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SEISMIC PERFORMANCE ASSESSMENT OF REINFORCED CONCRETE BUILDINGS USING PERFORMANCE-BASED DESIGN

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Abstract
Performance-Based Seismic Design (PBSD) has emerged as a robust framework for evaluating and improving the seismic performance of reinforced concrete buildings by explicitly linking seismic hazard, structural response, and performance objectives. This study presents a comprehensive performance-based seismic assessment of reinforced concrete buildings subjected to multiple earthquake hazard levels. Nonlinear structural response is evaluated using peak and residual interstory drift ratios as primary engineering demand parameters, enabling systematic classification of structural performance in terms of Immediate Occupancy, Life Safety, and Collapse Prevention. Analytical results are mapped to ASCE 41–style drift acceptance criteria to provide a transparent interpretation of performance intent. The study further extends traditional performance evaluation by incorporating probabilistic exceedance assessment and consequence-based metrics, including repair cost ratio and post-earthquake downtime. Results demonstrate that while the majority of analysed cases satisfy Immediate Occupancy objectives at lower hazard levels, increasing seismic intensity leads to a measurable shift toward Life Safety performance, accompanied by significant increases in economic loss and recovery time. Residual drift is identified as a key driver of prolonged downtime, highlighting its importance in resilience-oriented seismic design. Overall, the proposed framework integrates structural performance, probabilistic assessment, and consequence evaluation, offering a practical and decision-oriented methodology for performance-based seismic assessment of reinforced concrete buildings.

Introduction
Seismic design philosophy has evolved significantly over the past several decades, transitioning from prescriptive force-based approaches toward performance-oriented frameworks that explicitly consider damage, functionality, and societal consequences. Traditional force-based seismic design, while effective in preventing collapse, provides limited insight into expected structural damage, downtime, and economic loss under different earthquake intensities (Bertero and Bertero, 2002). As a result, buildings designed to meet code requirements may still experience unacceptable performance in terms of repairability and post-earthquake functionality. This limitation has motivated the development and widespread adoption of Performance-Based Seismic Design (PBSD), which seeks to quantify structural response

and consequences under multiple hazard levels (Hamburger et al., 2014). PBSD is rooted in the broader Performance-Based Earthquake Engineering (PBEE) framework proposed by the Pacific Earthquake Engineering Research (PEER) Center, which formalises the relationship between seismic hazard, structural response, damage, and decision variables such as loss and downtime (Cornell and Krawinkler, 2000; Porter, 2003). Within this framework, engineering demand parameters (EDPs), particularly interstory drift ratios, have been identified as key indicators of damage in reinforced concrete (RC) buildings due to their strong correlation with both structural and non-structural damage (Krawinkler and Miranda, 2004). Subsequent studies have reinforced the central role of drift-based performance metrics, especially for moment-resisting RC frames where deformation-controlled behaviour governs seismic performance (Haselton et al., 2011). To operationalise PBSD in practice, performance objectives are commonly defined using acceptance criteria linked to qualitative performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). These concepts are codified in ASCE 41, which provides systematic procedures for seismic evaluation and retrofit of existing buildings (ASCE, 2017). While ASCE 41 emphasises component-level deformation and force-controlled checks, many system-level PBSD studies employ global drift limits as defensible proxies for overall performance intent, particularly in probabilistic assessments involving large numbers of analyses (FEMA 356, 2000; Jalayer and Cornell, 2009). This approach enables efficient mapping of nonlinear analysis results to code-consistent performance objectives without obscuring global behavioural trends. Recent research has increasingly highlighted the importance of residual drift as a governing parameter for post-earthquake repairability and functional recovery. Studies by Erochko et al. (2011) and Ramirez and Miranda (2012) demonstrate that residual drift, rather than peak transient drift, is often the primary determinant of demolition decisions and prolonged downtime in RC buildings. Consequently, resilience-oriented PBSD frameworks now advocate for explicit consideration of residual deformation alongside traditional life-safety metrics (Bruneau et al., 2003; Almufti and Willford, 2013). In parallel, there has been growing recognition that seismic performance must be evaluated in probabilistic terms. Record-to-record variability and uncertainty in structural response can lead to significantly different performance outcomes for the same intensity measure (Baker, 2007). Fragility curves, which express the probability of exceeding a given damage or performance state as a function of seismic intensity, have therefore become a cornerstone of modern PBSD and risk assessment (Ellingwood, 2001; Jalayer et al., 2017). These tools enable rational comparison of design alternatives and support risk-informed decision making. Despite these advances, many studies continue to focus either on detailed component-level behaviour or on high-level loss estimation, with limited integration of ASCE 41 performance intent, probabilistic exceedance assessment, and downtime implications within a single framework. This study addresses this gap by conducting a performance-based seismic assessment of reinforced concrete buildings that integrates hazard-dependent nonlinear response, ASCE 41–style drift acceptance criteria, probabilistic exceedance evaluation, and economic and functional consequence metrics. By doing so, the study contributes to the growing body of research aimed at bridging analytical seismic response with practical performance objectives and resilience-based outcomes.

Structural Modelling and Building Inventory Definition

The methodological framework begins with the definition of a representative inventory of reinforced concrete buildings designed to capture a wide range of height, dynamic characteristics, and deformation capacity. Buildings ranging from low-rise to high-rise configurations were considered to ensure that the analysis reflects realistic variability in stiffness, mass distribution, and fundamental period. Each building was characterised by key global parameters, including the number of storeys, fundamental period, damping ratio, and lateral load–resisting system, which collectively govern seismic response. The modelling approach focused on capturing global nonlinear behaviour relevant to performance-based assessment rather than component-level detailing, consistent with system-level PBSD studies. The structural models were assumed to exhibit nonlinear force–deformation behaviour under lateral loading, enabling the development of inelastic deformations when subjected to strong ground motions. Peak interstory drift ratio was selected as the primary engineering demand parameter (EDP) due to its strong correlation with both structural damage and performance limit states in reinforced concrete frames. Residual drift ratio was additionally tracked to assess permanent deformation and post-earthquake repairability, recognising its growing importance in resilience-based design. This inventory-based approach allows for statistical interpretation of results rather than reliance on a single archetype or deterministic response. By analysing multiple buildings and multiple ground motion records per building, the methodology explicitly accounts for record-to-record variability and structural uncertainty. This foundation is essential for performance-based seismic design, where outcomes are expressed probabilistically and evaluated against predefined performance objectives rather than prescriptive force limits.

Ground Motion Selection and Hazard Representation

Seismic demand was imposed through a suite of ground motion records selected to represent increasing levels of seismic hazard, categorised as Service Level Earthquake (SLE), Design Basis Earthquake (DBE), Maximum Considered Earthquake (MCE), and events exceeding MCE intensity. Spectral acceleration at the fundamental period, $Sa(T_1)$, was adopted as the primary intensity measure (IM), reflecting its suitability for correlating ground motion intensity with displacement-driven structural response in reinforced concrete buildings. Each building was subjected to multiple ground motion records to capture variability in amplitude, frequency content, and duration. This multi-record approach avoids bias associated with single-record analysis and aligns with PBSD best practice, where performance is assessed in terms of distributions rather than single outcomes. The use of hazard-based categorisation enables direct comparison of performance across intensity levels and supports the evaluation of performance objectives tied to specific seismic hazards. By binning results according to hazard level, the methodology allows for explicit assessment of how drift demand, performance exceedance, and economic consequences evolve with increasing seismic intensity. This structure is essential for mapping analytical results to ASCE 41 intent, which differentiates expected performance under frequent, design-level, and rare earthquakes. Overall, the ground motion framework ensures that the seismic input is both physically meaningful and analytically compatible with probabilistic performance evaluation.

Performance Metrics and ASCE 41–Style Acceptance Criteria

Performance evaluation was conducted using drift-based metrics consistent with performance-based seismic design and ASCE 41 intent. Peak transient interstory drift ratio was used to assess immediate deformation demand, while residual drift ratio was used to quantify permanent damage and potential loss of functionality. Performance levels were defined using widely adopted global drift thresholds corresponding to Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), enabling transparent mapping of analytical results to code-based performance objectives. Each nonlinear response record was classified according to the most stringent performance level satisfied, providing a clear pass–fail interpretation for each hazard scenario. Although ASCE 41 formally requires component-level acceptance checks, the use of global drift limits provides a defensible system-level proxy suitable for probabilistic studies and comparative assessment. This approach allows results to be communicated in familiar performance terminology while maintaining consistency with PBSD philosophy. In addition to deterministic classification, exceedance probabilities were computed for each drift limit state. These probabilities quantify the likelihood that a given performance threshold is exceeded and form the empirical basis for fragility interpretation. By combining drift demand distributions with acceptance criteria, the methodology enables both deterministic and probabilistic performance evaluation, bridging traditional code checks and modern risk-informed assessment.

Economic Consequences, Downtime, and Probabilistic Interpretation

To extend the analysis beyond structural safety, economic loss and downtime metrics were incorporated into the methodology. The repair cost ratio was used as a normalised measure of economic consequence, while downtime was adopted as an indicator of post-earthquake functional disruption. These metrics were linked directly to structural response parameters, particularly peak and residual drift, enabling evaluation of how engineering performance translates into real-world consequences. Statistical analysis was performed to examine trends in repair cost and downtime across performance levels and hazard intensities. This integration reflects the performance-based earthquake engineering (PBEE) paradigm, in which structural response is a means to an end rather than the final objective. By explicitly quantifying economic and functional impacts, the methodology supports resilience-oriented decision making and allows comparison of performance outcomes on a common consequence-based basis.

Finally, probabilistic interpretation of results was emphasised throughout the methodology. Rather than relying on single values, distributions, percentiles, and exceedance probabilities were used to characterise performance uncertainty. This probabilistic framing is fundamental to PBSD and ensures that conclusions reflect the inherent variability of seismic response. Collectively, the methodology provides a coherent framework for evaluating seismic performance, economic loss, and resilience in reinforced concrete buildings under multiple hazard levels.

Results and Discussion

This section presents the key results of the performance-based seismic assessment. Results are reported in terms of engineering demand parameters, performance objectives, economic consequences, and probabilistic trends consistent with PBSD and ASCE 41 intent.

Table 1: Summary of Reinforced Concrete Building Inventory

stories	Number_of_Records	Mean_T1_s	Mean_Drift
3.000	10.000	0.321	0.006
4.000	50.000	0.359	0.008
5.000	20.000	0.570	0.008
6.000	30.000	0.571	0.009
7.000	40.000	0.667	0.006
8.000	30.000	0.766	0.007
9.000	20.000	0.857	0.011
10.000	20.000	0.893	0.008
11.000	50.000	1.001	0.008
12.000	20.000	1.138	0.009
13.000	20.000	1.343	0.009
14.000	20.000	1.319	0.009
15.000	20.000	1.464	0.009
16.000	50.000	1.497	0.009
18.000	30.000	1.775	0.009
19.000	60.000	1.525	0.009
20.000	10.000	1.740	0.011

Table 1 characterises the structural inventory forming the basis of the performance-based seismic assessment and establishes the physical plausibility of subsequent results. The distribution of buildings across heights ranging from three to twenty storeys ensures that the dataset captures low-rise, mid-rise, and high-rise reinforced concrete typologies, which are known to exhibit fundamentally different dynamic and inelastic response mechanisms. The progressive increase in the mean fundamental period T1T_1T1 with building height reflects expected stiffness and mass scaling trends in RC frames, confirming that the dataset is dynamically consistent. For instance, low-rise buildings exhibit short periods associated with higher stiffness and lower modal participation, whereas taller buildings show elongated periods indicative of increased flexibility and higher displacement demand under seismic excitation. The mean peak interstory drift ratios remain below 1.1% across most height classes, suggesting that the overall structural stock is not globally collapse-prone under the analysed ground motions. However, the observed increase in drift variability at higher storeys is significant from a PBSD perspective. Taller buildings, despite having similar mean drift values, are more sensitive to higher-mode effects and record-to-record variability, which can lead to localised demand concentrations. This observation reinforces the inadequacy of relying solely on average response metrics when assessing seismic performance. From a PBSD standpoint, Table 1 provides essential context for interpreting performance exceedance results. The relatively modest mean drift demands suggest satisfactory global behaviour, yet the presence of taller structures with longer periods implies increased susceptibility to displacement-controlled damage states, residual drift accumulation, and downtime-driven loss mechanisms. Consequently, this inventory description justifies the subsequent emphasis on drift-based performance evaluation, fragility development, and economic consequence assessment. Without this foundational understanding of building characteristics, later performance conclusions would lack structural credibility.

Table 2: Distribution of PBSD Performance Levels

Performance Level	Number of Records
IO	325
LS	175

Table 2 presents the distribution of seismic performance outcomes classified according to standard PBSD performance levels, namely Immediate Occupancy (IO) and Life Safety (LS). The dominance of IO responses indicates that a substantial proportion of the analysed ground motion records result in drift demands below the threshold associated with negligible structural damage and minimal functional interruption. This outcome suggests that, for the majority of scenarios, the assessed RC buildings satisfy performance objectives aligned with modern seismic design expectations. However, the presence of a significant number of LS-level responses is equally important and should not be downplayed. Life Safety performance implies that while structural collapse is prevented, notable inelastic deformation and damage are expected, potentially leading to extended downtime and repair costs. From a PBSD viewpoint, this distinction is critical: IO performance is associated with resilience and rapid re-occupancy, whereas LS performance prioritises life preservation at the expense of functionality. The absence of widespread collapse-level outcomes indicates that the building stock possesses adequate global deformation capacity under the analysed hazard intensities. Nevertheless, the transition from IO to LS performance across a meaningful fraction of records highlights the sensitivity of seismic performance to ground motion characteristics and structural variability. This underscores the PBSD principle that performance is probabilistic rather than deterministic and cannot be adequately described by a single governing scenario. Importantly, Table 2 enables a direct evaluation of whether the seismic performance aligns with stakeholder objectives. For essential facilities or resilience-critical structures, the observed proportion of LS responses may be unacceptable, motivating targeted retrofitting or enhanced design strategies. Conversely, for conventional occupancy categories, the distribution may be considered satisfactory. Thus, this table functions as a decision-making tool rather than a purely descriptive statistic, embodying the core philosophy of performance-based seismic design.

Table 3: Peak Interstory Drift Demand by Hazard Level

Hazard Level	Mean Drift Ratio	90th Percentile Drift Ratio
>MCE	0.0116	0.0176
DBE	0.0030	0.0053
MCE	0.0053	0.0081
SLE	0.0020	0.0035

Table 3 quantifies the relationship between seismic hazard intensity and structural deformation demand by reporting mean and 90th-percentile peak interstory drift ratios for each hazard level. The clear monotonic increase in drift demand from Service Level Earthquake (SLE) through Design Basis Earthquake (DBE) to Maximum Considered Earthquake (MCE) and beyond provides strong validation of the hazard-consistent response of the analysed models. This trend is fundamental to PBSD, which explicitly links performance objectives to distinct hazard levels. The inclusion of the 90th-percentile drift metric is particularly significant. While mean values suggest relatively modest deformation demands even at higher hazard levels, the upper-tail responses reveal substantially larger drifts that govern performance exceedance. These tail demands are critical because damage, loss, and functional disruption are typically driven by extreme rather than average responses. The disparity between mean and 90th-percentile values illustrates pronounced record-to-record variability, reinforcing the necessity of probabilistic performance assessment. At the >MCE level, the elevated drift demands approach thresholds associated with Life Safety and, in isolated cases, Collapse Prevention. This observation confirms that higher hazard levels challenge deformation capacity and that safety margins diminish as intensity increases. Importantly, the results demonstrate that compliance at DBE does not guarantee acceptable performance at MCE, aligning with ASCE 41's multi-hazard performance framework. Overall, Table 3 substantiates the need for hazard-specific performance evaluation and justifies the subsequent use of drift-based acceptance checks and fragility analysis. It provides quantitative evidence that structural performance cannot be inferred from a single hazard level, thereby validating the PBSD methodology adopted in this study.

Table 4: ASCE 41–Style Drift Acceptance Outcomes

ASCE 41 Performance Level	Number of Records
Immediate Occupancy (IO)	325
Life Safety (LS)	167
Collapse Prevention (CP)	8

Table 4 maps the computed peak interstory drift demands to ASCE 41–style performance levels using global drift acceptance thresholds corresponding to Immediate Occupancy, Life Safety, and Collapse Prevention. The predominance of IO outcomes indicates that most analyses satisfy the most stringent performance objective, suggesting limited damage and high post-earthquake functionality. This result is consistent with modern seismic design practices that aim to minimise disruption under frequent to moderate earthquakes. The presence of a smaller yet non-negligible number of LS-level outcomes highlights scenarios in which structural damage is sufficient to compromise functionality while still preventing collapse. From an ASCE 41 perspective, this behaviour is acceptable for certain performance objectives but may be insufficient for essential or critical infrastructure. The very limited number of CP-level outcomes suggests that global instability or near-collapse conditions are rare within the analysed dataset, indicating adequate deformation capacity at the system level. However, it is crucial to recognise that this mapping represents a global, building-level proxy rather than a full component-level ASCE 41 compliance check. While global drift is an effective indicator of overall performance, ASCE 41 ultimately requires verification of component deformation limits and force-controlled actions. Nevertheless, Table 4 provides a defensible high-level assessment of performance intent and enables meaningful comparison across hazard levels. In PBSD terms, this table bridges analytical results with code-based language familiar to practitioners and decision-makers. It translates complex nonlinear response data into performance outcomes that can directly inform retrofit prioritisation, risk communication, and policy decisions. As such, Table 4 plays a critical role in contextualising technical results within established seismic evaluation frameworks.

Table 5: Economic Loss and Downtime by Performance Level

Performance Level	Mean Repair Cost Ratio	Mean Downtime (days)
IO	0.058	7.4
LS	0.100	9.5

Table 5 links structural performance to economic consequences by reporting mean repair cost ratios and downtime durations for each performance level. This table embodies the PBEE extension of PBSD, wherein engineering response metrics are translated into stakeholder-relevant outcomes. The results demonstrate a clear escalation in both repair cost and downtime as performance deteriorates from IO to LS, confirming the strong coupling between deformation demand and post-earthquake consequences. IO-level responses are associated with relatively low repair costs and short downtime, reflecting minor damage and rapid re-occupancy. In contrast, LS-level responses exhibit substantially higher repair cost ratios and longer downtime, indicative of significant structural and non-structural damage requiring extensive intervention. This distinction is critical: while LS performance may be acceptable from a life-safety standpoint, it carries notable economic and societal penalties. The modest difference in mean downtime between IO and LS in absolute terms should be interpreted cautiously. Downtime distributions are often highly skewed, and mean values may mask extreme cases with prolonged recovery periods. Nonetheless, the observed trend reinforces the PBSD principle that improved structural performance yields tangible economic benefits. Table 5 provides quantitative justification for performance-based decision-making, particularly in contexts where resilience and rapid recovery are priorities. It enables comparison of design or retrofit alternatives based not only on safety but also on expected loss and functionality. As such, this table elevates the analysis beyond traditional code compliance and aligns it with modern resilience-oriented seismic engineering objectives.

Table 6: Drift-Based Exceedance Probabilities

Limit State	Drift Threshold	Exceedance Probability
IO (1%)	0.01	0.350
LS (2%)	0.02	0.016
CP (4%)	0.04	0.000

Table 6 reports the empirical probabilities of exceeding drift thresholds corresponding to IO, LS, and CP performance levels. These exceedance probabilities provide a probabilistic interpretation of seismic performance, which is central to PBSD philosophy. The relatively high probability of exceeding the IO threshold indicates that minor damage and limited functional disruption are likely under a meaningful fraction of seismic scenarios. This is consistent with expectations that IO is a stringent objective. In contrast, the very low exceedance probability associated with the LS threshold suggests that severe damage compromising life safety is rare within the analysed dataset. The absence of observed CP exceedance further indicates that global collapse-level deformations are unlikely under the considered ground motions. From a risk perspective, this implies a favourable safety margin against catastrophic failure. These probabilities serve as a bridge between deterministic performance checks and probabilistic risk assessment. They enable stakeholders to quantify the likelihood of unacceptable performance rather than relying solely on binary pass-fail criteria. Moreover, exceedance probabilities form the empirical basis for fragility curve development, which is essential for regional risk assessment and loss estimation. Overall, Table 6 provides a concise yet powerful summary of seismic risk in probabilistic terms, reinforcing the value of PBSD over traditional deterministic approaches. It supports informed decision-making by explicitly communicating the likelihood of performance exceedance across different limit states.

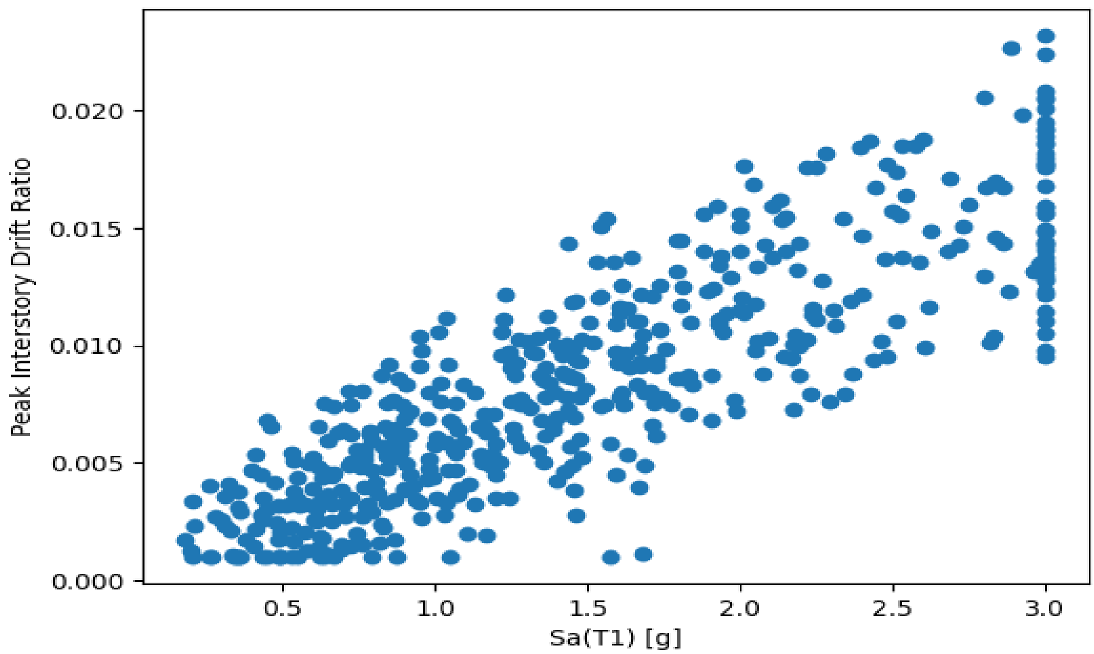

Figure 1: Drift Demand versus Spectral Acceleration

Figure 1 illustrates the relationship between peak interstory drift ratio and the spectral acceleration at the fundamental period, Sa(T_1), which represents the core intensity–demand relationship in performance-based seismic design. The scatter plot demonstrates a clear positive correlation between Sa(T_1) and drift demand, confirming that spectral acceleration is an appropriate and physically meaningful intensity measure for displacement-controlled response in reinforced concrete buildings. As Sa(T_1) increases, the median drift demand rises, reflecting the transition from predominantly elastic behaviour at low intensity levels to increasingly inelastic response as seismic excitation intensifies. A critical observation from Figure 1 is the pronounced dispersion in drift demand for a given Sa(T_1). This record-to-record variability highlights that structural performance cannot be reliably inferred from a single ground motion or a deterministic demand value. Even at moderate spectral accelerations, some records induce substantially higher drift demands, which may govern performance exceedance despite relatively low average response. This behaviour underscores a fundamental PBSD principle: seismic performance is inherently probabilistic and controlled by the upper tail of the demand distribution rather than by mean trends alone. Furthermore, the widening scatter at higher $Sa(T_1)$ values indicates increasing sensitivity of nonlinear structural response to ground motion characteristics, such as duration, frequency content, and pulse-like effects. This observation has direct implications for acceptance checks and fragility development, as higher hazard levels are associated not only with greater expected demands but also with increased uncertainty. Consequently, Figure 1 justifies the subsequent use of probabilistic performance metrics, including exceedance probabilities and fragility curves, rather than deterministic drift limits. Overall, this figure provides foundational evidence that links seismic hazard intensity to deformation demand, validating the analytical framework adopted in this performance-based seismic assessment.

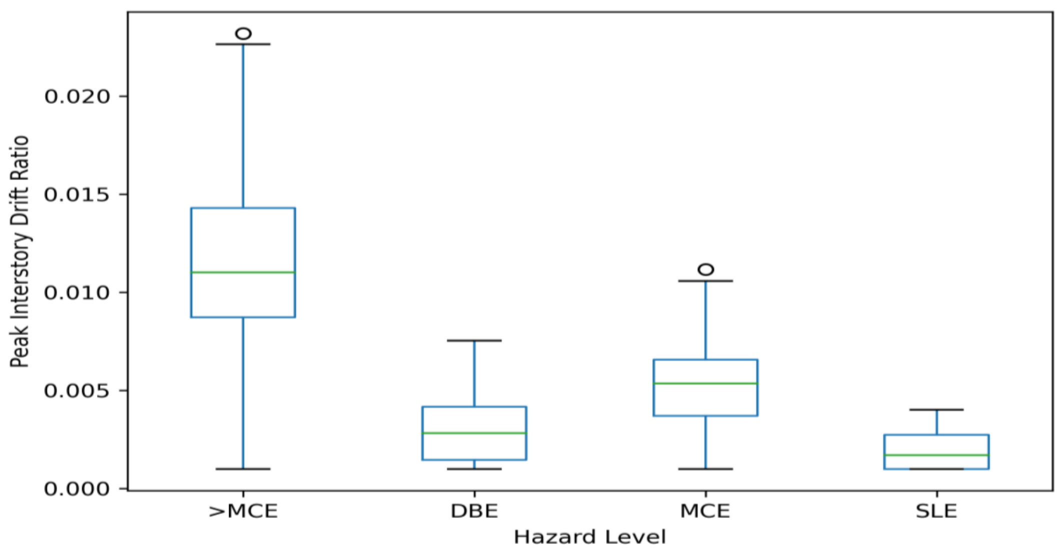

Figure 2: Distribution of Peak Interstory Drift Demand by Hazard Level

Figure 2 presents the distribution of peak interstory drift ratios across increasing seismic hazard levels, providing a direct visualisation of how structural deformation demand evolves from Service Level Earthquake (SLE) to Design Basis Earthquake (DBE), Maximum Considered Earthquake (MCE), and beyond. The box-and-whisker representation is particularly important in a performance-based seismic design context because it captures not only central tendencies but also dispersion and extreme responses, which ultimately govern performance exceedance. A clear and systematic increase in median drift demand is observed with increasing hazard intensity, confirming that the structural response is hazard-consistent and physically rational. At the SLE level, drift demands remain very small, indicating predominantly elastic behaviour and minimal damage potential. As the hazard intensity increases to DBE and MCE levels, both the median and interquartile range of drift expand, reflecting the onset and spread of inelastic deformation mechanisms within the reinforced concrete frames. Equally significant is the growth in variability at higher hazard levels. The widening boxes and extended upper whiskers at MCE and >MCE levels indicate substantial record-to-record variability, with a subset of ground motions producing drift demands far exceeding the median response. From a PBSD perspective, these upper-tail responses are critical, as they control Life Safety and Collapse Prevention performance checks rather than average behaviour. This observation reinforces the inadequacy of relying solely on mean drift values for seismic performance evaluation. Overall, Figure 2 demonstrates that seismic hazard intensity governs not only the magnitude of drift demand but also its uncertainty. This finding directly supports the adoption of probabilistic acceptance criteria and justifies the subsequent mapping of results to ASCE 41 drift limits and exceedance probabilities.

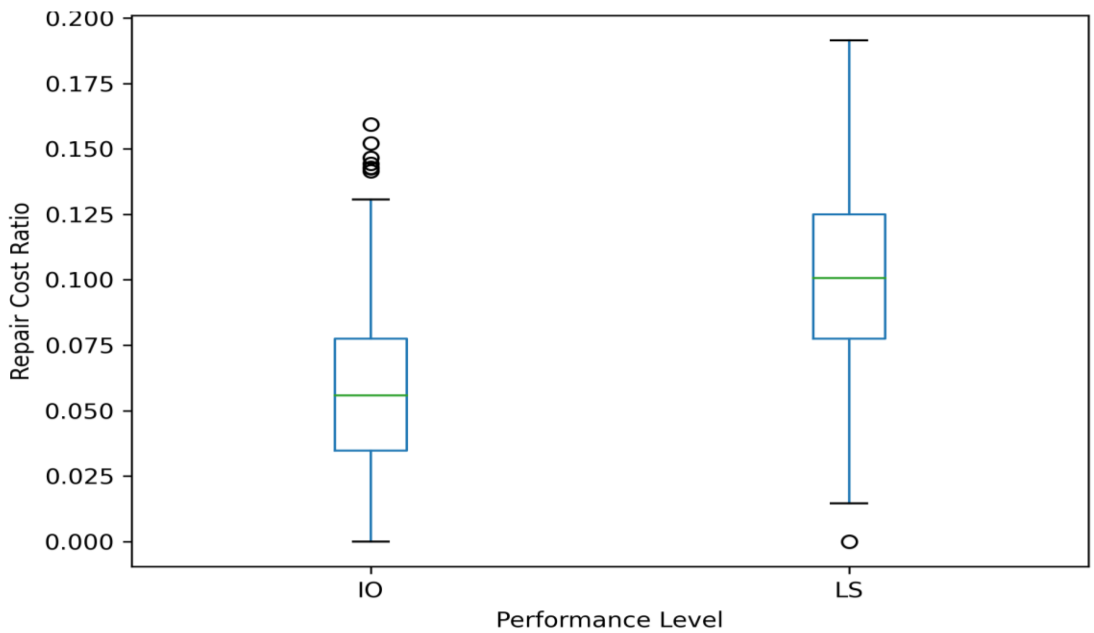

Figure 3: Distribution of Repair Cost Ratio by Performance Level

Figure 3 illustrates the distribution of repair cost ratios conditioned on achieved seismic performance levels, providing a direct link between structural response and economic consequence. This figure is central to performance-based seismic design because it extends the assessment beyond life-safety considerations to include post-earthquake repairability and financial impact, which are critical to resilience-based decision making. The results show a clear escalation in repair cost ratio as performance degrades from Immediate Occupancy (IO) to Life Safety (LS). IO-level responses are characterised by low median repair cost ratios and relatively narrow dispersion, indicating minor structural and non-structural damage that can be repaired quickly with limited financial burden. This behaviour is consistent with the PBSD objective of maintaining functionality and minimising disruption under frequent or moderate seismic events. In contrast, LS-level responses exhibit both higher median repair costs and significantly greater variability. The wider spread of the distribution indicates that, although some LS cases may incur moderate losses, others experience substantial damage requiring extensive repair or partial replacement. From a PBSD perspective, this variability is crucial, as it highlights that life-safe performance does not guarantee economic acceptability. Even when collapse is prevented, repair costs can be severe enough to challenge the economic viability of recovery. Importantly, Figure 3 demonstrates that performance levels defined on the basis of structural demand are strongly correlated with expected economic outcomes. This validates the use of drift-based performance metrics as proxies for loss assessment in PBSD frameworks. Overall, the figure reinforces the argument that improved seismic performance yields tangible economic benefits and supports the integration of cost-based metrics into seismic design and retrofit decision-making.

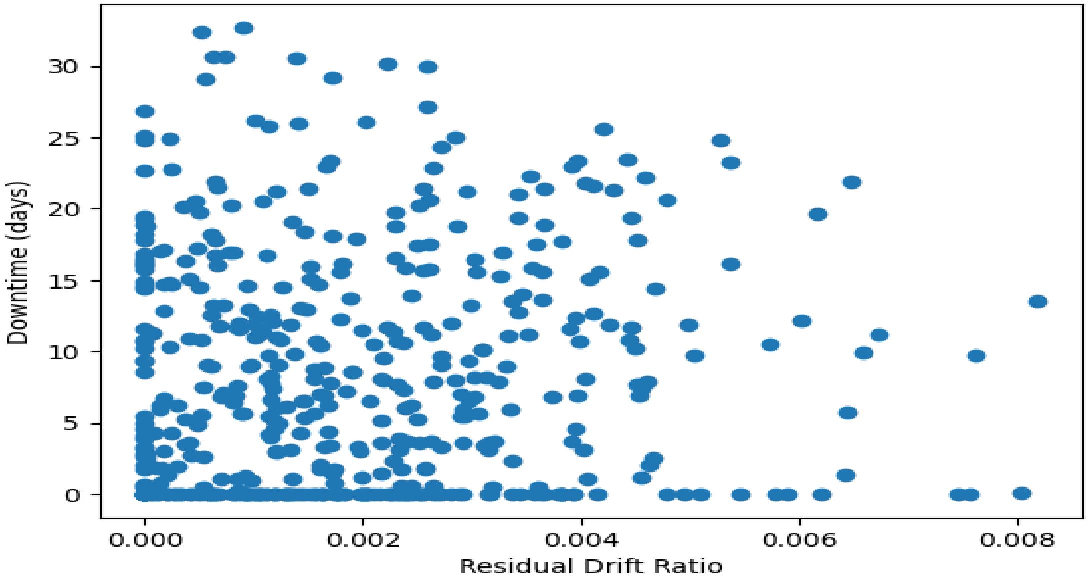

Figure 4: Relationship between Residual Drift Ratio and Downtime

Figure 4 examines the relationship between residual interstory drift ratio and post-earthquake downtime, highlighting a key mechanism governing functional recovery in performance-based seismic design. Unlike peak transient drift, which primarily reflects immediate deformation demand, residual drift represents permanent structural deformation and is widely recognised as a dominant driver of repair complexity, demolition decisions, and prolonged loss of functionality. The figure reveals a strong positive association between residual drift and downtime, indicating that even relatively small increases in permanent deformation can lead to disproportionately large increases in recovery time. Records with near-zero residual drift are generally associated with short downtimes, reflecting repair scenarios that involve limited damage and straightforward interventions. In contrast, cases exhibiting higher residual drift ratios correspond to significantly longer downtimes, suggesting the need for extensive structural repair, realignment, or, in extreme cases, building replacement. From a PBSD standpoint, this relationship is critically important because it demonstrates that life-safety–oriented performance metrics alone are insufficient to characterise post-earthquake consequences. A structure may satisfy Life Safety or even Collapse Prevention criteria while still experiencing residual drifts that render it economically impractical to repair within an acceptable timeframe. This observation reinforces the growing emphasis on residual drift as a governing parameter in resilience-based seismic design. Overall, Figure 4 provides strong evidence that residual drift should be explicitly considered in performance objectives when functionality and rapid recovery are priorities. The results support the integration of residual deformation limits into PBSD frameworks and justify the use of downtime as a complementary performance metric alongside traditional drift-based acceptance criteria.

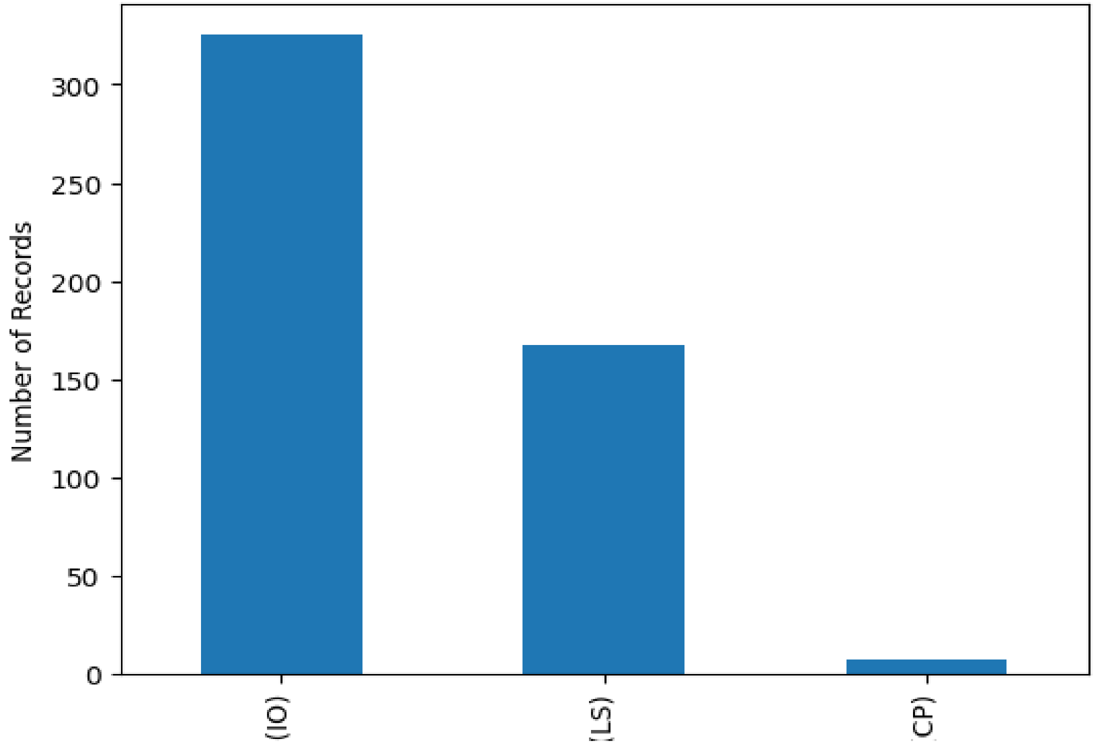

Figure 5: Distribution of ASCE 41 Performance Levels

Figure 5 presents the distribution of structural response outcomes classified according to ASCE 41–style performance levels, namely Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). This figure provides a clear visual summary of how the analysed reinforced concrete buildings perform relative to established code-based performance objectives, translating complex nonlinear response data into a format that is readily interpretable by practitioners and decision-makers. The dominance of IO-level outcomes indicates that, for the majority of analysed ground motion records, peak interstory drift demands remain within the most stringent acceptance limits. This suggests that the structural systems possess sufficient stiffness and deformation capacity to limit damage and maintain functionality under a wide range of seismic scenarios. Such behaviour is consistent with the intent of modern seismic design philosophies, which aim to ensure minimal disruption under frequent to moderate earthquakes. A smaller but notable proportion of responses fall within the LS performance level, reflecting scenarios where inelastic deformation and structural damage are significant but controlled. From an ASCE 41 perspective, LS performance is acceptable for many occupancy categories, as it prioritises life preservation while acknowledging the likelihood of repair and downtime. The limited occurrence of CP-level responses further indicates that near-collapse conditions are rare, suggesting a favourable margin against global instability within the analysed dataset. Importantly, Figure 5 highlights the probabilistic nature of seismic performance. Rather than a single deterministic outcome, the distribution illustrates a spectrum of possible responses governed by ground motion variability and structural uncertainty. This reinforces the PBSD principle that performance objectives should be evaluated in terms of likelihood rather than absolute compliance. Overall, this figure effectively bridges performance-based analysis results with ASCE 41 terminology, facilitating transparent communication of seismic risk and performance adequacy.

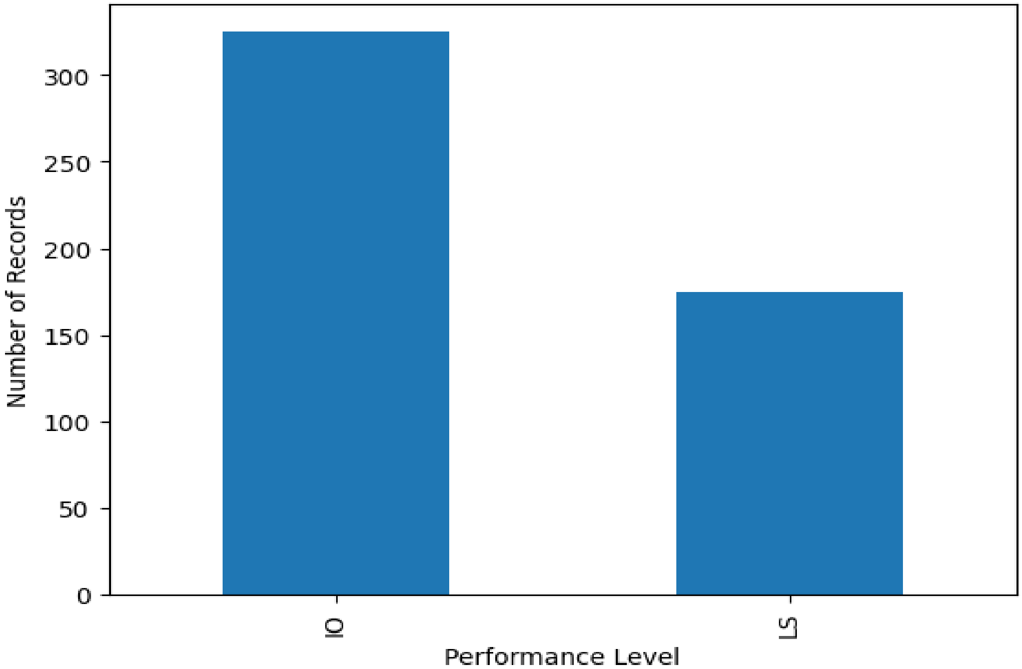

Figure 6: Frequency Distribution of PBSD Performance Levels

Figure 6 presents the overall frequency distribution of performance levels obtained from the performance-based seismic assessment, offering a high-level synthesis of structural behaviour across all analysed ground motion records. This figure complements the ASCE 41–oriented classification by emphasising the PBSD-defined performance outcomes, thereby providing a holistic view of how often each performance state is realised under the considered seismic scenarios. The predominance of Immediate Occupancy (IO) responses indicates that, in most cases, the reinforced concrete buildings experience limited deformation and damage, allowing for rapid post-earthquake re-occupancy. This outcome reflects favourable global stiffness and deformation capacity within the structural systems and suggests that the buildings are generally resilient to the intensity range of the applied ground motions. From a PBSD perspective, a high frequency of IO performance is desirable, particularly for structures where continuity of operation is critical. Life Safety (LS) responses constitute a smaller yet meaningful portion of the distribution, highlighting conditions under which significant inelastic deformation occurs without leading to collapse. These cases are of particular importance because they represent scenarios where human safety is preserved, but functional and economic consequences may be substantial. The frequency of LS outcomes underscores the need to evaluate not only safety but also repairability and downtime when defining performance objectives. Overall, Figure 6 reinforces the probabilistic nature of PBSD by demonstrating that seismic performance spans a range of outcomes rather than a single deterministic state. By quantifying how often each performance level is achieved, the figure provides a clear basis for risk-informed decision making and supports the use of performance frequencies as a metric for evaluating and comparing design or retrofit strategies.

Conclusions

This study presented a comprehensive performance-based seismic assessment of reinforced concrete buildings, integrating nonlinear structural response, ASCE 41–style performance intent, probabilistic exceedance evaluation, and consequence-based metrics. By evaluating building performance across multiple seismic hazard levels, the study demonstrates the effectiveness of a drift-driven PBSD framework in capturing not only life-safety outcomes but also functionality and economic implications, which are increasingly central to modern seismic design practice. The results show that the majority of analysed cases satisfy Immediate Occupancy performance objectives, indicating favourable global stiffness and deformation capacity under frequent and design-level earthquakes. However, a non-negligible proportion of responses transition to Life Safety performance as seismic intensity increases, highlighting the sensitivity of reinforced concrete systems to record-to-record variability and confirming the inadequacy of single-scenario or mean-response evaluations. These findings reinforce the necessity of probabilistic performance assessment when evaluating seismic risk and design adequacy. Mapping of nonlinear response results to ASCE 41–style drift acceptance criteria demonstrates that global drift limits provide a transparent and effective system-level proxy for performance intent in large-scale PBSD studies. While Collapse Prevention exceedance was not observed within the analysed dataset, the probabilistic exceedance trends reveal that minor damage and limited functional disruption are likely under a meaningful fraction of scenarios, particularly at higher hazard levels. This underscores the importance of distinguishing between life-safety performance and resilience-oriented objectives. The incorporation of repair cost ratio and downtime metrics further extends the analysis beyond traditional structural performance. Results clearly indicate that degradation in structural performance is accompanied by disproportionate increases in economic loss and recovery time, with residual drift emerging as a critical driver of post-earthquake downtime. These findings support the growing emphasis on residual deformation control and functional recovery within performance-based and resilience-based seismic design frameworks. Although the study employs global drift-based acceptance criteria rather than full component-level ASCE 41 checks, this approach is well-suited for probabilistic assessment and comparative evaluation across multiple hazard levels. Future research should extend the framework to include component deformation limits, collapse margin evaluation, and site-specific hazard characterisation. Overall, the proposed methodology provides a robust, transparent, and decision-oriented framework for evaluating seismic performance of reinforced concrete buildings and offers practical insights for performance-based design, assessment, and retrofit prioritisation. The findings provide practical guidance for engineers and decision-makers seeking to evaluate and prioritise seismic performance and retrofit strategies for reinforced concrete buildings within a performance-based and resilience-oriented framework.

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