing for this caveat, the shift illustrates that the boundary of which threshold framework or building class applies to a given archetype is not a fixed determination but one that can move with the analytical approach adopted by the same authors within a single year.

Both pairs point to the same underlying mechanism, with differing degrees of certainty. Threshold divergence in the literature is not confined to disagreement between independent research groups working on nominally similar but actually distinct buildings. The fully controlled pair demonstrates that it persists, at a magnitude large enough to materially affect a fragility curve's reported median, even when authorship, archetype basis, and broad structural population are held constant, and the only variable that changes is the analytical or classification choice made by the same researchers between two publications. The near-controlled pair suggests the same mechanism operates even where some genuine refinement of the studied population accompanies the methodological change, though the two influences cannot be fully separated from the published record alone.

6.3 Implications for Loss Estimation and Risk Assessment

The threshold divergence documented above does not remain a methodological curiosity once a fragility curve is used for its intended purpose, which in many of the reviewed studies is to inform a loss estimate, a retrofit prioritisation decision, or a post-earthquake risk classification. A fragility curve's median is the primary determinant of the probability mass assigned to each damage state at a given hazard level, and because loss is typically computed as a damage-state-weighted sum of repair or replacement costs, a shift in the threshold that defines a damage state propagates directly into the expected loss computed for that level of shaking (Federal Emergency Management Agency 2012a). Cardone and Perrone (2017) and Baradaran Shoraka et al. (2013) both carry their threshold-based fragility assessments through to explicit loss estimation, and Ramos et al. (2026) extend this pathway further by incorporating non-structural and contents losses into a regional risk assessment built on the same drift-based damage-state logic. In each case, the magnitude of divergence documented in Table 1, applied within the study's own loss framework, would be sufficient to shift the building from one nominal damage-state bracket to an adjacent one at a fixed hazard level, with a corresponding change in estimated repair cost or loss ratio that has nothing to do with the building's actual physical condition.

This has a specific and consequential implication for risk-informed decisions that depend on a binary or near-binary threshold crossing rather than a continuous loss estimate. Post-earthquake building tagging, retrofit eligibility determinations, and insurance-triggering damage classifications may rely on whether a recorded or predicted drift exceeds a specific damage-state boundary, most often the boundary separating moderate from extensive or significant damage, the threshold pair most directly analogous to life-safety and collapse-prevention decisions under ASCE 41 (American Society of Civil Engineers 2017). Khan and Rizwan (2024, 2025) and Liel and Deierlein (2012) all frame their fragility and collapse-risk results explicitly around retrofit and policy decisions for older, code-deficient reinforced concrete stock, the precise decision context in which a threshold boundary functions as a trigger rather than as one point on a continuous loss curve. Where this boundary is reported at a markedly lower drift value by one framework-derived study than by another addressing a structurally similar non-ductile population, as the ranges in Table 1 demonstrate occur in practice, the same recorded drift value could be classified as having exceeded or not exceeded the relevant damage state purely as a function of which study's threshold the assessing engineer, retrofit programme, or loss model happened to adopt.

The mechanism-dependent failure modes that characterise non-ductile reinforced concrete construction compound this problem rather than mitigating it. Where a threshold is calibrated on a flexure-governed archetype but applied to a structure whose actual response is governed by column shear, joint shear, or lap-splice bond failure, the divergence is not merely a difference between two published numbers but a mismatch between the threshold's calibration basis and the physical mechanism actually occurring in the assessed building, a distinction with direct consequences for which engineering demand parameter the threshold should have been defined on in the first place. Opabola et al. (2021) and Jeon et al. (2015) both demonstrate that the deformation capacity associated with a given nominal damage state shifts substantially according to which mechanism governs, meaning that the loss or risk estimate produced by applying a borrowed threshold to a non-ductile structure carries an additional layer of uncertainty beyond the inter-study divergence quantified in Table 1, one that is rarely propagated explicitly into the reported loss or risk output that ultimately reaches a retrofit programme, an insurer, or a post-earthquake tagging team.

Taken together, the comparative analysis in Table 1 and Table 2, the controlled and near-controlled author-held-constant pairs, and the downstream loss-estimation pathway indicate that threshold divergence in the seismic fragility literature on non-ductile reinforced concrete buildings is neither small in magnitude nor confined to disagreement between unrelated studies. It is large enough, even within a single structural class and even within the work of a single author pair, to alter the classification of identical structural response, and it propagates without correction into the loss and risk estimates that this literature is ultimately produced to inform.

7. Transferability of Threshold Definitions to Non-Ductile RC Buildings

7.1 Current Practice: Prevalence and Transparency of Threshold Transfer

Disclosure of threshold values themselves is, on the whole, adequate across the reviewed literature: 49 of the 62 included studies report full numerical values for every damage state they define, a further 11 report partial values, ranges, or formulae from which a value can be derived, and only two studies cite a threshold source without reporting any value at all (Hamidia and Ganjizadeh 2022; Pavel and Florescu 2026). The more consequential transparency gap lies not in whether a value is reported but in whether the reasoning behind adopting that value, rather than deriving it independently, is disclosed.

Some form of threshold transfer from an external framework or a prior study occurs in 48 of the 62 reviewed studies, against 14 that derive thresholds independently through study-specific calibration. Transfer is therefore the modal practice in this literature rather than the exception, a pattern consistent with the framework-distribution finding established earlier in this review, in which adaptation of an existing framework outweighs independent derivation as a route to a usable threshold set even among studies that ultimately depart from the source framework's published values. Of the 48 studies in which transfer occurs, the majority transfer a threshold outright and state the source explicitly (39 studies). A further five transfers with the source implied rather than stated, or combine implied sourcing with partial modification. Two studies transfer with explicit structural modification to adapt the source framework to the population under study. One study transfer partially, and one, Carrillo et al. (2019), represents a documented departure in the opposite direction: the authors explicitly reject the original Park-Ang damage index formulation on the stated grounds that it was calibrated mainly for flexure-dominated reinforced concrete members, and recalibrate the index for squat, thin, lightly reinforced shear walls whose governing mechanism is shear rather than flexure. This is the clearest example in the reviewed literature of a researcher identifying a mechanism mismatch between a source framework's calibration basis and the population under study, and responding by recalibrating rather than transferring the threshold unchanged.

Where transfer occurs, the justification accompanying it is frequently incomplete rather than absent outright. Of the 48 studies that transfer a threshold, 16 provide a full structural or empirical justification for why the transferred value is considered appropriate to the population being assessed, 28 provide partial justification, typically a citation to the source framework combined with a brief structural rationale rather than a demonstrated equivalence, and a small remaining group, four studies, provide no justification beyond the citation itself (El-Kholy et al. 2012; Adom-Asamoah and Osei 2018; Avulapalle et al. 2023; Radman Ahmed et al. 2025). These four are not unusual in their conclusions or analytical method; what distinguishes them is only that the transfer step, present in the substantial majority of the reviewed literature, happens here without any accompanying argument, making explicit a gap in justification that more commonly remains only partially addressed elsewhere in the reviewed literature. The overall pattern, full justification in roughly a third of transferring studies, partial justification close to two-thirds, and no justification in a small residual group, suggests that transparency about transfer is treated as a methodological courtesy in this literature rather than as a verifiable condition for using a borrowed threshold.

7.2 Structural and Contextual Variables Governing Threshold Validity

Whether a transferred threshold retains its intended physical meaning depends on at least four variables that recur, with varying degrees of explicit treatment, across the reviewed literature: the detailing quality of the source population relative to the population under assessment, the failure mechanism each was calibrated to represent, the compatibility of the engineering demand parameter used in both studies, and the transparency with which the adopting study discloses its reasoning on the first three. These four variables are interdependent rather than separable, but each can fail independently, and the reviewed literature contains illustrations of each kind of failure.

Detailing quality is the variable most frequently acknowledged, if inconsistently applied. HAZUS-derived thresholds, used by Adom-Asamoah and Osei ((2018), Jeon et al. (2015), and Khan and Rizwan (2024) among others, originate from a building classification that distinguishes design era but not detailing quality within an era, a limitation discussed earlier in this review and one that several adopting studies note in general terms without quantifying its effect on the specific threshold transferred. Eurocode 8 Part 3 and ASCE 41 encode a binary detailing distinction directly into their deformation-capacity computation, providing the closest equivalent among the reviewed frameworks to an explicit detailing-quality check, though even this distinction does not discriminate among the range of non-ductile failure mechanisms documented earlier (European Committee for Standardization 2005; American Society of Civil Engineers 2017).

The governing failure mechanism is the variable least consistently addressed despite being, on the evidence reviewed here, the most consequential. Jeon et al. (2015) and Opabola et al. (2021) both demonstrate that deformation capacity at a nominally identical damage state differs substantially according to whether flexure, shear, joint failure, or lap-splice bond failure governs the response, yet most transferred thresholds in the reviewed literature carry no accompanying statement of which mechanism the source threshold was calibrated to represent, nor any verification that the same mechanism governs the population to which it is applied.

Engineering demand parameter compatibility interacts with both of the preceding variables rather than operating independently of them. A threshold transferred correctly in terms of detailing and mechanism can still lose its physical meaning if the demand parameter on which it was originally defined, roof drift, chord rotation, or a component-level capacity ratio, is not the same quantity as the one computed in the adopting study, a distinction established earlier in this review and equally relevant to the question of transfer.

Structural system type provides the clearest illustration of how these variables can diverge without an accompanying change in the transferred value. Amirsardari et al. (2019) and Amirsardari et al. (2022), the same author group, report an identical threshold set, 0.40%, 0.80%, 1.50%, and 2.00% drift at the four respective damage states, for two structurally distinct populations: a reinforced concrete shear-wall and core-wall system in the earlier paper and a pre-code reinforced concrete moment frame in the later one. A shear wall's deformation is governed by combined flexural and shear interaction distributed over its full height, while a moment frame's deformation, particularly where capacity design is absent, is governed by discrete hinge or shear-failure formation at storey level, a distinction this review has already established as structurally consequential for damage-state definition. The repetition of an identical threshold set across these two systems is not, on its own, evidence of an error; it more plausibly reflects how readily an established threshold set can be carried forward into a new study without independent re-derivation, even where the structural system under consideration changes materially between publications, and where the published account does not state explicitly why deformation-capacity equivalence should be expected to hold across both systems.

7.3 Conditions for Defensible and Non-Defensible Transfer

The pattern across earlier two sections suggests that threshold transfer in this literature sits along a spectrum rather than dividing cleanly into acceptable and unacceptable practice, and the four governing variables identified above offer a basis for locating a given transfer along that spectrum rather than a binary test. A transfer is best supported where detailing quality and governing mechanism in the source and adopting populations are shown to correspond, where the engineering demand parameter is held constant between the two, and where the adopting study states explicitly which of these correspondences it is relying upon. Cardone and Perrone (2017) illustrate this combination directly: rather than applying the FEMA P-58 component fragility library to pre-1970 Italian reinforced concrete frames unmodified, they document the library's insufficient representativeness for that population's deficient detailing and develop experimental fragilities specific to it, retaining the FEMA P-58 damage-logic structure while replacing its component-level calibration with one matched to the population actually under assessment (Federal Emergency Management Agency 2012b). Carrillo et al. (2019) meet the same standard from a different direction, identifying a mechanism mismatch between the Park-Ang index's flexure-dominated calibration basis and a shear-governed wall population, and recalibrating rather than transferring the index unchanged.

Where one or more of the four variables is left unaddressed and undisclosed, the basis for the transfer becomes correspondingly harder to evaluate, though the available evidence does not always permit a confident judgement that the transfer is wrong, only that it is unverifiable from the published account. The small group of studies that transfer a threshold with no accompanying justification at all (El-Kholy et al. 2012; Adom-Asamoah and Osei 2018; Avulapalle et al. 2023; Radman Ahmed et al. 2025) represents the clearest case of this kind, since no basis is offered on which a reader could assess whether the source population's detailing or mechanism corresponds to the population being assessed. The Amirsardari pair illustrates a softer version of the same problem: justification is present in each paper in general terms, yet the repetition of an identical threshold set across a shear-wall and a moment-frame population, without an explicit statement addressing why deformation-capacity equivalence should hold across two systems with different governing mechanisms, leaves the transfer's structural basis open to question rather than demonstrably unsound.

A further form of threshold transfer occurs when generic framework equations are applied across structurally different systems without independent verification that the assumed damage-state locations remain physically representative. This practice appears not only in studies adopting thresholds directly from previous literature but also in studies that generate system-specific numerical values through generic interpolation rules. For example, HAZUS-based yield–ultimate interpolation equations have been applied to bare frames, open-ground-storey infilled frames, shear-wall systems, jacketed frames, and braced frames while retaining the same assumed relative locations of damage states along the capacity curve (Avulapalle et al. 2023). A related pattern is observable in Sharafi and Saito (2024), whose reported threshold values of 0.33, 0.67, 1.00, and 1.33 percent drift are exactly evenly spaced at one-third percent intervals. This arithmetic regularity is inconsistent with independent calibration from pushover or incremental dynamic analysis results, which rarely produce values of such uniform spacing, and is more consistent with linear interpolation between assumed endpoints. Like the generic interpolation practice identified above, this illustrates that threshold generation through mathematical convention, rather than through structural evidence, can produce values that appear numerically precise while remaining physically unanchored to the system under assessment.

The practical implication for this review's broader argument is that transferability cannot be assessed, by a reader or by a subsequent researcher seeking to reuse a published threshold, from the threshold value alone. Two studies reporting numerically identical or near-identical thresholds, as Table 1 demonstrates occurs repeatedly across the reviewed literature, may still differ in whether that value is well supported for a given non-ductile reinforced concrete population, depending on documentation that the threshold value itself does not carry. Where detailing quality, governing mechanism, and demand parameter are addressed and disclosed, as in Cardone and Perrone (2017) and Carrillo et al. (2019), the transfer or its rejection can be evaluated on its structural merits. Where this documentation is thin or absent, the threshold functions less as a verified description of the structure it is applied to and more as a number carried forward from elsewhere, with the reasoning that would establish its applicability left for the reader to supply.

8. Discussion, Limitations, and Future Directions

8.1 What the Collective Evidence Reveals

Taken together, the preceding sections indicate that damage-state threshold definition functions, in current seismic fragility practice, as a methodological step subordinate to model construction, ground-motion selection, and statistical fitting, rather than as a primary determinant of the resulting fragility prediction in its own right. This ordering of priorities is not supported by the evidence assembled in this review. The threshold values examined across the 62 reviewed studies originate from five named calibration frameworks plus a substantial residual category of hybrid and study-specific derivations, the latter accounting for 45.2% of the reviewed studies and representing the largest single grouping, and none of these sources was developed with a non-ductile, gravity-load-designed, or code-deficient reinforced concrete population as its primary target, and reported values for nominally equivalent damage states diverge by a magnitude sufficient to alter exceedance probabilities substantially at a common hazard level. Roughly three-quarters of the reviewed studies transfer a threshold from an external source rather than deriving one independently, and where transfer occurs, full structural justification for the transferred value is provided in only a third of cases. A methodological choice with this much latitude and this little routine scrutiny is not a secondary input to fragility assessment; it is a primary one, comparable in its influence on the final result to the choice of ground-motion suite or analysis method, yet it does not currently receive comparable methodological attention in the way fragility studies are designed, reported, or reviewed.

The consequences of this asymmetry are not confined to the academic literature. Parizat et al. (2024) provide a documented instance of exactly the failure mode this review's evidence predicts: applying generic HAZUS fragility curves to pre-code reinforced concrete apartment buildings in Israel, a population the original HAZUS calibration was never intended to represent, produced a fragility estimate the authors themselves conclude overestimates the building's actual seismic resilience, with direct implications for household displacement projections in a national risk model. This is not a hypothetical concern raised here in the abstract; it is a documented case in which a borrowed threshold, applied to a structurally distinct population without local recalibration, produced a risk estimate that a subsequent reassessment found to be unconservative. Where threshold divergence of the magnitude documented in this review intersects with risk-informed decisions, retrofit prioritisation, post-earthquake tagging, or insurance-relevant loss estimation, the consequence is not an abstract loss of precision but a concrete possibility that the decision reached depends on which study's threshold happened to be adopted, independent of the actual physical condition of the building being assessed. This concern applies with particular force to the regions represented in the reviewed sample, spanning South and Central Asia, the Mediterranean, and other settings where non-ductile or pre-code reinforced concrete construction remains in active use, since these are precisely the contexts in which a risk estimate is most likely to inform a real retrofit or insurance decision rather than remaining a purely academic exercise.

8.2 Limitations

This review is subject to several methodological boundaries that should inform the interpretation of its findings. The primary databases used were Dimensions and Google Scholar, rather than Scopus or Web of Science, due to institutional access constraints; while Dimensions indexes a broad peer-reviewed literature and the search strategy was supplemented by citation chaining from a seed set of well-established fragility studies, some relevant publications indexed exclusively in other databases may not have been captured. The search was restricted to peer-reviewed journal articles and primary framework documents; conference papers, technical reports, and these were excluded, which may underrepresent early or practice-oriented fragility work, particularly from PEER, WCEE, and related proceedings where non-ductile RC assessment has a significant presence. The review was conducted in English, and studies published in other languages were not included, introducing a potential geographic bias toward English-language research traditions.

No formal quality-assessment instrument was applied to the included studies. The transparency and justification analysis performed in this review addresses one dimension of study quality — the rigour of threshold sourcing — but does not constitute a comprehensive methodological appraisal of each study's analytical choices, ground-motion selection, or statistical fitting procedures. Screening and data extraction were performed by the lead author with independent verification of a proportion of records by a second author; formal inter-rater reliability statistics were not computed. The two-tier extraction approach, which retains studies that cite a threshold without reporting its value, avoids one form of selection bias but introduces asymmetry in the depth of data available across the two tiers. Finally, the divergence analysis in this review is descriptive rather than causal: the observed spread in threshold values across studies reflects the combined influence of structural population differences, framework-origin effects, regional methodological traditions, and genuine modelling choices, and these contributions cannot be fully separated from the published record alone.

8.3 Future Directions

Three directions follow from this assessment, each addressing a distinct point in the gap between current practice and the standard the evidence here suggests is needed.

The first is system-specific experimental calibration for non-ductile construction classes, rather than continued reliance on thresholds developed for ductile or generically classified populations and applied to non-ductile structures by assumption. Cardone and Perrone (2017) and Carrillo et al. (2019) already demonstrate, within the reviewed studies, that this is achievable: both identify a mismatch between a source framework's calibration basis and the population under study, and recalibrate rather than transfer the threshold unchanged. Dede et al. (2025), working on tunnel-form construction, reach the same conclusion independently after finding that no existing damage scale adequately represented that structural typology, and that prior studies in the same field had been transferring thresholds from unrelated systems. The pattern across both examples indicates that bespoke calibration is not merely desirable in principle but achievable in practice once a mismatch between a borrowed threshold and the population under study is explicitly identified, and that the more substantial barrier is the initial recognition that such a mismatch exists rather than any inherent infeasibility in the calibration work itself.

The second direction is standardised reporting requirements for threshold justification, addressing a gap already established in this review: among studies that transfer a threshold from another source, the majority provide only partial justification and a small remaining group provide none. A minimum disclosure standard, requiring an adopting study to state the source population's detailing quality, governing failure mechanism, and engineering demand parameter alongside the transferred value, would not prevent transfer, nor should it, since transfer of a well-matched threshold is legitimate and often unavoidable given the practical constraints on component testing. It would instead make the basis for transfer auditable by a reader in the way the threshold value itself currently is and the reasoning behind adopting it currently is not.

The third direction is sensitivity analysis of threshold choice as a routine component of fragility assessment, rather than an occasional methodological refinement. Opabola, Liel and Elwood (2024) provide direct precedent for this recommendation, demonstrating that accounting for failure-mode uncertainty, a closely related source of variability to the threshold uncertainty documented throughout this review, can shift median collapse fragility by more than twenty percent and fifty-year collapse risk by at least thirty percent. If failure-mode uncertainty alone produces shifts of this magnitude, the threshold divergence documented across the reviewed studies, often exceeding that magnitude within a single structural class, warrants comparable treatment. Reporting a fragility curve's sensitivity to the threshold values adopted, alongside its sensitivity to ground-motion selection and structural modelling assumptions, would allow a reader to assess how much of a given study's conclusion depends on a threshold choice that, as this review demonstrates, is frequently inherited rather than independently established.

9. Conclusions

This review set out to examine how damage-state threshold definitions are sourced, applied, and justified in seismic fragility assessment of non-ductile reinforced concrete buildings, and to determine whether the divergence in reported threshold values reflects genuine structural differences between studied populations or methodological artefacts of framework origin, demand parameter selection, and transfer practice. The evidence assembled across 62 systematically reviewed studies supports four conclusions.

First, the threshold values in current use originate from five named calibration frameworks, expert consensus, field observation, code-based performance levels, mechanics-based component derivation, and experimental component fragility, plus a substantial residual category of hybrid and study-specific derivations that accounts for 45.2% of the reviewed studies and represents the largest single grouping. None of these sources was developed with a non-ductile, gravity-load-designed, or code-deficient reinforced concrete population as its stated primary target. Nearly half of the reviewed studies depart from any single named framework altogether, adopting hybrid, modified, or independently derived thresholds instead, indicating that researchers working on this structural population frequently treat established frameworks as a starting point rather than a directly applicable source.

Second, reported threshold values for nominally equivalent damage states diverge substantially across the reviewed literature, and this divergence appears to increase rather than narrow as damage progresses from slight to severe states, on the basis of the visual pattern observed across the reviewed studies. The divergence is attributable in part to genuine differences in the structural populations under study, but controlled comparisons in which authorship and archetype basis are held constant demonstrate that a comparable magnitude of divergence can arise from methodological refinement alone, independent of any change in the building being assessed.

Third, threshold transfer from an external source is the dominant practice rather than the exception, occurring in the substantial majority of reviewed studies, yet the justification accompanying that transfer is frequently partial and occasionally absent. Detailing quality, governing failure mechanism, and engineering demand parameter compatibility emerge as the structural variables that determine whether a transferred threshold retains its intended physical meaning, and the available evidence indicates that these variables are inconsistently addressed and disclosed across the reviewed literature.

Fourth, this pattern of underspecified transfer and divergent values is not a methodological curiosity confined to the academic literature. Where threshold-dependent fragility outputs feed retrofit prioritisation, post-earthquake tagging, or loss estimation, a borrowed threshold's mismatch with the structural population it is applied to can shift a real risk-informed decision in a documented and consequential way.

Damage-state threshold definition, on the evidence presented here, functions as a primary determinant of fragility prediction rather than a secondary methodological choice, and the seismic risk assessment of non-ductile reinforced concrete buildings would benefit from treating it accordingly: through system-specific calibration where existing frameworks demonstrably do not represent the population under study, through reporting standards that make the basis for threshold transfer auditable, and through routine sensitivity analysis that exposes how much of a given fragility prediction depends on a threshold choice that is, more often than not, inherited rather than independently established.

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Statements and Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Muhammad Abubakar conceived the study, developed the review methodology, designed the data-extraction framework, conducted the literature search and screening process, performed data curation and formal analysis, prepared the visualisations, and wrote the original manuscript draft. Muhammad Awaib contributed to the literature search, study screening, data extraction, and preparation of the original manuscript draft. Faheem Butt supervised the research, provided academic guidance, critically reviewed the manuscript, and contributed to editing and refinement of the final version. Ibrahim contributed to data curation and validation of extracted threshold values All authors read and approved the final manuscript.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Code Availability

Not applicable.

Ethics Approval

Not applicable. This study is based exclusively on published literature and does not involve human participants or animals.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.