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RESEARCH ARTICLE

Seismic Fragility Characterization of Grid-Like Frame Structures

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ABSTRACT – Historically, the design of reinforced concrete (RC) moment-resisting frames in regions of moderate seismicity, such as Malaysia, has been predominantly governed by gravity load requirements, which renders a considerable portion of the existing building stock vulnerable to earthquake-related risks. This study presents a parametric seismic fragility assessment of low-rise reinforced concrete (RC) grid-like frames, representative of structures in Malaysia where design has traditionally emphasized gravity loads. A suite of building archetypes was developed to capture systematic variations in key structural and geometric parameters, including plan configuration, story height, bay aspect ratio, column and beam cross-sectional area. Each archetype was subjected to Incremental Dynamic Analysis (IDA) using nine ground motion records from the PEER NGA-West2 database. Peak Ground Acceleration (PGA) was employed as the intensity measure, and maximum interstory drift ratio (MaxIDR) was adopted as the engineering demand parameter. Fragility functions were constructed for five predefined damage states specified by international seismic performance guidelines, ranging from Slight Damage to Collapse. Results indicate that archetypes with smaller member sizes and more rectangular bay layouts (lower aspect ratios) exhibit a significantly higher probability of extensive damage at lower shaking intensities. The proposed framework which comprises a fragility catalog for detailed risk evaluation and a computationally efficient regression model for rapid vulnerability screening—provides a valuable tool for seismic risk assessment, disaster mitigation planning, and prioritization of retrofitting strategies in Malaysia and similar regions.

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1. INTRODUCTION

In urban construction, reinforced concrete (RC) moment-resisting frames have become one of the most common systems because of their cost efficiency, architectural flexibility, and functional suitability. Historically, the design of these frames has been governed mainly by gravity load requirements, while seismic considerations have often been overlooked in regions of moderate seismicity, including Malaysia. As a result, although such practices may be sufficient under routine loading, a considerable portion of the existing building stock remains exposed to earthquake-related risks. Beyond financial disruption, the failure of these structures can also generate serious social and human consequences, emphasizing the importance of reassessing their seismic vulnerability [1]. Rapid urbanization and the growing complexity of infrastructure in Malaysia have made seismic safety evaluations increasingly critical. While the Malaysian Annex to Eurocode 2 does incorporate seismic provisions, their implementation in practice is still limited, primarily due to financial constraints and the widespread belief that earthquake hazards are minimal in the country [2, 3]. The occurrence of recent earthquakes, including the [4] Sabah event, has challenged this perception and underscored the necessity for more systematic vulnerability assessments [5, 6]. The regional seismicity and potential tremor zones are illustrated in the seismic hazard map of Malaysia (shown in Figure 1). And Also experiences from international earthquakes, such as those in Mexico City in 1985 and Loma Prieta in 1989, further demonstrate the devastating outcomes of insufficient seismic design [7, 8].

Fragility functions provide a powerful tool for quantifying the probability of structural damage across varying levels of ground shaking. They are widely used to inform risk assessment, prioritize retrofitting strategies, and strengthen disaster preparedness. While fragility studies have been extensively applied to bridges and other structural systems [9]. There remains a lack of systematic investigations into RC moment-resisting frames that dominate Malaysia's urban building stock. In particular, the influence of structural and geometrical parameters—such as bay aspect ratio, column cross-sectional area, and beam stiffness—on seismic fragility is not yet fully understood [10]. Grid-like rectangular RC frames, which dominate much of Malaysia's built environment, exhibit considerable sensitivity to changes in member dimensions, reinforcement arrangements, and bay configuration. Such variations strongly influence stiffness, ductility, and the capacity to dissipate energy, and therefore play a decisive role in determining vulnerability under seismic actions

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[11, 12]. However, prior research has often examined these factors collectively or within narrow parameter ranges, leaving a gap in understanding which specific variables most significantly influence seismic fragility [13].

This study aims to fill the identified research gap by performing a parametric seismic fragility analysis of low- to mid-rise RC grid-like frames, representative of Malaysia and other regions with comparable levels of seismicity. To capture the influence of design variations, a series of archetype models is developed, systematically altering parameters such as bay aspect ratio, member dimensions, and stiffness characteristics. The structural performance of these archetypes is assessed through Incremental Dynamic Analysis (IDA) using ground motion records from the PEER NGA-West2 database, with fragility curves derived for predefined damage states ranging from slight to complete collapse. In addition, a meta-regression approach is employed to generalize the relationship between structural parameters and seismic capacity, thereby identifying the parameter ranges with the greatest impact on fragility outcomes.

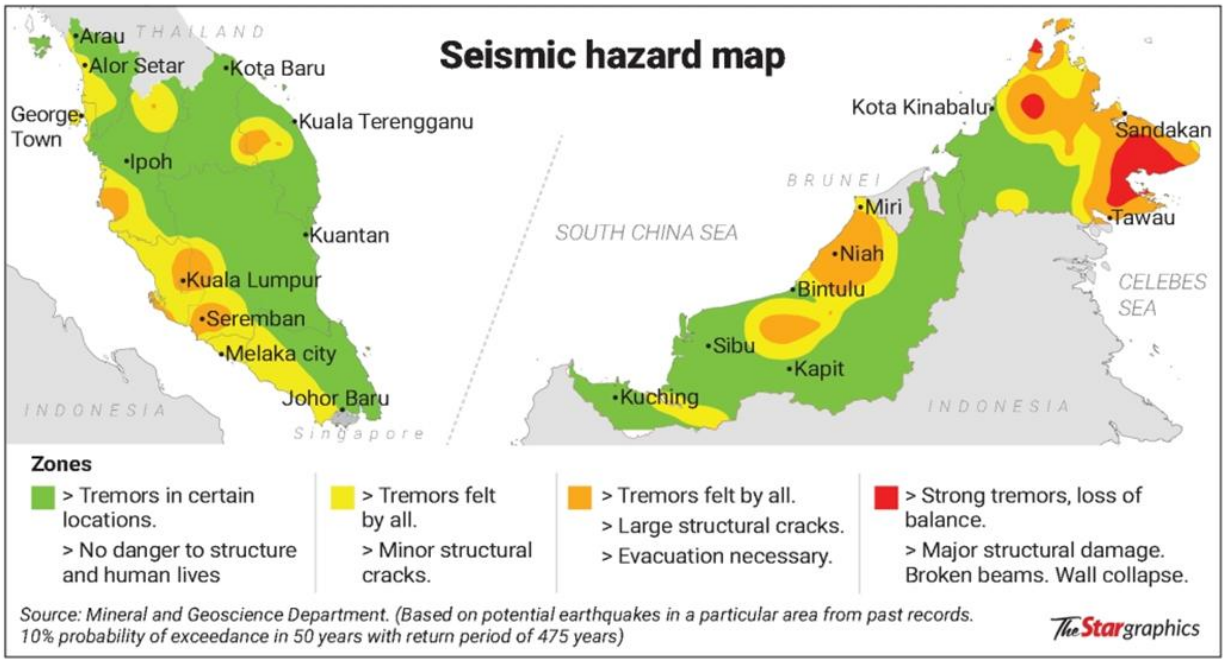


Figure 1. Seismic Hazard Map of Malaysia (Department of Mineral and Geoscience Malaysia, 2018) [34]

1.1 Related Work

Seismic fragility curves - probabilistic relationships that capture a seismic vulnerability - represent a structure's susceptibility to damage during earthquake ground shaking and are a major part in understanding overall seismic risk. In areas of moderate seismicity (such as Malaysia), the extensive use of (RC) moment resisting frames, which are mainly designed for gravity loads, represent a notable, often unquantified, risk [14]. This design paradigm does not usually consider ductile detailing, which is a key consideration for ensuring structures can accommodate large inelastic deformations without failing in catastrophic manner [6]. A principal concern in such gravity designed frames is the high probability of creating an undesirable weak column/ strong beam collapse mechanism, where plastic hinges are created within the columns instead of the beams, and can culminate in catastrophic soft story failures [10].Although traditionally considered a region of low to moderate seismic hazard, recent events such as the 2015 Sabah earthquake have served to emphasise that Malaysia is not immune to seismic risk and this has created an urgent need to evaluate the vulnerability of existing infrastructure [4, 14]. The analysis of this vulnerability can be carried out using a number of established methodologies which are broadly grouped into empirical, analytical and hybrid methodologies [10]. Empirical methods use the observed damage to obtain fragility functions from antecedent earthquakes, but their application is limited by the lack of robust post-earthquake data in many parts of the world [15]. Consequently, the most commonly used alternative are analytical methods that use computational modeling. These range from simple nonlinear static (pushover) analysis to more accurate nonlinear response-history analysis (NRHA) [9, 16]. A powerful extension of NRHA is IDA, a parametric technique which provides a detailed description of structural behavior from elasticity to collapse and forms a sound basis for obtaining probabilistic fragility functions [17]. Given the paucity of empirical data regarding the building stock in Malaysia, a parametric analytical methodology using IDA is considered to be the most scientifically rigorous method for a complete assessment. Accordingly, many researchers have performed parametric studies to investigate the sensitivity of seismic performance with respect to a wide range of design parameters. These investigations have provided some valuable insights in the several factors influencing vulnerability factors, including vertical irregularities like setbacks [18], and irregularities in plans causing torsional effects [19, 20] and the complex effect of dynamic soil-structure interaction (SSI) [21, 22]. However, a search of the literature shows that many of these studies are geared towards structures in high seismic regions or dealing with special, complicated configurations. A unique gap exists in the research literature that systematically studies the effect of basic geometric and structural design parameters such as bay aspect ratio, column and

beam cross-sections and stiffness ratios for the common gravity-load designed low and midrise RC frames in moderate seismic zone locations.

The available literature supports the fact that a number of key parameters are important determinants of seismic performance. A building's plan geometry is one of the main reasons for its torsional response and asymmetric arrangements of stiffness or strength can increase displacement demands [19, 20]. The number of stories directly affects the dynamic properties of a building and has a strong correlation with the fragility [23]. Moreover, the relative size and strength of columns and beams is one of the most important, as a low column - to - beam strength ratio, that is common for gravity - designed frames, can lead to a highly undesirable mechanism of soft - story collapse [9]. A cornerstone of any dynamic analysis-based fragility assessment is the selection of an appropriate ground motion intensity measure (IM). An optimal IM should be both efficient - showing low dispersion in the prediction of response - and sufficient - ensuring conditional independence of response from other ground-motion parameters [24]. Common IMs include PGA and spectral acceleration at the fundamental period of the structure, denoted Sa(T1), 1 is often considered as theoretically better; however, one usually considers the peak ground acceleration (PGA) and this has been shown to be useful for stiff, short period structures, which are a considerable fraction of the low to medium rise building stock. The acceleration at the fundamental period of the structure, denoted Sa(T1), 1 is often considered as theoretically better; however, one usually considers the PGA, and this has been shown to be useful for stiff, short period structures, which are a considerable fraction of the low to medium rise building stock). The result of such analyses is normally a fragility curve, which provides a probabilistic relation between an intensity measure (IM) and the probability that a structure will reach or exceed a given damage state (DS) [25]. This curve is usually modelled by a lognormal cumulative distribution function Phi with median capacity u and dispersion [26]. To produce theses curves, structural performance is discretised into a number of damage states, typically Slight, Moderate, Extensive and Complete (Collapse), associated with quantitative thresholds of an engineering demand parameter (EDP), such as inter story drift ratio [10]. Fragility parameters are then estimated by fitting the lognormal function to the cloud of data obtained from parametric analyses, usually by maximum likelihood estimation [27]. Finally, the large data sets generated by the parametric studies can be synthesized into useful tools using meta-regression and machine learning (ML) models. These models provide a direct mathematical link between the physical characteristics of a building and related parameters of its seismic fragility, thus eliminating the need for intensive IDA for each new building being assessed [28]. The accuracy of this approach has been shown in recent studies [28, 29]. The originality of the present research work is the development of a meta-regression model, based on a purpose-built, coherent parametric data set, specifically developed for gravity-designed reinforced-concrete frames. This allows for more controlled and targeted predictive modelling and is a robust and scientifically grounded tool for the rapid vulnerability screening of building portfolios.

2. METHODOLOGY

The analytical framework in this study (shown in figure 2) was designed to systematically quantify the seismic vulnerability of low rise reinforced concrete frames typical in Malaysian buildings before the implementation of modern seismic codes. The methodology includes five main steps, namely: (1) formulation of structural archetypes; (2) identification of suitably sized ground-motion records; (3) implementation of IDA; (4) statement of damage states for the subsequent fragility analysis; and (5) modeling of a predictive meta-regression model.

2.1 Fragility Curves

The central output of this research is a set of seismic fragility curves, which are essential tools in modern performance-based earthquake engineering and risk assessment [25]. A fragility curve provides a probabilistic relationship (shown in figure 3) between a given level of seismic intensity and the likelihood that a structure will reach or exceed a predefined damage state [10, 30]. Based on extensive research and common practice, the fragility curve is modeled as a lognormal cumulative distribution function (Φ), a choice supported by the statistical nature of both seismic demand and structural capacity [26]. The function is defined by the equation see Eq. 1).

$$P[DS \geq ds_i | IM = x] = \Phi\left[\frac{\ln(x) - \ln(\mu ds_i)}{\beta_{ds_i}}\right] \quad (1)$$

where:

- $P[DS \geq ds_i | IM = x]$ is the probability that the structural damage (DS) will exceed a specific damage state threshold ds_i given that the Intensity Measure (IM) has a value of x.
- Φ [·] is the standard normal (Gaussian) cumulative distribution function.
- μds_i is the median capacity, representing the IM value at which there is a 50% probability of reaching or exceeding the damage state ds_i.
- β_{ds_i} is the lognormal standard deviation, or dispersion, which represents the total uncertainty in the system, including variability arising from the ground motion, structural modeling, and capacity definition [24].

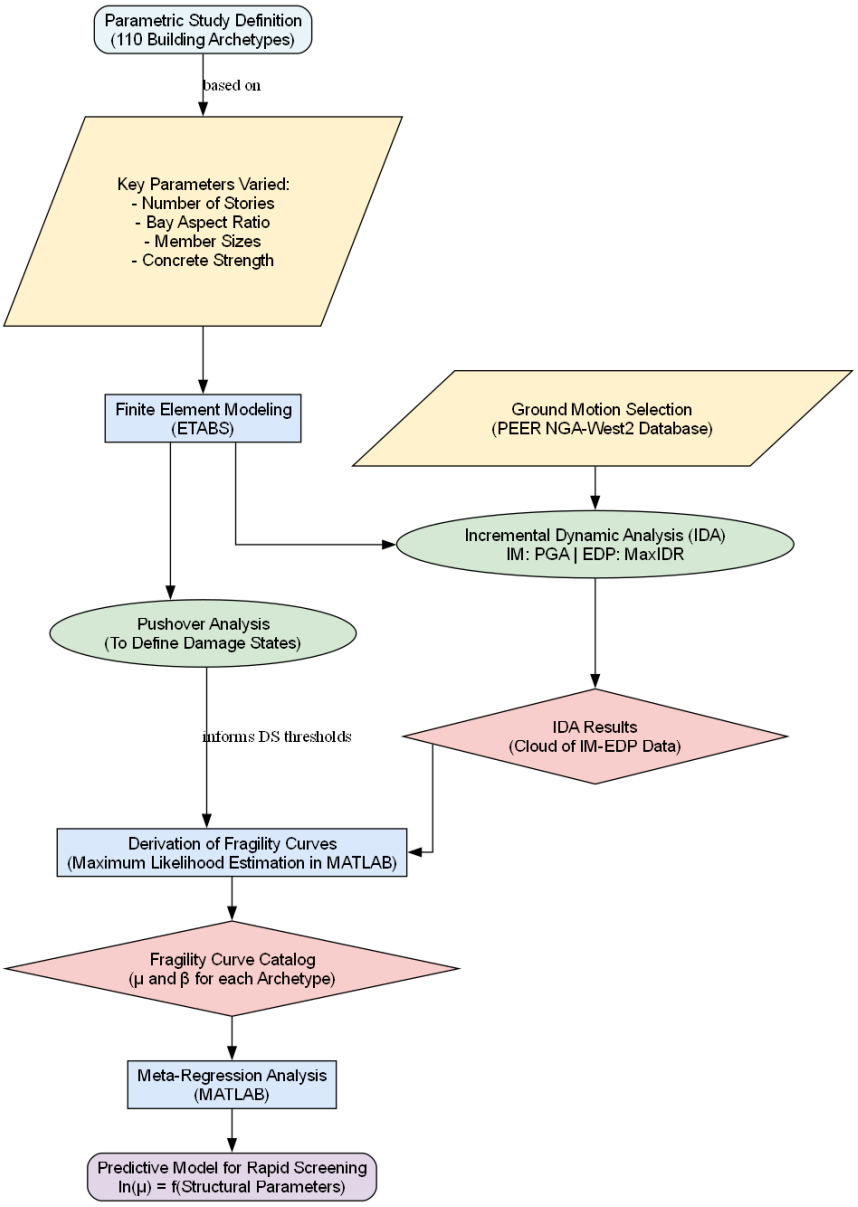


Figure 2. Methodology flowchart

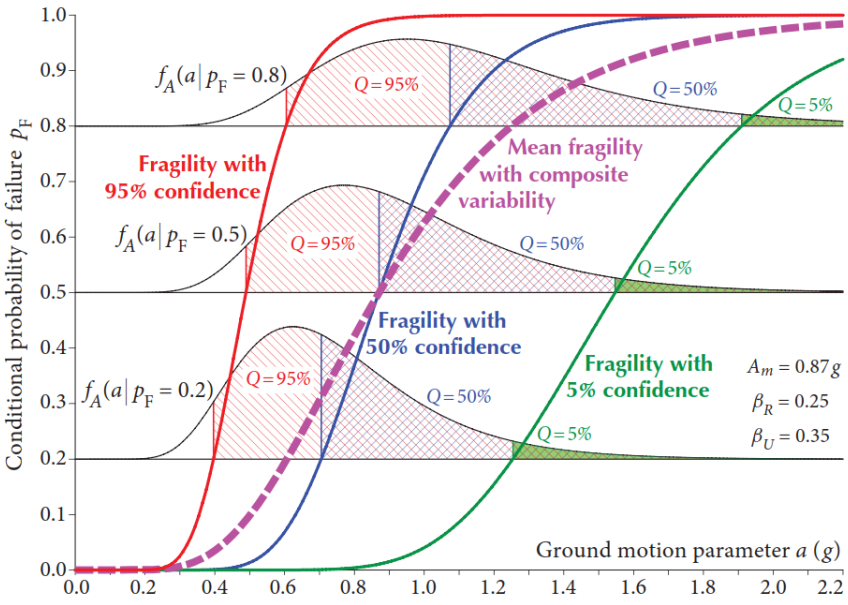


Figure 3. Fragility curves

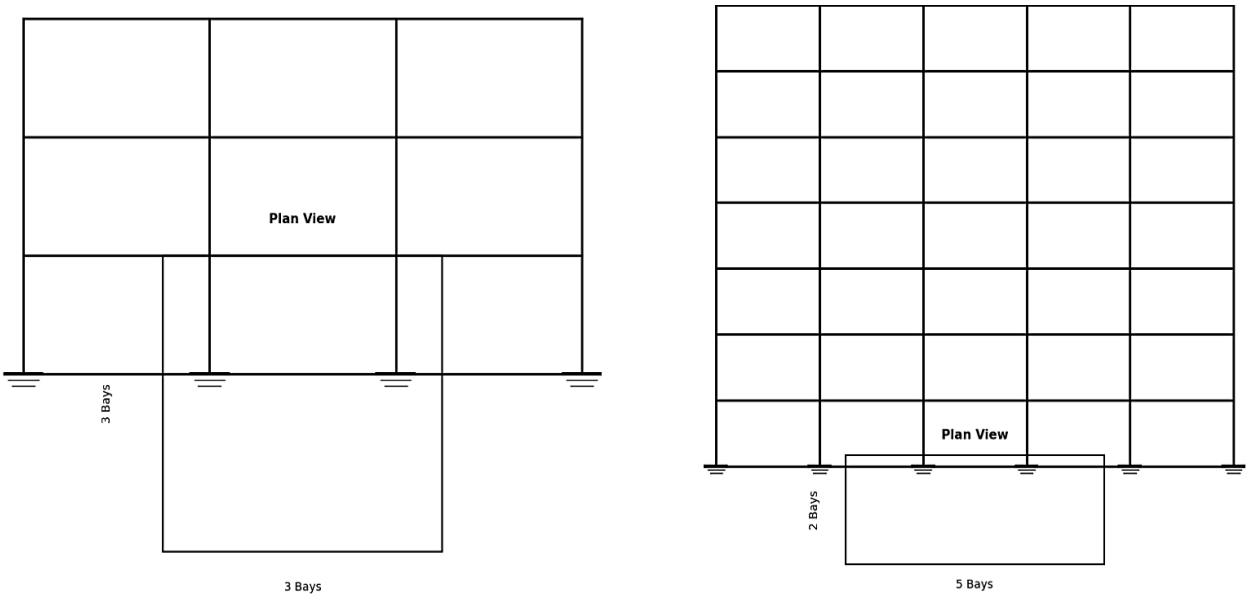
2.2 Archetype Development

A parametric approach was used to systematically investigate the influence of the key design variables on seismic vulnerability of the targeted building stock. This is essential in developing a general understanding of the structural behavior in the absence of extensive experimental data [10]. To this end, a catalogue of 110 archetypes of buildings was created as detailed in Table 4, these models incorporate variations in bay aspect ratio (1, 0.5, 0.33), member cross-sectional dimensions, slab thickness, and concrete compressive strength (30 MPa and 40 MPa). The chosen archetypes are representative of the low-to mid-rise building inventory usually found in Malaysia and similar areas of moderate seismicity [14]. The development process involved the creation of an initial base model, and then a systematic variation of a set of key structural and geometrical parameters to create a matrix of unique structural variants. All numerical models were created and analyzed by the finite-element analysis software ETABS (Computers and [31] shown in fig 4). This methodology has been effectively used in past research to study the effect of certain variables like geometrical irregularities and plan asymmetry [18-20]. The parameters obtained by varying the simulation results are indicated in Table 1.

Table 1. Range of parameters for structural archetypes

Parameter	Minimum Value	Maximum Value
Number of Stories	1	7
Bay Aspect Ratio	0.2	4
Column Size (mm)	600 x 300	750 x 450
Beam Size (mm)	300 x 150	750 x 400
Concrete Strength (MPa)	25	50
Slab Thickness (mm)	150	180

Table 1 describes the comprehensive parametric envelope considered for this research. The investigation methodically covers a vast range of pragmatic structural construction, from one- or two-story edifices to seven story mid-rise constructions. The variation of bay aspect ratio from 0.2 (with great rectilinearity) to 4.0 (with great elongation) is intended to capture the consequences of plan irregularity. Moreover, the range of column and beam geometries explains austere and robust typologies, and the range in the compressive strength of concrete and slab thickness accommodates the divergent construction methodologies. While these geometrical determinants are part of an indispensable foundation, a model that is limited to such parameters would be the equivalent of an idealized construct predicted upon homogenous, characterized material attributes. seismic response. To overcome this limitation, in the present study a fourth important variable is considered: concrete compressive strength (fc"). The integration of material variability is one necessary step towards a more authentic and resilient vulnerability appraisal. [32]. This paradigm shift changes the analytical focus from a juxtaposition of idealized designs to an exploration of the performance envelope inherent to the as - built building stock. Consequently, the approach implicitly recognizes the inherent uncertainties associated with material quality, batching contingencies, and curing conditions that characterize actual construction practice, and thus, it addresses a principal source of dispersion observed within seismic fragility analyses. The structural configurations selected for this study, including variations in story height and bay arrangement, are illustrated in the elevation and plan views (as shown in Figure 4).



(a) (b)

Figure 4. Elevation and plan views of representative building archetypes, illustrating variations in the number of stories and plan aspect ratio. (a) 3-story, 3 bay square-plan model. (b) 7-story, 6x3 bay rectangular-plan model

A suite of nine ground motion records shown in Table 2 was selected from the PEER NGA-West2 database for the IDA. To simplify the extensive computational analysis and limit the study's scope, only a single horizontal component of each record was used (as shown in Figure 5). This approach allowed research to focus directly on the primary objective—assessing the influence of structural and geometric parameters on fragility—without the added complexities of bi-directional or vertical seismic loading.

Table 2. Characteristics of selected ground motion

Earthquake Name	Year	Magnitude	Station Name	Fault Mechanism	PGA (g)
Imperial Valley	1940	6.9	El Centro Array #9	Strike-Slip	0.35
Northridge	1994	6.7	Newhall - Fire Sta	Reverse	0.59
Loma Prieta	1989	6.9	Capitola	Oblique Strike-Slip	0.53
Imperial Valley	1979	6.5	El Centro Array #5	Strike-Slip	0.44
Nanggroe Aceh Darussalam, Indonesia	2016	6.4	Nanggroe Aceh Darussalam	Strike-Slip	0.26
San Fernando	1971	6.6	Pacoima Dam	Reverse-Thrust	1.25
Kern County	1952	7.5	Taft Lincoln School	Reverse	0.18
Landers	1992	7.3	Lucerne Valley	Strike-Slip	0.78
Kobe, Japan	1995	6.9	Takatori	Strike-Slip	0.68

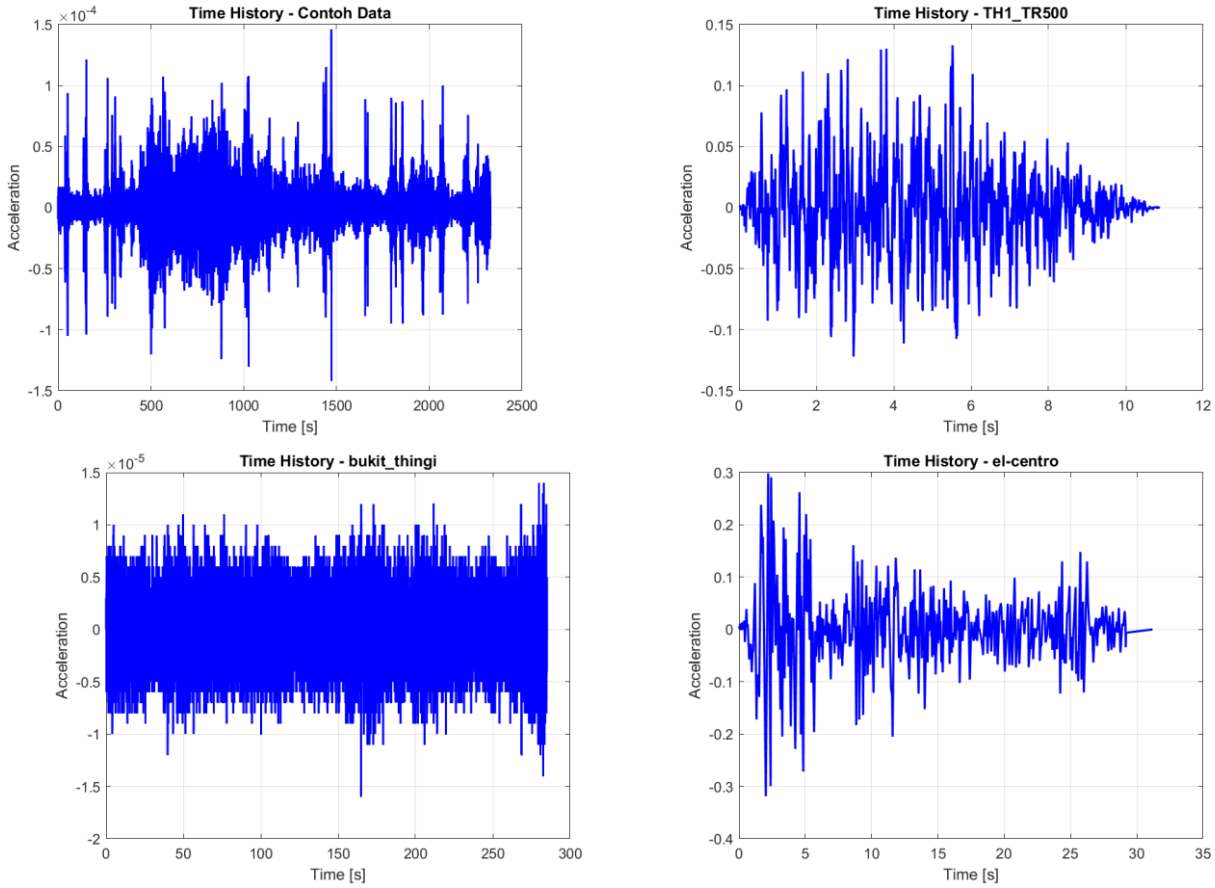


Figure 5. Time histories used in the study

2.3 Derivation of Fragility Function and Definition of Damage States

The fragility functions were calculated from the IDA results five different damage states giving a detailed spectrum of performance. These states, based on the various existing frameworks e.g. HAZUS, are defined as Slight, Moderate, Extensive and Complete (Collapse) [18]. Each of the qualitative damage states was assigned to a quantitative threshold of the MaxIDR. To help put these thresholds into the physical behavior of the structures, nonlinear static (pushover) analysis was performed on each archetype using ETABS. This analysis resulted in an insight on a sequence of yielding and a possible ultimate drift capacity for guiding the choice of MaxIDR limits for each damage state.

The data produced in the IDA simulations in ETABS was exported for further post processing. The resulting cloud of data points was statistically analyzed to calculate fragility function parameters (mu and beta) using custom scratch

programs in the Statistics and Machine Learning Software product line [33] of MathWorks Inc. Maximum likelihood estimation (MLE) was used to estimate these quantities that provides robust and efficient system for fitting the fragility curves to analytical data [27]. Table 3 defines the damage state criteria used in this study, aligning the observed structural degradation with standard performance levels such as Immediate Occupancy and Collapse Prevention. The corresponding drift limits were established to capture the progression from slight damage (DS1) to complete collapse (DS5)

Table 3. Damage state definitions and corresponding inter-story drift ratio (IDR) threshlds

Damage State	Qualitative Description	Median IDR Threshold (%)	Primary Reference Basis
DS1: Slight	Minor hairline cracking in beams and columns; no structural degradation.	0.40	Onset of nonlinear behavior, consistent with Immediate Occupancy (IO) performance level.[1]
DS2: Moderate	Widespread flexural cracking; minor concrete spalling; yielding of some reinforcement.	0.65	Corresponds to significant yielding, aligning with Damage Control or Life Safety (LS) objectives.[1]
DS3: Extensive	Large flexural cracks; significant spalling; buckling of some longitudinal bars.	1.60	Ultimate capacity of some elements reached; significant structural damage.[1]
DS4: Severe	Severe degradation of lateral strength and stiffness; partial collapse of some elements possible.	2.50	Approaching global instability; aligns with Collapse Prevention (CP) performance level.[1]
DS5: Complete	Global dynamic instability; loss of gravity-load-carrying capacity; full or partial collapse.	4.00	Represents the onset of structural collapse.[1]

2.4 Incremental Dynamic Analysis IDA

The seismic performance of each archetype was evaluated using IDA. According to [17] IDA is a robust parametric approach that allows an exhaustive calculation of the recovery performance under seismic loading from elastic limit to the yield and culminating to a global collapse. The IDA process was enacted as follows: Ground Motion Scaling: For each of the nine selected ground motion records a set of scaled accelerograms was generated. Scaling was affected by multiplying the whole-time history by a scaling factor, a (l), in such a manner that the resulting intensity measure corresponded to l times that of the original one: IMscaled = μ IMscaled. In this study, the intensity measure was PGA with target intensities ranging from low intensities (e.g. 0.1 g) to high intensities high enough to cause collapse in the models (Figure 6). Nonlinear Response History Analysis (NRHA): For each scaled accelerogram, a full nonlinear response-history analysis was performed for the selection of archetype. Recording the EDP: The peak value of the engineering demand parameter (EDP) (represented as MaxIDR) recorded at the end of each analysis was recorded and correlated with the corresponding PGA which produced it. Generation of IDA Curves: Pairing values for the energetic rigor hypotheses resulted in only one IDA curve for each archetype-record curve pair. The process was run on all nine records to provide a range of IDA curves for each building archetype. The resulting set of curves represents the record-to-record variability in the seismic response and becomes the main base of data used in the derivation of fragility functions

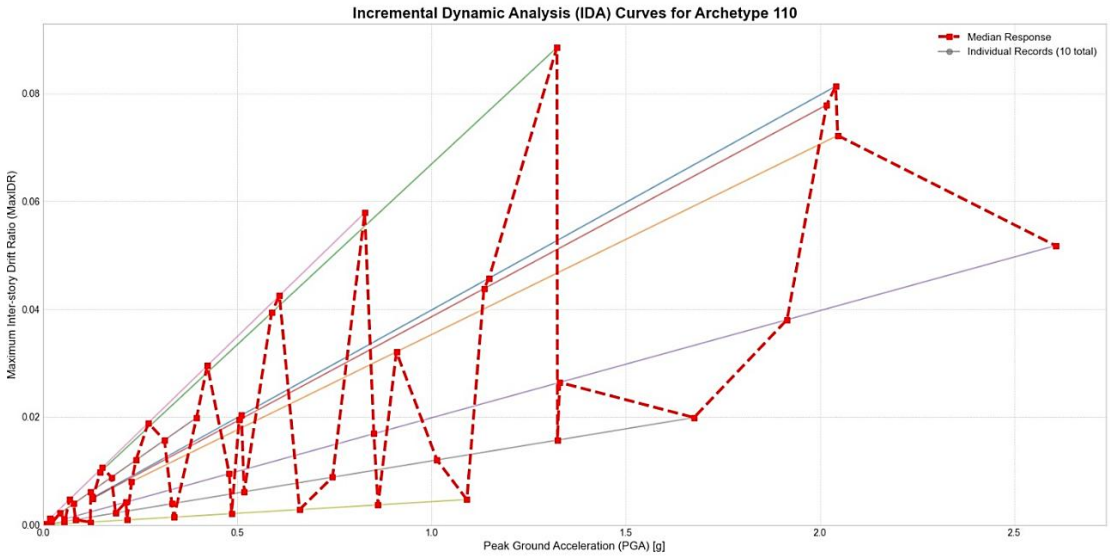


Figure 6. IDA curves for archtype 110, Each thin line represents the response to a single ground motion record, scaled across a range of PGA values. The thick red line shows the median response, and the plot illustrates the significant record-to-record variability in the maximum inter-story drift ratio (MaxIDR)

Figure 6 IDA curves for Archetype 110. Each thin line represents the response to a single ground motion record, scaled across a range of PGA values. The thick red line shows the median response, and the plot illustrates the significant record-to-record variability in the maximum inter-story drift ratio (MaxIDR).

Table 4. Parametric study matrix of building archetypes

Archetype ID	Bay Aspect Ratio	Column Size (mm)	Beam Size (mm)	Slab Thickness (mm)	Concrete Strength (MPa)
1	1	600x300	600x300	160	30
2	0.5	750x450	750x400	150	30
3	0.33	750x450	600x300	180	40
4	1	650x350	600x250	160	30
5	0.5	700x400	300x150	170	40
6	0.33	650x350	750x400	160	30
7	1	700x400	300x150	170	30
8	0.5	600x300	600x250	150	40
9	0.33	600x300	600x300	150	30
10	1	750x450	750x400	150	40
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110	0.33	700x400	600x250	180	40

2.5 Meta-Regression Analysis for Predictive Model Development

One of the most interesting novelties of the present study is the proposal of a prognostic tool for fast vulnerability screening using meta-regression analysis. Finally, the ultimate phase translates all of the vast amount of information resulting from the parametric study into a model that defines a lean, efficient, and functioning protocol. Meta regression analysis was performed using MATLAB toolbox. This procedure builds a dependency between the output of the fragility analyses (that is the fragility parameters) obtained for each archetype and the input parameters that include structural and geometric parameters varied between the analyses. The approach takes advantage of the latest developments in the use of machine learning and statistical modeling techniques for the direct estimation of fragility parameters based on building characteristics [28, 29]. The analysis yields a group of predictive expressions, or "trend line" figures, which relate in a straightforward manner the median seismic capacity associated with each damage state to basic structural design parameters. The general form of regressive model is:

$$\ln(\mu_{DS}) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \quad (2)$$

where μ_DS is the natural log of the median capacity for a given damage state, is the vector of structural parameters (representing number of stories, column area, etc.), are the regression coefficients determined from the analysis, and is the error term. The ultimate goal is to produce a computationally efficient model that can be used by engineers and stakeholders to quickly estimate the vulnerability of large portfolios of buildings without the need to perform complex and time-consuming IDA for each individual structure.

3. RESULTS

3.1 Dynamic Response of Archetype Structures via Incremental Dynamic Analysis

The seismic performance of the 110 building archetypes (see Table 6) was determined by IDA, a detailed process for assessing structural response for a wide range of seismic intensities [17]. For each archetype, a series of nonlinear, response history analyses were carried out with nine different ground-motion records, lineally scaled to several different levels of PGA. The resulting correlation between seismic intensity (PGA) and structural response (in this case maximum inter-story drift ratio (MaxIDR)) is represented in the form of IDA curves. A significant result of this investigation is the large record-to-record variability that was observed in structural response. As an example, in Figure 7 for a representative seven-story archetype, different ground motion recordings result in significantly different drift magnitudes, even if adjusted to the same PGA. This dispersion, which occurs as the familiar "fan" of curves, indicates the degree of uncertainty built into estimating seismic performance and highlights the importance of using a set of ground motions, not one record, for a sound vulnerability assessment [24].

The IDA curves usually have a characteristic pattern of behaviour. At low values of PGA response is approximately linear indicating structure is still within the elastic domain. The greater the intensity, the smaller is the slope of the curves, which indicates the manner through which nonlinearity and structural yielding begin. At higher intensities are many curves which are essentially horizontal or 'flatline', representing the point of dynamic instability or global collapse for the

particular ground motion. This extensive dataset, including the full range of behaviour of all the 110 archetypes, forms the main input of the subsequent fragility analysis.

One of the main governing factors that influence the response of the structure to the earthquake is the overall building height. A comparison of the IDA curves for a low (one-story) building, a mi tes the peak response (MaxIDR) for a ground motion of a specified PGA for an individual. The accumulation of these points for a series of ground motions results in the formation of a "cloud" of results, often the median response d (four-story) building, and a high (seven-story) building structure is shown in Figure 7. Each point on the plot indica is drawn to represent the median or central tendency of the response. The plots clearly show an increase in building flexibility (greater inter-story drift at lower PGA levels) with increasing building height. The first slope of the IDA curves that represents the elastic stiffness is highest for the building with one story and gradually decreases toward the building with seven stories. This pattern is typical of the longer fundamental period of taller, more flexible structures allowing an increase in the susceptibility to the infliction of damage by displacement [35, 36].

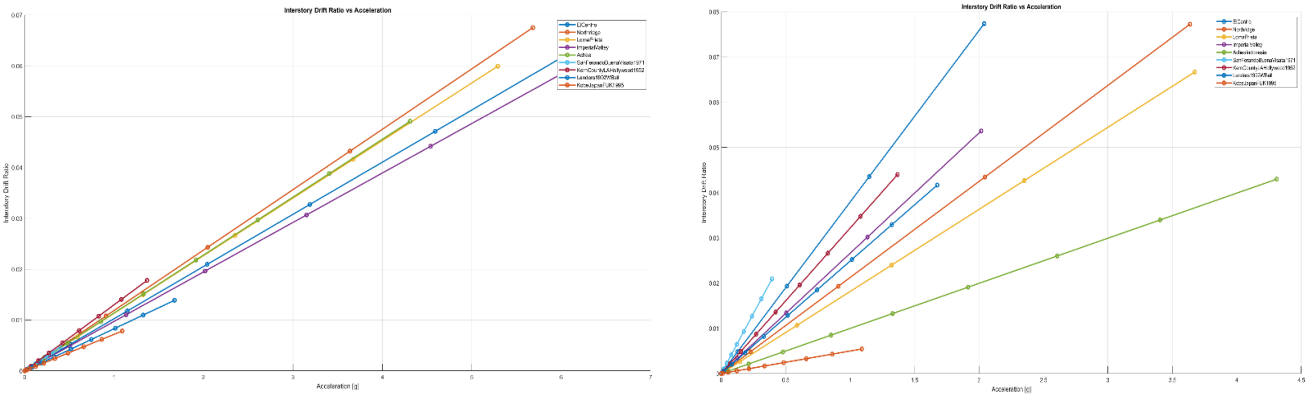


Figure 7. IDA curves for low and midrise structures

3.2 Development of Seismic Fragility Curves

The large amount of data produced through IDA was used to create the probabilistic seismic fragility functions for each one of the 110 building archetypes. The resulting functions give quantitative measure of seismic vulnerability by relating ground-shaking liquidity (PGA) and the probability of damage. When the structural fragility functions were developed using a lognormal cumulative distribution function, with a median capacity (μ) and a dispersion parameter (β), For example as can be seen in table 5,6 and 7, analysis of the three-storey archetype (ID 31) gave a median collapse capacity (μ 50%) of 1.056 g and a dispersion (β) of 0.456, while for the seven-storey archetype (ID 101) the median collapse capacity was significantly lower (50% μ = 0.579 g; β = 0.446, that is, greater vulnerability). Which means that the vulnerability increaseswith the increase in story height i.e. with higher stories the value of the mean decreases as can be seen in Table 5.

Table 1. Fitted coefficients for the meta-regression model for median capacity

Parameters	DS1 (Slight)	DS2 (Moderate)	DS3 (Extensive)	DS4 (Complete)
Intercept	-1.1392	-0.7289	-0.2172	0.2319
Story	-0.1227	-0.1378	-0.1511	-0.1651
BayX	-0.0638	-0.0768	-0.0911	-0.1042
BayY	-0.0436	-0.0526	-0.063	-0.0725
ColumnSize	0.8358	0.9634	1.0968	1.2531
BeamSize	0.1704	0.1293	0.0811	0.0384
SlabThickness	0.514	0.5513	0.5841	0.6091
ConcreteStrength	0.2974	0.3015	0.3039	0.3021

This process started by extracting five different damage states (DS), which varied from Slight to Complete (Collapse), each of which was associated with a quantitative maximum value of inter-story drift ratio (MaxIDR). For each of the archetypes and for each of the damage states, the IDA results were interpreted to identify the PGA value at which the damage state threshold was exceeded by that record. The resulting family of curves, as exemplified for the five-storey model (Iteration 66) is a comprehensive summary of its seismic vulnerability. Median capacity decreases with building height were found for all buildings, evidencing quantitatively that a taller and more flexible building from the studied stock presents a greater likelihood of presenting a severe damage state at lower levels of ground shaking. Figure 8 shows the Fragiliy Curves for Damage State (DS1 to DS5) from Story 1 to Story 7.

Table 6. Fitted coefficients for the meta-regression model for dispersion SD

Parameter	DS1 (Slight)	DS2 (Moderate)	DS3 (Extensive)	DS4 (Complete)
Intercept	0.6121	0.6019	0.5888	0.5802
Story	-0.0101	-0.0118	-0.0135	-0.0145
BayX	0.0051	0.0053	0.0055	0.0055
BayY	0.0035	0.0037	0.0038	0.0039
ColumnSize	-0.1167	-0.1343	-0.1524	-0.1685
BeamSize	-0.0031	-0.0021	-0.0009	-0.0002
SlabThickness	-0.0205	-0.0209	-0.0211	-0.0212
ConcreteStrength	0.0008	0.0009	0.001	0.0011

Table 7. Combined matrix of meta-regression coefficients for median capacity, ln(μ)

Parameter	Level	DS1 (Slight)	DS2 (Moderate)	DS3 (Extensive)	DS4 (Complete)
Intercept	-	-1.1392	-0.7289	-0.2172	0.2319
Story	Story1	0	0	0	0
	Story2	-0.1088	-0.2175	-0.435	-0.8701
	Story3	-0.1668	-0.3337	-0.6673	-1.3347
	Story4	-0.2229	-0.4458	-0.8916	-1.7832
	Story5	-0.2426	-0.4852	-0.9703	-1.9406
	Story6	-0.2347	-0.4694	-0.9388	-1.8777
	Story7	-0.2468	-0.4935	-0.987	-1.9741
BayX	1	0	0	0	0
	2	-0.0078	-0.0156	-0.0313	-0.0626
	3	-0.0064	-0.0128	-0.0257	-0.0513
	4	-0.0169	-0.0337	-0.0675	-0.135
BayY	1	0	0	0	0
	2	-0.0106	-0.0213	-0.0425	-0.0851
	3	-0.0172	-0.0343	-0.0686	-0.1373
	4	-0.0132	-0.0264	-0.0528	-0.1057
	5	0.0092	0.0184	0.0368	0.0736
ColumnSize	600 x 300	0	0	0	0
	650 x 350	0.0077	0.0153	0.0307	0.0613
	700 x 400	0.0501	0.1001	0.2003	0.4006
	750 x 450	0.0858	0.1715	0.3431	0.6862
BeamSize	300 x 150	0	0	0	0
	450 x 200	0.0034	0.0068	0.0136	0.0273
	600 x 250	0.0431	0.0863	0.1726	0.3451
	600 x 300	0.0348	0.0695	0.139	0.278
	650 x 250	0.0323	0.0646	0.1293	0.2586
	650 x 300	0.0267	0.0534	0.1068	0.2136
	700 x 350	0.0379	0.0759	0.1518	0.3036
	750 x 400	-0.0025	-0.0049	-0.0098	-0.0196
SlabThickness	150	0	0	0	0
	160	-0.0151	-0.0303	-0.0605	-0.1211
	170	-0.0164	-0.0329	-0.0657	-0.1315
	180	-0.0157	-0.0314	-0.0629	-0.1257
Concrete Strength	25	0	0	0	0
	30	0.0095	0.019	0.038	0.076
	35	0.0024	0.0048	0.0096	0.0191
	40	0.0136	0.0272	0.0543	0.1086
	50	0.0064	0.0129	0.0258	0.0515

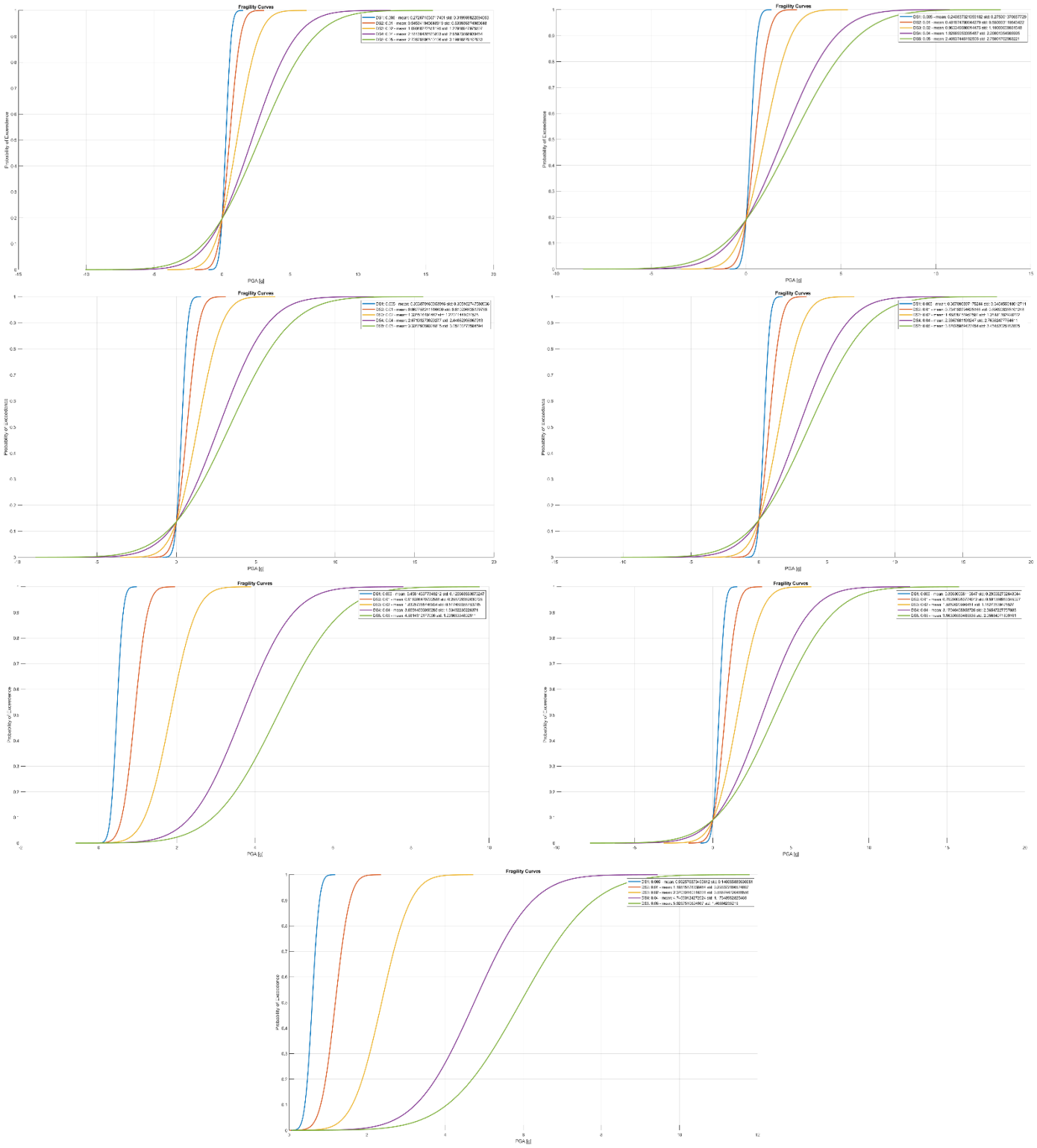


Figure 8. Fragiliy curves for damage state (DS1 to DS5) from story 1 to story 7

4. DISCUSSION

The present study has developed a complete fragility catalog for a class of gravity-loaded reinforced concrete frames typical of Malaysia and other moderate seismic regions. The parametric approach, which includes 110 building archetypes, has provided significant insights into the factors influencing seismic vulnerability. The results of the meta-regression analysis (Tables 5, 6, and 7), in which fundamental design parameters are quantitatively correlated with seismic performance, enable a deeper interpretation of these results. A key finding is the clear hierarchy of importance among the structural parameters. The number of stories and the cross-sectional area of the columns were found to be the main factors in seismic vulnerability. This is immediately evident in the regression coefficients for collapse (DS4) in Table 5, where ColumnSize (1.2531) and Story (-0.1651) show a significantly larger impact on median capacity than any other parameter.

The strong negative correlation between the number of stories and the median collapse capacity confirms known principles of structural dynamics: as building height increases, its flexibility grows, which extends the fundamental period of vibration. This can aggravate displacements and the P-Delta effect, accelerating collapse. The model quantifies this dramatically; analysis of Table 7 shows that, all else being equal, a seven-story building has a median collapse capacity (μ coefficient of -1.9741) that is approximately 86.2% lower than an equivalent one-story building. This is a crucial aspect for the fast-growing urbanity in areas like Malaysia, where mid-rise buildings are common.

Conversely, the high influence of column size reflects the critical role of column strength and stiffness in providing lateral resistance. The meta-regression model in Table 7 shows that increasing the column size from the smallest (600x 300 mm) to the largest (750 x 450 mm) provides a benefit of +0.6862. This translates to an approximate 98.6% increase in median collapse capacity, highlighting that strong columns are highly effective in preventing soft-story mechanisms a failure mode to which gravity-designed frames are notoriously prone. Perhaps the most sophisticated inference is the dual role of column size. As noted, it exerts the largest positive impact on the median seismic capacity (for DS4, per Table 5). Simultaneously, it also exerts the largest negative impact on the fragility dispersion, or uncertainty (-0.1685 for DS4, per Table 6). Consequently, larger columns not only make a building more structurally robust on average but also make its seismic performance more reliable and predictable. This minimization of uncertainty has huge practical significance in risk assessment, as it leads to a higher level of confidence in performance predictions.

The influence of other parameters, such as beam size, was found to be secondary. For collapse (DS4), the regression coefficient for column size (1.2531) is over 32 times larger than that for beam size (0.0384), as shown in Table 5. The model also supports the "strong column-weak beam" design philosophy, showing that an indiscriminate increase in beam size has low benefit and, in some instances, can even slightly diminish the collapse capacity. Table 7 shows that while moderate beams add capacity, the largest beam size (750 x 400) actually has a small negative coefficient (-0.0196), suggesting it may contribute to a less desirable failure mode. The practical consequences of these results for moderate seismic areas are enormous. The meta-regression model that has been developed is a scientifically-based and computationally-fast method to screen large building inventories. Rather than requiring non-linear analyses on a per-building basis, engineers and policymakers can use this model to quickly identify vulnerable building typologies and prioritize them for detailed analysis or retrofitting. Such a targeted approach is essential for the effective allocation of limited resources to maximize risk reduction.

Finally, it is important to note the limitations of this study. The analyses are computer-based on ideal numerical models. Although the archetypes were developed systematically, they cannot cover the full range of irregularities and as-built conditions in the real building stock. Moreover, the study considered a specific set of ground motions and did not explicitly incorporate epistemic uncertainties in material properties or damage state definitions. Future research could expand on this work by increasing the parametric space to include additional irregularities (e.g., vertical setbacks), verifying the models with experimental testing, and incorporating a wider variety of uncertainties in the fragility analysis.

5. CONCLUSION

This study undertook an exhaustive parametric seismic vulnerability analysis of low - mid - rise, gravity - load - designed, reinforced reinforcement of moment resisting frame, a building typology that is common in Malaysia, and areas of moderate seismicity. A catalog of 110 building archetypes was created by the systematic variation of selected structural and geometric parameters. Using IDA an elaborate fragility catalog was produced. This data set was then synthesized into a predictive meta-regression model that can conduct rapid screening for vulnerability. Based on the results of this research the following important conclusions are drawn: A reasoning through all detailed fragility database for non-ductile RC frame has been developed in which a quantitative measure of its vulnerability to seismic events are provided. The results are a confirmation that many common configurations within this building class have a significant chance of substantial damage or collapse at PGA levels which could realistically be experienced in moderate seismic zones. The number of stories and column cross section area are the two dominant parameters that control the seismic behavior of these frames. Vulnerability is increased considerably by building height; greater columns giving the best chance of increasing seismic capacity and averting catastrophe as buildings collapse. Column size was another factor that was identified as the most critical factor for reducing uncertainty in the seismic response. Archetypes with larger columns had reduced fragility dispersion (with a beta value) reflecting a more reliable and predictable performance, which is a vital attribute for consideration of life safety. The developed meta-regression model makes an accurate prediction of median seismic capacity of the archetypes in function of the fundamental characteristics of those archetypes, in terms of their design parameters (R-squared = 0.89). This model provides a validated and computationally efficient tool for rapid seismic screening of large building inventories.

Ultimately this research offers actionable, data driven insight for engineers, planners and policymakers. By categorizing the structural components of critical infrastructure of Malaysia and determining the states which are most vulnerable to the earthquake occurrence, this study provides the scientific foundation for tasks like prioritization of retrofitting work, serving as the foundation for future design guidelines, and/or including how to improve the urban resilience of Malaysia and other regions facing similar seismic threats.

6. RECOMMENDATIONS

Based on the findings and limitations of this study, several areas are recommended for future research. Future models could expand the parametric space to incorporate a wider range of structural complexities, such as vertical irregularities (e.g., setbacks) and plan asymmetries, to assess their impact on fragility. The current study was also limited to uni-directional horizontal ground motion; future analysis should investigate the effects of bi-directional horizontal loading and the influence of the vertical component of ground motions. Furthermore, this analysis focused on record-to-record variability, so future work could provide a more comprehensive risk profile by incorporating epistemic uncertainties related to material properties, construction quality, and damage state definitions. Finally, physical testing of representative frame-joint-assemblies or shake-table tests could be conducted to experimentally validate the numerical models and their damage state assumptions.

DECLARATIONS

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

Muhammad Waqas (Conceptualization, Investigation, Methodology, Writing Original Draft)
Saffuan Wan Ahmad (Supervision, Validation, Writing, Review & Editing, Project Administration, Funding Acquisition)
Omair Shafiq (Methodology, Software, Formal Analysis, Data Curation, Visualization, Writing Original Draft)
Faheem Ishaq (Investigation, Validation, Writing Review & Editing)
Muhammad Aim Amzar Kamaruddin (Writing Review & Editing)

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