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A COLLABORATIVE FRAMEWORK TO MODEL THE SEISMIC VULNERABILITY OF RC BUILDINGS USING SIMULATED DESIGN

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Abstract

The seismic vulnerability assessment of the diverse categories of buildings found across building stocks requires specific methodologies that can capture the wide range of standards, regulations, construction practices, architectural layouts, earthquake design scenarios, and available knowledge. Previous vulnerability models have employed varying assessment approaches, building taxonomies, representations of seismic loading, and, in some instances, relied on a limited number of representative structures to represent an entire building class. Consequently, these models often fail to fully capture building-to-building variability and inadequately address multiple sources of uncertainty, particularly in models intended for large regional applications. Addressing these issues requires a probabilistic approach where seismic vulnerability is assessed using models of building portfolios that are able to reflect, in a unified manner, features related to engineering design practice, as well as construction variability and quality.

In this context, this paper introduces a collaborative framework that performs the simulated design of European reinforced concrete buildings, and presents its integration into the Built Environment Data platform via developed open-source software tools. In particular, it describes how the simulated design approach considers past and current seismic design procedures and how it reflects building-to-building variability. Through the use of open-source software and open data, the structural engineering community in Europe can contribute to the database of design codes covered by the framework. Following the design process, the referred tools generate the *OpenSees* computational models that can then be used to perform nonlinear analyses of the designed buildings and obtain probabilistic seismic demand models. These will ultimately support the development of fragility functions and vulnerability models. The framework's simulated design capabilities are demonstrated through a series of examples that highlight notable distinctions among the building classes under consideration and emphasize the importance of the attributes involved in the analysis.

Keywords: building portfolio, building variability, design codes and regulations, nonlinear model, open-source; seismic design, simulated design, reinforced concrete.

1. Introduction

In seismic risk assessment, physical vulnerability modelling plays a crucial role in evaluating the seismic performance of buildings during earthquakes. This typically involves developing fragility functions, which describe the probability of a structure reaching or exceeding a certain damage state, given the occurrence of a specific intensity of ground shaking. Several methodologies exist for deriving fragility functions [1], with analytical approaches (e.g., [2,3]) being widely adopted due to their transparency and objectivity, despite high computational demands.

Over the years, several national [4–7] and regional [8–10] initiatives have contributed to the development of fragility functions. While these studies have significantly advanced the field, they often rely on generalized building classes, limited archetype models, or simplified assessment approaches that fail to fully capture building-to-building variability and multiple sources of uncertainty. A systematic approach is needed to integrate diverse construction practices, evolving design codes, and regional seismic demands into vulnerability models.

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To tackle some of these challenges, which are also prevalent across Europe, the European exposure model [11], developed as part of the Horizon 2020 SERA project (http://www.sera-eu.org), introduced an improved taxonomy for RC frame buildings. This approach integrates seismic design code evolution and seismic demand zonation as key classification attributes. Traditional exposure models mainly use morphological characteristics such as construction year, number of storeys, material type. However, these parameters alone do not adequately reflect a building's strength or ductility. Earlier methods attempted to classify ductility levels based on construction era and regional seismicity, but they lacked adaptability across different time periods and geographical areas. To address this, Crowley et al. [12] proposed a novel mapping scheme that separates seismic strength (represented by the design lateral force coefficient, β) from seismic design principles (reflecting ductility-related aspects). In that mapping scheme, the taxonomy is comprised of four design classes, representing the prevalent seismic design practices in Europe during different periods (CDN: absence of seismic design, CDL: designed for lateral resistance using allowable stress design, CDM: designed for lateral resistance with modern limit state design, and CDH: designed for lateral resistance as in CDM coupled with target ductility requirements). The adoption of these categories provided a harmonised classification of seismic design practices across Europe, capturing not only significant changes in seismic zonation but also the evolution of seismic design regulations, structural engineering principles, and construction techniques. While initially developed for RC frame structures in Europe, this framework has the potential to be expanded to include additional building taxonomies tailored to specific national contexts.

While Crowley et al. [12] improved RC building classification, exposure models still lack detailed geometric and structural attributes. In this regard, simulated design procedures, as recognized in Eurocode 8 – Part 3 [13], offer a solution by reconstructing historical design decisions with minimal input variables such as geometry, material properties, and construction quality. Previous studies (e.g., [14–17]) have applied these methods to automate building layout generation and reduce epistemic uncertainty in vulnerability assessments. This methodology was also applied in developing vulnerability curves for low- to mid-rise RC frame buildings, reflecting typical European construction practices, as part of the 2020 European Seismic Risk Model [18]. To account for variability among buildings within the same classification, unknown geometric variables and attributes were stochastically assigned based on statistical distributions.

However, building properties such as span lengths, story heights, and material strengths vary significantly by region, and building codes can evolve differently in response to the seismic events. In fact, a detailed analysis of a specific country's standards (e.g., [19]) can reveal deviations from the generalised building class definitions proposed in Crowley et al. [11]. Current simulated design methods are usually in line with specific design codes, but they lack a broader, adaptable framework. Additionally, despite their influence on seismic performance, many approaches do not incorporate common design practices, such as column uniformity, preferred section dimensions, and reinforcement limits. A further limitation is the discrepancy between real buildings and those strictly modelled using design rules, as construction quality affects material properties, detailing, and geometric configurations. These factors are rarely integrated into seismic design frameworks, reducing the accuracy of risk assessments [20]. Furthermore, no existing framework systematically incorporates modelling strategies to address building class deficiencies identified through experimental (e.g., [21,22]) or post-earthquake reconnaissance studies (see [23,24]).

To address these challenges systematically, this paper briefly introduces a flexible, unified simulated design framework that extends the SERA project's advancements using object-oriented programming in Python. A key innovation is the adoption of composition over inheritance, enabling the development of scalable structural design solutions that accommodate past and present design codes while maintaining the adaptability and generality of the design procedures. The framework generates simulated designs for building portfolios having randomised general characteristics and produces corresponding computational models that account for construction quality effects. These will ultimately support the development of fragility functions and vulnerability models that account for building-to-building variability. While the current focus is RC moment-resisting frame (MRF) buildings, the framework is adaptable to other structural types. As an open-source tool based on widely used

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programming languages, the framework encourages contributions from the engineering community, facilitating the integration of diverse seismic design practices. To further support collaboration, the *SimDesign* framework proposed herein will be incorporated into the Built Environment Data (BED) initiative (www.builtenvdata.eu). To demonstrate its applicability, a series of case studies are carried out based on European design practices, highlighting influence of the variations in building taxonomy attributes and geometry on seismic design and capacity.

2. Methodology

The proposed simulated design framework offers a clear four-step workflow (illustrated in Figure 1) for generating representative structural designs of a building stock within a specific region and their corresponding 3D nonlinear numerical models in *OpenSees* [25]. These models support the development of vulnerability models, ensuring that key variables influencing building behaviour are clearly defined, thereby enabling an accurate description of building taxonomy.

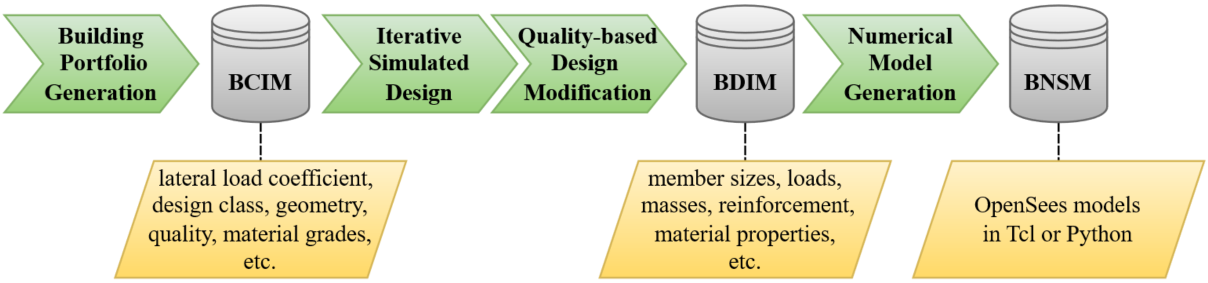

Figure 1. General overview of the workflow defined for the proposed simulated design framework.

The first step of the framework involves generating an information dataset that defines the general characteristics of buildings within a given portfolio. This dataset includes primary attributes, such as the number of storeys, β, and design class, which reflect region-specific seismic design practices in effect. Additionally, secondary attributes, including material grades and construction quality levels, as well as geometry variables like in-plan configurations and storey heights, are assigned to account for building-to-building variability. These attributes are determined through random sampling from probability distributions, which can be derived from existing databases or adjusted to align with regional contexts. The dataset generated at this stage is stored in the *Building Class Information Model (BCIM)* database, serving as the foundation for the subsequent design process.

In the second step, each building realization within the BCIM undergoes a simulated design process that replicates engineering decision-making to produce feasible structural solutions. Accounting for regional seismicity through β, this process iteratively determines structural member dimensions and reinforcement layouts, ensuring compliance with applicable seismic design codes and construction practices. The design methodology is adaptable, allowing for buildings to be modelled using gravity-load-only designs, as in older structures, or seismic load combinations, as in modern seismic-resistant buildings. Likewise, the framework can integrate country-specific design classes while preserving the flexibility of its iterative design algorithms. This adaptability supports the ongoing enhancement of the framework, ensuring its relevance across various regions and its ability to accommodate changing seismic design standards.

The third step introduces construction quality modifications to reflect real-world deviations from idealized designs. Variations in material properties, reinforcement detailing, and potential spatial irregularities are incorporated to capture differences in workmanship and construction standards. These modifications account for construction quality levels categorized as *low*, *moderate*, or *high*, ensuring that the final structural models realistically represent as-built conditions rather than purely theoretical designs. At the end of this stage, the *Building Design Information Model (BDIM)* database is created, storing final building details, such as material properties, reinforcement configurations, and section dimensions.

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The final step involves the development of numerical models in *OpenSees*, utilizing both *.tcl* and *.py* interpreters [26]. These models incorporate structural features associated with both construction quality and design classifications, enabling realistic seismic performance assessment. Specific failure mechanisms, such as shear failure in non-capacity-designed columns and bond-slip effects in low-quality construction, are explicitly modelled. Additionally, along with the generated numerical models, modal and nonlinear static pushover analyses routines are stored in the *Building Nonlinear Structural Model (BNSM)* database.

To support future extensions and facilitate its applicability the framework is implemented in Python [27] using object-oriented programming to ensure modularity and scalability (available at https://github.com/builtenvdata/simulated-design). Its implementation for the RC-MRF systems consists of four core packages: *geometry*, *bcim*, *bdim* and *bnsm*, each contributing to the execution of the described workflow. The following sections provide a detailed explanation of the general steps followed in this implementation while omitting software-specific details for brevity.

3. Building Portfolio Generation

For large-scale seismic risk assessments, buildings within an exposure model are categorized based on key structural attributes [28]. In the SERA project, the primary attributes used for classification include the construction material, lateral load-resisting system, number of storeys, and expected ductility level, which is inferred from the seismic design regulations in place at the time of construction (i.e., the design class) and the hazard level (represented by β). These attributes are combined to generate a taxonomy string [28,29], which serves as an identifier for each building class. When additional data is available, the taxonomy can be further refined to include beam and column types, construction quality levels, and material properties. However, since detailed structural information is often unavailable, the uncertainty associated with these secondary attributes must be incorporated into the building portfolio. Additionally, buildings sharing the same taxonomy string can exhibit significant geometric variations, such as differences in in-plan layouts, bay widths, and storey heights. These variations are inherent to the building stock and must be accounted for to adequately capture the building-to-building variability.

To address these uncertainties, the framework utilizes the primary attributes (i.e., number of storeys, design class, and β coefficient) to generate probabilistic samples of secondary attributes and geometry variables. The secondary attributes include those provided in Table 1, and steel and concrete grades, which are mapped to their respective material properties during the design process. The geometry variables considered in sampling include typical and ground storey heights, bay widths along principal directions (X and Y), staircase bay width along the X axis, and layout configurations. The layout database currently represents each configuration by the number of evenly spaced bays in both horizontal directions and the designated staircase location, though it can be expanded to include irregular plan layouts. The resulting BCIM dataset, generated for a given sample size or portfolio, provides a comprehensive set of attributes and geometric properties for each building, guiding the simulated design process.

Table 1. The secondary taxonomy attributes in BCIM concerning beams, columns and slabs.

Colum Type	Beam Type	Slab Type	Construction Quality
Square	Emergent (EB)	Solid two-way cast-in-situ slabs (SS2)	Low
Rectangular	Wide (WB)	Solid one-way cast-in-situ slabs (SS1)	Moderate
-	-	Composite slabs with pre-fabricated joists and ceramic blocks (HS)	High

The sampling process, managed by the *bcim* package and illustrated in Figure 2, employs random generators and decision trees informed by engineering experience and judgment. The random generators apply probability distributions to model the general characteristics of a given building stock, while the decision trees establish correlations between certain random properties and other structural

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attributes, often incorporating assumptions from the design process. Before initiating the sampling, the framework retrieves probabilistic model parameters from a corresponding data file (a .json[1] file specific to the design class, e.g. CDL). While default values are provided for each parameter, they can be modified by the user to reflect more accurate or region-specific building data.

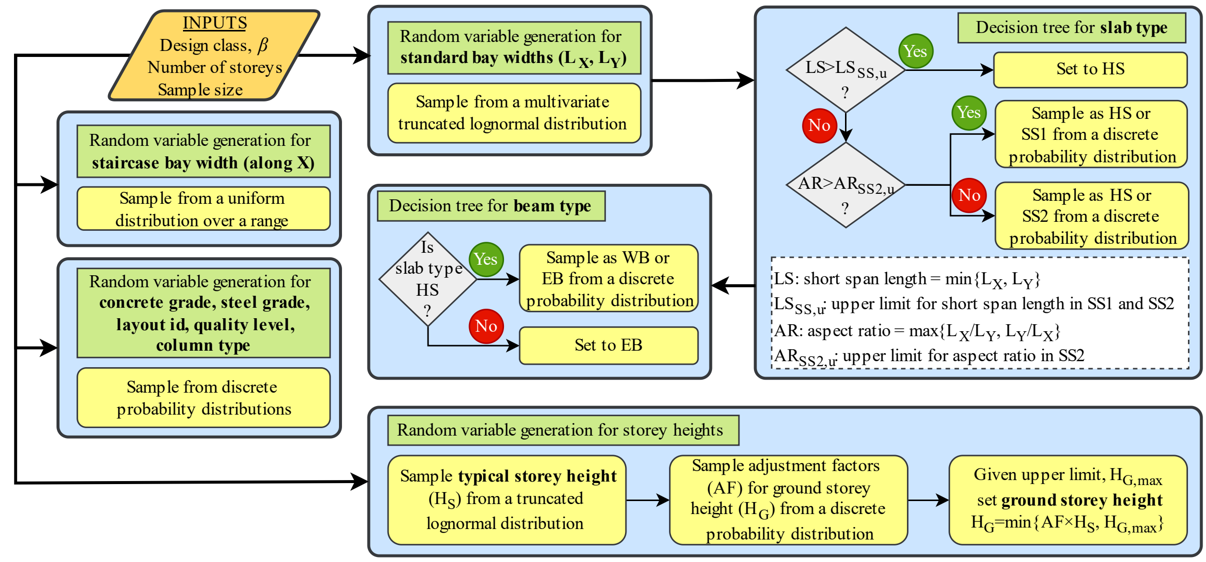
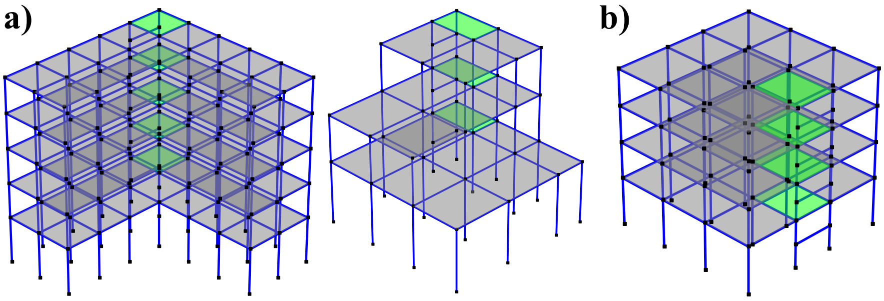


Figure 2. Illustration of the sampling process for BCIM data generation, with sampled data highlighted in bold.

After generating the dataset, the framework utilises the *geometry* package to initialize building geometries as Python objects, defining each building's grid system based on its in-plan layout and number of storeys, with grid spacing determined by bay widths and storey heights. Structural components, i.e., beams, columns, joints, slabs and staircases, are represented as mesh objects, ensuring proper connectivity during design and numerical modelling. While the framework supports irregular geometries, the current layout database is limited to regular, orthogonal configurations (see Figure 3). Moreover, it is worth noting that the buildings feature a single continuous staircase, supported by X-direction beams at mid-storey levels. Once the BCIM dataset and building geometry objects are created, they serve as inputs for the simulated design process, and guide the development of the BDIM dataset.

a) b)



Layouts Database

Layout ID	Number of bays in X	Number of bays in Y	Staircase grid in X	Staircase grid in Y
B01	3	2	1	0
B02	5	2	2	0
B03	7	2	3	0
B04	3	3	1	0
B04b	3	3	1	1
B05	5	3	2	0
B06	7	3	3	0
B07	3	3	0	0
B08	3	4	0	0
B09	3	5	0	0
B10	3	6	0	0

Figure 3. Example of a-) Irregular and b-) regular frame geometries (green indicates staircase location).

4. Iterative Simulated Design

Regardless of the country or region, the seismic design of RC frame buildings follows a structured sequence of steps based on engineering principles and regulatory building codes. The process begins with defining seismic loads and general building characteristics. Engineers determine the seismic

[1] An example of .json file, available on the following GitHub repository:
https://github.com/builtenvdata/simulated-design/blob/main/simdesign/rcmrf/bcim/data/eu_cdl.json

hazard level for a given location and return period, typically represented by peak ground acceleration or derived from an elastic acceleration response spectrum. These are then adjusted based on site-specific conditions, building importance, and behaviour factors to determine the design lateral force coefficient or the design acceleration response spectrum. It is worth noting that, herein, the former serve as the seismic hazard input for the framework. Simultaneously, the architectural layout is assessed to identify the placement of key structural components, including beams, columns, and slabs, and to define the lateral load-resisting system. Finally, the initial structural member types and materials are selected, completing the conceptual design phase. As outlined previously, the framework compiles this information in the first step to guide simulated design process, which implements the iterative design algorithm illustrated in Figure 4.

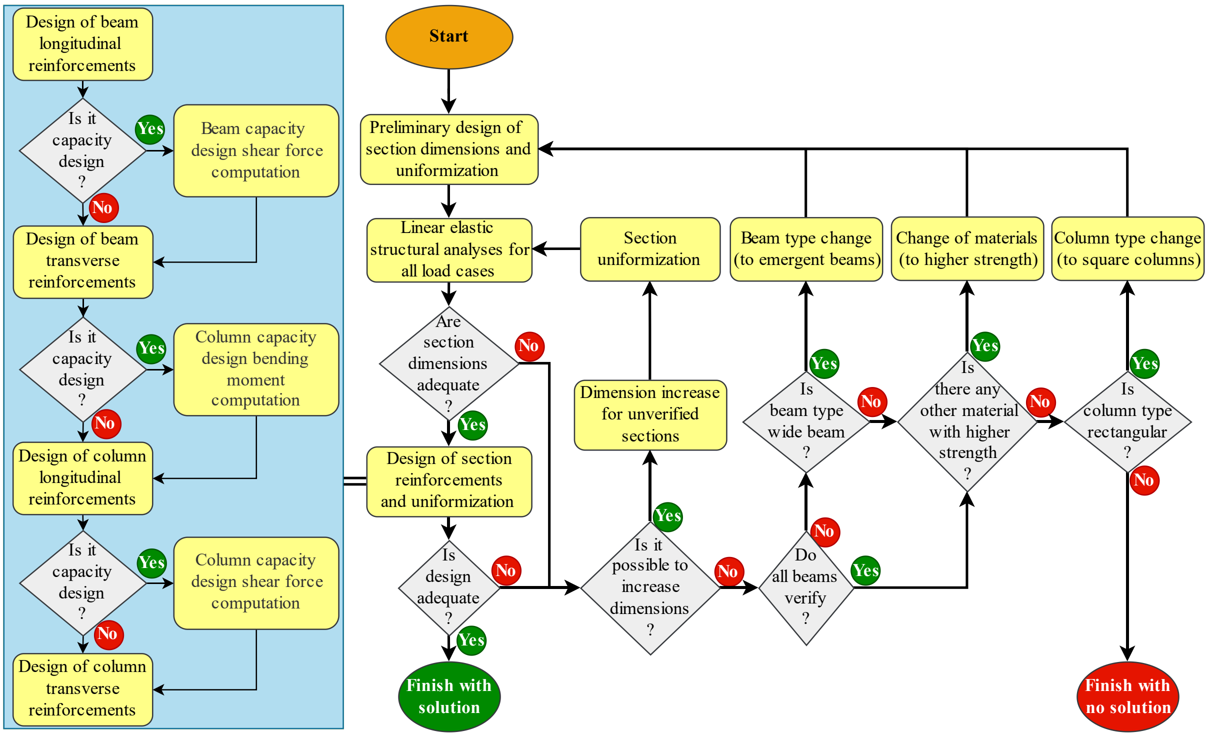


Figure 4. Iterative design algorithm implemented in the framework.

The iterative simulated design procedure begins with the preliminary member sizing, where initial dimensions for columns, beams, and slabs are established based on engineering practice rules, building code requirements, and expected gravity loads. These initial dimensions serve as a baseline for subsequent design iterations. As a common practice, the section dimensions are then standardised to ensure uniformity in beam sections along continuous spans and column sections along the building height. Notably, column dimensions can be uniformised over a specified number of storeys based on the construction practices rather than the entire building height.

Following the preliminary design, an elastic numerical model is developed, and linear elastic analysis is conducted for various loading scenarios. Seismic loads are applied using the equivalent lateral force method, with stiffness adjustments are made to account for cracked section properties where required. The computed member forces are then combined following the load combinations prescribed by building codes. Subsequently, the section dimensions of each member are verified against the design forces. This process includes assessing economic feasibility, verifying admissible stresses, and performing global checks such as drift limits if required by the code.

The next step involves reinforcement design, which follows either working (or allowable) stress design (for older codes) or limit state design (for modern codes). The reinforcement configuration is determined based on available steel diameters and detailing practices. If capacity design principles apply, the procedure also includes:

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- Determining beam longitudinal reinforcement and computing capacity design shear forces for transverse reinforcement.
- Computing capacity design bending moments for columns to define longitudinal reinforcement, followed by deriving capacity design shear forces for transverse reinforcement.

Once the reinforcement layouts are configured for each relevant member section, they are adjusted to align with construction practices. Lastly, the local ductility checks like verification against the maximum longitudinal reinforcement ratio are also performed to verify compliance with reinforcement ratio limits.

If the design fails verification or no suitable reinforcement configuration is found, section dimensions are increased, and the process is repeated. This iterative approach continues until a valid design is achieved. If maximum allowable section dimensions are exceeded without a feasible solution, materials or types of structural members (i.e., beam and column types) must be revised, requiring a restart of the design process. This iterative methodology has been systematically automated within the framework, ensuring efficient convergence toward structural designs compliant with regional or national design practices.

The *bdim* package is structured to align with the iterative design procedure, serving as a key component of the framework that facilitates the simulated design of buildings while ensuring compliance with regional and historical seismic design standards. It consists of multiple sub-packages, each corresponding to a specific building design class, collectively referred to as Design Class Constructors (DCCs). These DCCs implement design methodologies and rules that reflect their respective seismic codes and regional construction practices. At the core of the *bdim* package is a foundational base library, which provides a general interface and shared methods, such as iterative design procedure, for all DCCs. This base library serves as a template, allowing DCCs to inherit general functionalities and modify or extend them as needed to align with specific seismic code requirements and regional practices. This modular design ensures that the *bdim* package remains highly flexible and reusable, enabling the seamless integration of new DCCs into the framework. Developers can focus on implementing specific design rules while leveraging the pre-existing functionalities provided by the base library.

5. Quality-Based Design Modification

Since the degree of conformity between the designed and constructed structure can vary construction quality, quality-based design modifications are added to the structural design solution which is determined by executing the iterative design algorithm. Specifically, spatial variations that commonly arise during the construction process are incorporated into the beam and column designs. This process is carried out using the *bdim* package. Depending on the quality level, the framework adjusts stirrup spacing, concrete cover thickness, concrete strength, and the yield strength of longitudinal and transverse reinforcement, ensuring that the modified design accurately represents expected in-situ conditions for numerical modelling. To determine the modification factors, the framework employs random sampling, considering a uniform distribution for stirrup spacing and lognormal distributions for the remaining parameters.

Additionally, the framework integrates quality-related nonlinear numerical modelling considerations based on the quality level. In particular, it defines bond-slip factors [30] (ranging from 0 to 1) that influence the plastic hinge properties of beams and columns, as well as the selection of the beam-column joint model, which can be *rigid*, *elastic*, or *inelastic*. Accordingly, for all considered quality levels (*low*, *moderate*, and *high*), the bond-slip factors, beam-column joint model type, and distribution parameters for sampling the quality factors are specified within DCC implementations to introduce the corresponding quality-based modifications. Unless modifications to additional design properties or alternative distribution types are necessary, the functionalities inherited from the base library are utilised without alteration.

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6. Numerical Model Generation

Following the adjustments for construction quality, the framework transforms the building design data stored in the BDIM into 3D nonlinear structural models, which can be analysed using *OpenSees* [25]. This is achieved through the *bnsm* package, which organizes structural components, including beams, columns, floors, joints, and foundations, as distinct objects, each encapsulating the necessary parameters for numerical modelling. Additionally, aside from the generation of the numerical models, the package facilitates modal analysis for dynamic characterization and nonlinear static pushover analysis for seismic performance assessment.

The nonlinear behaviour of frame elements is captured using a lumped plasticity approach, where plastic hinges at the ends of beams and columns are modelled using *zero-length* elements while accounting for rigid joint offsets. The in-plane flexural behaviour of beams is represented by a single rotational spring, whereas columns are assigned two rotational springs, one for each orthogonal direction. These springs utilise the *Hysteretic* uniaxial material model in *OpenSees*, with yielding moment and yielding rotation capacity determined according to Panagiotakos and Fardis [30] and Eurocode 8 – Part 3 [13], while other parameters are derived following Haselton et al. [31] and ASCE/SEI – 2017 [32]. The influence of construction quality on the plastic rotation capacity is incorporated through a bond-slip factor [30,31], ensuring that material and detailing deficiencies are accounted for in hinge properties. Additionally, each zero-length element is connected in series with a linear elastic interior element, whose stiffness is adjusted following Zareian and Medina [33] to prevent spurious damping forces from occurring during the dynamic analyses.

To account for shear failure in columns where capacity design principles are not enforced, shear springs are integrated into the *zero-length* elements. The *LimitState* model with a *ThreePoint* limit curve [34] is adopted for modelling shear hinges. In particular, the shear strength degradation model proposed by Sezen and Moehle [35], which defines a trilinear limit curve based on displacement ductility, is considered for shear hinges defined in each orthogonal direction. The shear strength is determined based on ASCE/SEI – 2017 [32], while the initial and degraded stiffness of the shear springs are derived from the expressions by LeBorgne and Ghannoum [36] and Shoraka and Elwood [37], respectively.

Beam-column joints are modelled using *zero-length* elements positioned between the central joint node and floor nodes, both of which share the same location. The central joint node, which carries the structural mass, provides connectivity between beams and columns, while floor nodes are constrained using a rigid diaphragm, simulating the effect of floor slabs. Joint flexibility is considered only in the rotational degrees of freedom along the two horizontal axes. The moment-rotation behaviour of joints is categorized as rigid, elastic, or inelastic, depending on the joint type assigned in the quality model. For inelastic joints, *Hysteretic* uniaxial material models are used, with parameters derived from expressions proposed by O'Reilly and Sullivan [38], accounting for variations in joint locations, such as roof, interior, or exterior joints. The stiffness of *elastic* joints is determined based on the first branches of their respective backbone curves.

7. Case-Study Applications

To demonstrate the framework's applicability, a sample portfolio of 50 buildings was generated. The selected RC frames were assumed to have four storeys, belong to the CDH design class, and be designed for a β value of 0.1, representing high seismicity. The sampled BCIM data exhibit noticeable variability in both secondary attributes and geometric properties, and thus, yielding significant differences in design and seismic performance of buildings. For instance, nonlinear static pushover analyses were performed for each building design using a first-mode load pattern. As shown in Figure 5, the normalized capacity curves reveal substantial differences among the buildings, highlighting the building-to-building variability within the given building class. Although not conducted in this study, further dynamic analysis using ground motion records could help develop fragility and vulnerability models for risk assessment.

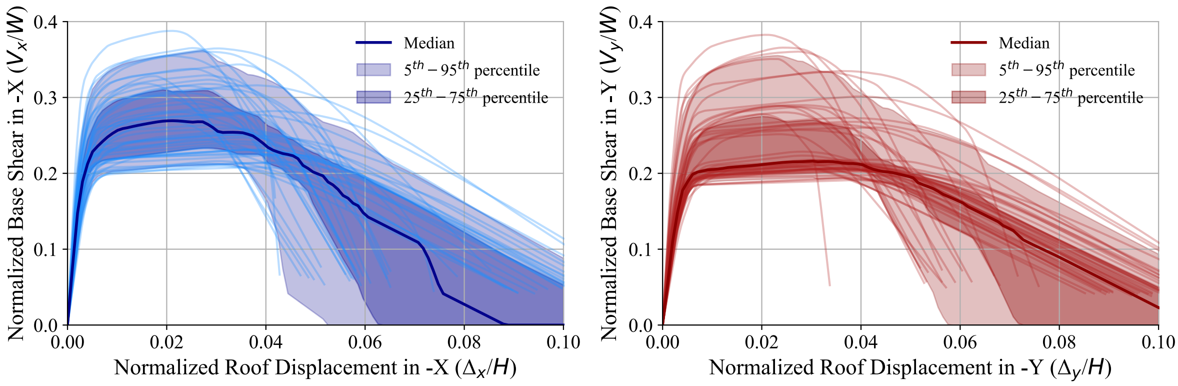

Figure 5. Capacity curves obtained for the sampled building portfolio.

To highlight the framework's simulated design capabilities, identical BCIM data—differing only in material grades specific to each design class—were processed for the design classes proposed in [11] to generate the corresponding BDIM data at various seismic hazard levels (i.e., different β values). In particular, the design classes CDN, CDL, CDM, and CDH represent seismic design practices from different periods: before the 1960s, from the 1960s to the 1970s, from the 1970s to the 2000s, and from the 2000s to the present, respectively. Following the design process, nonlinear static pushover analyses were performed, and the normalized capacity curves, shown in Figure 6, were obtained for each building design. Notably, the curves remain constant for CDN, as it follows only gravity design. In contrast, for the other design classes, the normalized base shear (or strength ratio) systematically increases with β. Moreover, in seismic design cases ($\beta > 0$), the strength ratio values progressively increase from CDN to CDH, reflecting the evolution of seismic design. Regarding ductility, CDH buildings exhibit highly ductile behavior regardless of the β value, as modern capacity design principles are followed in their design. Conversely, buildings in the other design classes demonstrate a similar limited level of ductility in the absence of seismic design. However, as the β value increases, CDL and CDM buildings generally begin to exhibit brittle behavior, with CDL showing a more extreme response, as shear or joint failure mechanisms are more likely to occur in these buildings. Overall, these outcomes show framework's capability to capture the critical differences in the design philosophies, which can be reflected in the generated portfolios.

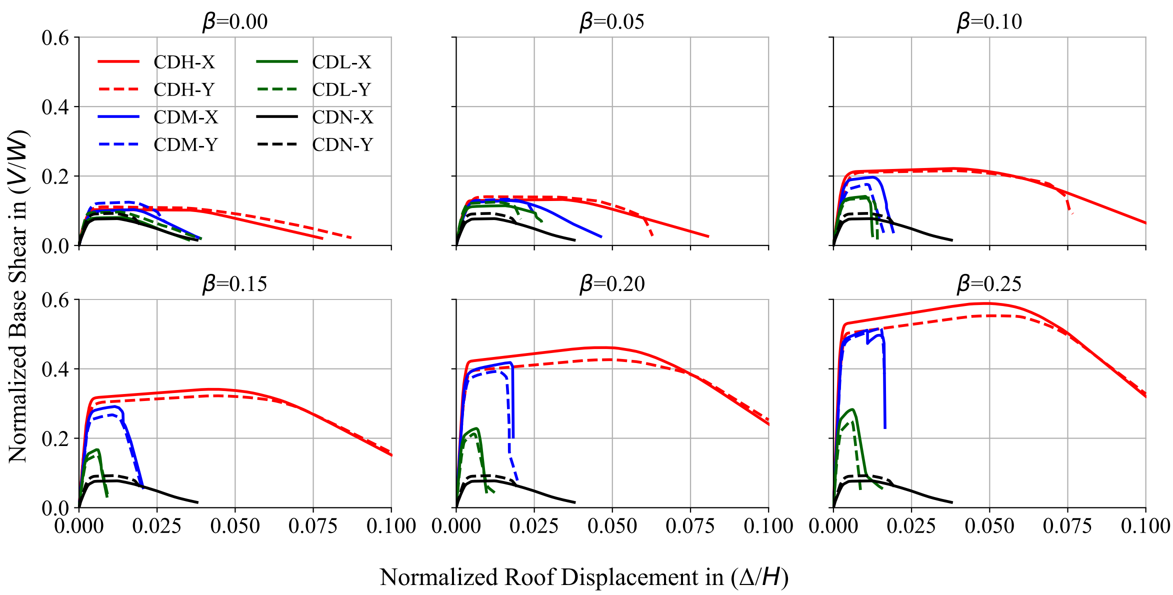

Figure 6. Capacity curves of buildings designed with different seismic design practices and hazard levels.

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8. Conclusions

This article presents an innovative framework for the simulated design of buildings, offering a structured and adaptable approach to capturing building-to-building variability and the evolution of seismic design practices across different regions over time. By integrating probabilistic sampling with iterative design algorithms, the framework enables the generation of realistic building designs and their corresponding numerical models, ensuring alignment with regional or country-specific contexts. These numerical models, in turn, support the development of vulnerability models that accurately reflect the inherent variability within a given building class, thereby enhancing the reliability of large-scale (i.e., regional) seismic risk assessments.

The framework's open-source Python implementation follows object-oriented programming principles, ensuring modularity and extensibility. This allows the earthquake engineering community to seamlessly integrate the framework into existing workflows, customize it for specific regional applications, and expand its capabilities to accommodate different seismic design standards and numerical modelling techniques. The framework's capabilities have been demonstrated through an example that highlights the influence of taxonomy attributes and geometric variables in the design process. The variability captured in the simulated structural designs, as reflected in the capacity curves, effectively illustrates the distinctions between historical and modern design philosophies. These findings validate the framework's ability to generate realistic and regionally representative building portfolios.

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