COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

A FRAMEWORK FOR ENHANCING SEISMIC VULNERABILITY MODELING THROUGH SIMULATED DESIGN

Volkan Ozsarac[1], Gerard J. O'Reilly[1], and Xavier Romão[2]

[1] European Centre for Training and Research in Earthquake Engineering (EUCENTRE)
Via Ferrata 1, 27100, Pavia, Italy
{ozsarac.volkan, gerard.oreilly}@eucentre.it

[2] CONSTRUCT-LESE, Faculty of Engineering, University of Porto
Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
xnr@fe.up.pt

Abstract

Effective seismic vulnerability assessment across varied building categories within large building stocks requires methodologies capable of addressing a broad range of construction practices, building codes, architectural layouts, seismic design scenarios, and available knowledge. Traditional vulnerability models often rely on diverse assessment techniques, taxonomies, and seismic loading representations, sometimes basing classifications on a limited number of representative structures. This approach may inadequately capture building-to-building variability and fail to address uncertainties effectively, especially when scaled for regional or portfolio-wide applications. To overcome these limitations, a unified probabilistic approach that models building portfolios with realistic representations of engineering practices and construction quality is essential. In this context, this paper presents a framework that enables the simulated design of reinforced concrete buildings, integrated into the Built Environment Data platform via open-source tools. This approach allows the structural engineering community to contribute to an expanding database of seismic design practices, encompassing both historical and modern codes to capture building-to-building variability accurately. After completing the design phase, the framework generates OpenSees models for nonlinear analysis, facilitating the development of probabilistic seismic demand models. These models can ultimately support the creation of fragility functions and vulnerability models. The framework's simulated design capabilities are showcased through examples of European design practices that reveal significant differences among building types, emphasizing the critical role of design and structural attributes in vulnerability assessment.

Keywords: Simulated Design, Building Codes, Building-to-building Variability; Reinforced Concrete; Open Source

1 INTRODUCTION

In assessing seismic risk, modeling the physical vulnerability of structures is vital for estimating how buildings respond during earthquakes. This is often achieved through the creation of fragility functions, which quantify the likelihood of a structure experiencing a particular level of damage given a certain intensity of seismic shaking. Numerous techniques have been developed to construct these functions [1], with analytical methods (e.g., [2,3]) being especially popular due to their clarity and objectivity, even though they are computationally intensive.

Various national [4–7] and regional [8–10] projects have contributed significantly to the creation of fragility models. While these efforts have advanced the field, many rely on broad building classifications, a limited set of archetype models, or simplified methods that do not sufficiently capture differences between individual buildings or account for diverse uncertainties. There remains a need for a structured methodology that incorporates diverse construction practices, changing building codes, and region-specific seismic demands into vulnerability assessments.

In response to some of these challenges, particularly within the European context, the Horizon 2020 SERA project (http://www.sera-eu.org) introduced a refined taxonomy for reinforced concrete (RC) frame buildings through the European exposure model [11]. This updated classification considers both changes in seismic codes and regional variations in seismic demand. Traditional exposure models often focus on physical traits like year of construction, number of stories, and material types, which do not always reflect a structure's actual strength or ductility. Previous efforts tried to infer ductility from the construction period and local seismicity, but these lacked flexibility across different regions and timeframes. To overcome this, Crowley et al. [12] proposed a new classification approach that distinguishes between seismic strength, represented by the design lateral force coefficient (β), and seismic design philosophy, which is more closely tied to ductility. Their system defines four design categories that reflect dominant European seismic design practices over time: CDN (no seismic design), CDL (basic lateral resistance using allowable stress), CDM (modern limit state design for lateral resistance), and CDH (modern limit state design with explicit ductility targets). This classification offers a consistent way to describe seismic design evolution across Europe, accounting for changing regulations, engineering approaches, and construction methods. Although originally intended for European RC frame buildings, the approach could be expanded to include other building types adapted to national contexts.

While the classification scheme proposed by Crowley et al. [12] improved how RC buildings are categorized, exposure models often lack comprehensive data on geometry and structural details. To bridge this gap, simulated design procedures, as recognized in Eurocode 8 - Part 3 [13], can be used to recreate historical design decisions with minimal input, such as geometry, materials, and construction quality. This method has been used in prior research (e.g., [14–17]) to automate building layouts and reduce uncertainty in vulnerability evaluations. For instance, the 2020 European Seismic Risk Model [18] employed these techniques to develop fragility curves for low- to mid-rise RC frames based on typical European construction. In these simulations, unknown structural attributes were assigned probabilistically using statistical distributions to reflect variability within the same building class.

However, characteristics like span length, story height, and material strength differ greatly by region, and seismic codes evolve in response to specific earthquakes. Close examination of national standards (e.g., [19]) often reveals discrepancies with generalized classifications such as those in Crowley et al. [11]. Existing simulated design strategies tend to be aligned with specific design codes, but they lack a flexible, comprehensive framework. Additionally, although real-world design choices, like uniform column dimensions, common section sizes, and reinforcement practices, affect seismic performance, they are often omitted in current modeling approaches. A further limitation arises from discrepancies between actual buildings and those designed strictly according to codes, as construction quality impacts the resulting material properties, detailing, and geometry. These real-world deviations are seldom considered, leading to reduced reliability in seismic risk assessments [20]. Moreover, none of the current frameworks consistently integrate modeling approaches that address weaknesses observed in experimental testing (e.g., [21,22]) or post-earthquake damage investigations (e.g., [23,24]).

To systematically address these issues, this paper introduces a versatile and unified simulated design framework, expanding on the SERA project's contributions by applying object-oriented programming in Python. A key feature of the framework is its use of composition rather than inheritance, allowing for the scalable creation of structural models that reflect both historical and contemporary design codes. It generates design models for a wide range of building portfolios with randomized attributes and includes construction quality effects in the resulting computational models. These capabilities support the generation of fragility functions and vulnerability assessments that better represent variability between individual buildings. Although the current focus is on RC moment-resisting frame (MRF) structures, the framework is adaptable to other building types. As an open-source initiative based on widely adopted programming languages, it is designed to foster collaboration and integrate a variety of seismic design approaches. Furthermore, the *SimDesign* framework will be integrated into the Built Environment Data (BED) platform (www.builtenvdata.eu) to encourage broader adoption. The paper also presents case studies reflecting European design practices, demonstrating how variations in taxonomy attributes and geometry affect seismic design and structural capacity.

2 WORKFLOW

The simulated design framework proposed in this study follows a structured four-stage process, shown in Figure 1, to create representative structural designs and corresponding 3D nonlinear numerical models in *OpenSees* [25] for a given regional building stock. These models serve as a foundation for developing vulnerability functions, ensuring that critical variables influencing structural behavior are well-defined and accurately linked to building taxonomy.

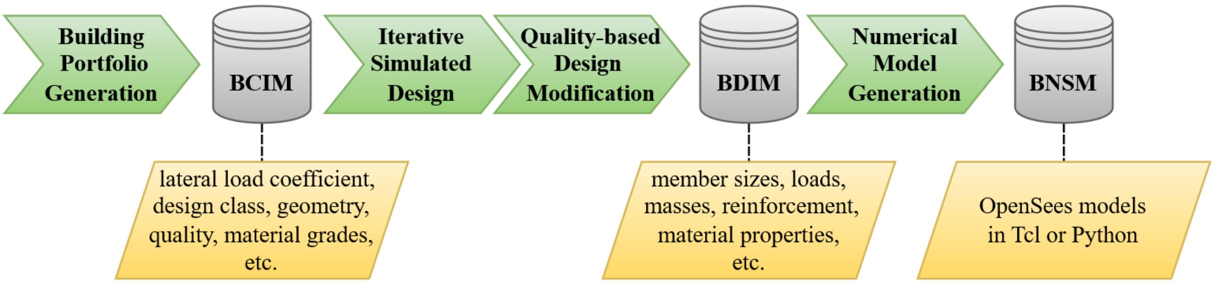


Figure 1: Overview of the simulated design framework workflow.

The workflow begins by assembling a dataset that defines the general characteristics of buildings in a specific portfolio. Among these, the primary attributes serve along with the portfolio size serve input to the framework. These attributes are the design class, representing seismic design practices, the number of storeys, and β coefficient. On the other hand, geometric variables (e.g., plan layout and storey height) and secondary attributes, such as material grades and construction quality, are included to represent variability among buildings. These are assigned via random sampling from probability distributions, which may be informed by existing databases or calibrated for specific regions. This initial dataset is saved within the *Building Class Information Model (BCIM)*, which underpins the next steps of the process.

In the second phase, each building described in the BCIM undergoes a simulated design process that emulates engineering judgment to generate viable structural systems. Incorporating regional seismic demand through β, the method iteratively calculates member dimensions and reinforcement layouts in accordance with relevant seismic design codes and typical construction practices. The approach is flexible enough to model both older buildings, which may have been designed for gravity loads only, and newer buildings that comply with seismic load combinations. The framework also accommodates country-specific design classifications, while retaining the adaptability of its core algorithms, making it suitable for evolving design practices across diverse regions.

The third step integrates construction quality adjustments to reflect potential deviations from idealized design conditions. These adjustments include variations in material strength, detailing of reinforcement, and geometric inconsistencies due to workmanship. By incorporating construction quality levels, categorized as low, medium, or high, the framework produces models that better approximate real-world, as-built structures. At this point, the refined information is stored in the *Building Design Information Model (BDIM)*, which records details such as section dimensions, reinforcement layouts, and material properties.

In the final step, numerical models are developed in OpenSees [25], leveraging both Tcl and Python interpreters [26]. These models are enhanced to capture structural behaviors associated with both construction quality and seismic design class. Failure mechanisms, such as shear failure in non-capacity-designed members or joint failure in poor constructions, are explicitly included. Each numerical model is saved in the *Building Nonlinear Structural Model (BNSM)* database, alongside routines for modal and pushover analyses.

To support scalability and adaptability, the entire framework is developed in Python [27] based on object-oriented programming principles, and is available open-source at https://github.com/builtenvdata/simulated-design. For RC moment-resisting frames, the framework is structured into four core sub-packages, `geometry`, `bcim`, `bdim`, and `bnsm`, which collectively drive the workflow described above. The following sections describe each of these steps in greater detail, excluding software-specific implementation details for brevity.

3 BUILDING PORTFOLIO GENERATION

In large-scale seismic risk modeling, buildings are typically grouped into categories based on essential structural characteristics [28]. Within the SERA project, the classification relies on primary attributes such as construction material, type of lateral force-resisting system, number of storeys, and anticipated ductility level, this last attribute being inferred from the prevailing seismic design code at the time of construction (i.e., the design class) along with the regional seismic demand, represented by the β coefficient. These characteristics are combined to form a taxonomy string [28,29], which acts as a unique identifier for each building type. When more detailed information is accessible, the taxonomy can be refined to include beam and column configurations, construction quality, and material specifications. However, because such detailed structural data is often missing, the uncertainty associated with these secondary attributes needs to be captured in the portfolio. Moreover, buildings with identical taxonomy strings can still differ significantly in their geometry, for instance, in terms of floor layouts, bay dimensions, or storey heights. These intrinsic differences across the building stock must be represented to properly reflect variability at the individual building level.

To account for this, the framework uses the primary classification attributes, namely, number of storeys, seismic design class, and β coefficient, as a basis to stochastically generate samples of secondary attributes and geometric variables. These secondary characteristics include those listed in Table 1, and the material grades, which are later mapped to their corresponding material properties during the design stage. The geometric variables sampled include standard and ground storey heights, bay widths in both the X and Y directions, width of staircase bays along the X axis, and overall floor layout. The current layout database encodes configurations based on the number of uniformly spaced bays in each direction, as well as the staircase's location. The framework is also capable of being expanded to support irregular floor plans. The outcome of this process is the BCIM dataset, generated for a specified sample size or building stock. This dataset provides a complete set of structural and geometric descriptors for each building, forming the basis for the subsequent simulated design process.

Colum Type	Beam Type	Slab Type	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

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

The sampling process, implemented through the `bcim` package and illustrated in Figure 2, relies on a combination of random generators and decision trees guided by engineering expertise. Random generators use predefined probability distributions to represent the general features of the target building stock, while decision trees introduce logical relationships between randomly assigned values and other structural attributes, often reflecting typical design assumptions. Prior to sampling, the framework loads the necessary probabilistic parameters from a corresponding JSON[1] file specific to the selected design class (e.g., CDL). Although each parameter comes with default values, users have the flexibility to adjust them to better reflect local conditions or more accurate building information.

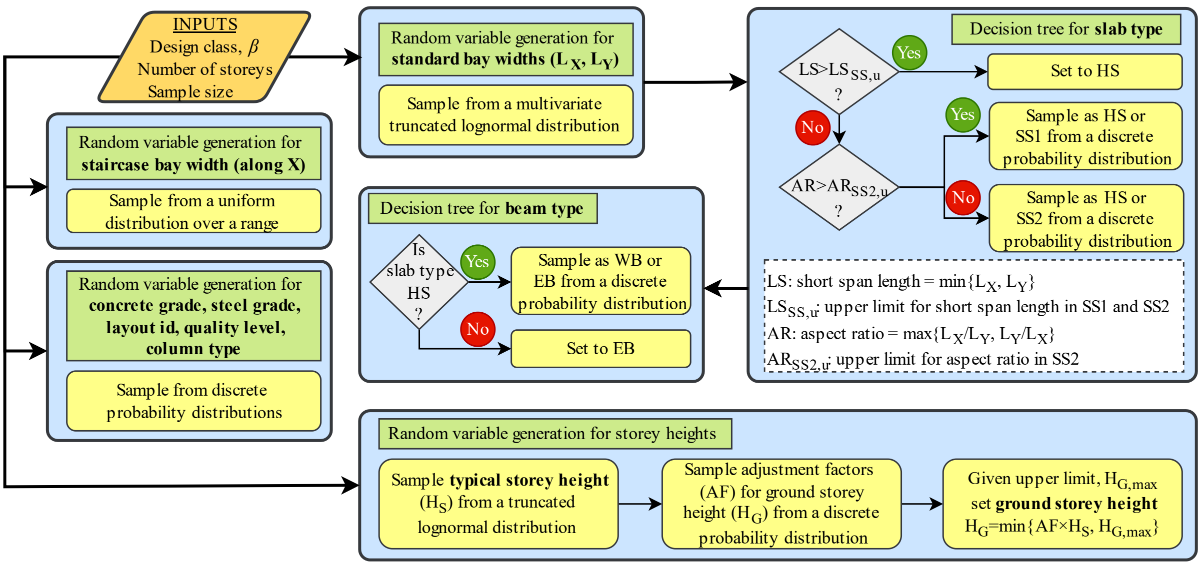
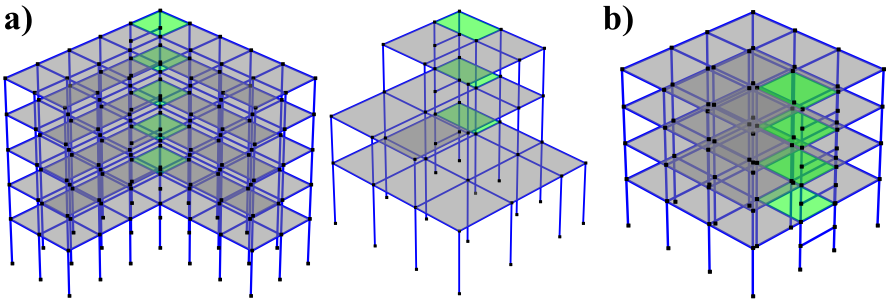


Figure 2. Illustration of the sampling process for BCIM data generation, with sampled data highlighted in bold.

[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

Once the dataset has been generated, the framework employs the `geometry` package to initialize each building's geometric configuration as a Python object. This involves defining the structural grid based on the number of storeys and the layout in plan, with bay widths and storey heights determining the spacing of the grid. Structural elements, including beams, columns, joints, slabs, and staircases, are modeled as mesh objects to ensure proper connectivity throughout the design and modeling stages. Although the framework is capable of handling irregular geometries, the current implementation focuses on regular, orthogonal floor plans (as shown in Figure 3). Each building includes a single staircase located consistently across floors, supported by beams in the X-direction at mid-storey levels. Together, the BCIM dataset and these geometry objects serve as the foundational inputs for the simulated design stage, informing the creation of the BDIM.



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

Across different countries and regions, the seismic design of reinforced concrete (RC) frame buildings generally follows a consistent, code-based sequence grounded in structural engineering principles. The process begins by establishing both the seismic loading conditions and the basic characteristics of the building. This involves identifying the seismic hazard level at a given site and for a defined return period, usually expressed as peak ground acceleration or obtained from an elastic acceleration response spectrum. These values are then adjusted for local site conditions, the importance of the structure, and behaviour (or response modification) factors, resulting in either a design acceleration spectrum or a lateral force coefficient. In this framework, the latter, i.e., β, is used as the input representing seismic demand. In parallel, the architectural floor plan is reviewed to determine the layout of key structural elements such as columns, beams, and slabs, and to define the lateral force-resisting system. Once this is done, the structural system is outlined through the selection of initial member types and material grades, marking the completion of the conceptual design stage. As previously described, the framework collects all of this information in its first step to initiate the simulated design procedure, which then follows the iterative algorithm shown in Figure 4.

After completing the initial design phase, an elastic structural model is created, and linear elastic analyses are performed under different loading conditions. Seismic effects are introduced using the equivalent lateral force procedure, with modifications to member stiffnesses applied where necessary to reflect cracked section behaviour. The resulting internal forces are then combined using load combinations specified by relevant design codes. Each structural element is subsequently checked to ensure its dimensions are adequate to resist the design forces. This stage also involves evaluating the cost-effectiveness of the design, checking that stress limits are not exceeded, and, when required by the code, verifying global performance criteria such as interstorey drift.

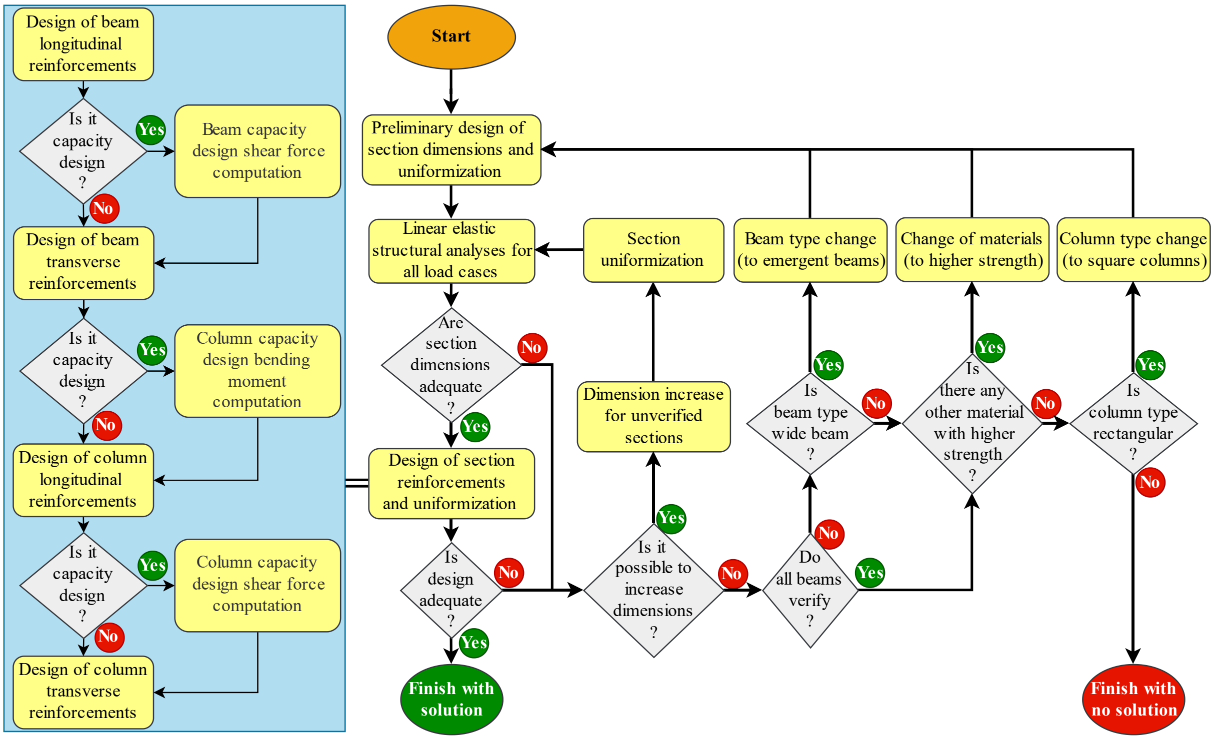


Figure 4. Iterative design algorithm implemented in the framework.

The next phase focuses on reinforcement design, which is conducted according to either the working (allowable) stress method, typical of older codes, or the limit state design approach, as used in modern standards. Reinforcement layouts are developed based on available steel bar sizes and standard detailing conventions. When capacity design principles are applicable, the process also includes the following steps:

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

Once reinforcement layouts are assigned to each relevant member section, they are adjusted to conform with practical construction practices. Additional checks are performed to ensure local ductility, including verifying that longitudinal reinforcement ratios do not exceed prescribed limits.

If a section fails these checks or no adequate reinforcement solution can be found, the section size is increased and the process is repeated. This iterative procedure continues until a code-compliant design is achieved. If the section dimensions exceed the allowable maximums without a viable solution, alternative materials or structural member types (e.g., different beam or column cross-section types) must be selected, requiring a full restart of the design process. This iterative design logic is fully automated within the framework to ensure convergence toward structurally sound and code-compliant designs based on national or regional standards.

The `bdim` package supports this process and plays a central role in the simulated design of buildings. It is built to reflect the iterative nature of the design methodology, ensuring alignment with both current and historical seismic codes. The package includes several submodules, each tailored to a particular building design class. These are collectively known as *Design Class Constructors (DCCs)*. Each DCC encodes the specific design logic and rules associated with its corresponding seismic design code and regional practices. At the heart of the `bdim` package is a shared base library, which provides a standard interface and common functions, such as the core iterative design procedure, for all DCCs. This base library acts as a blueprint, allowing individual DCCs to inherit generic features and adapt them as needed to meet specific code requirements. This modular structure enhances the flexibility and reusability of the `bdim` package, enabling developers to easily integrate new DCCs while focusing only on the unique aspects of each design code.

5 QUALITY-BASED DESIGN MODIFICATION

Since there can be discrepancies between the intended design and the final constructed building, the framework incorporates construction quality adjustments into the structural design output produced by the iterative design algorithm. These quality-based modifications, applied through the `bdim` package, account for spatial inconsistencies that typically occur during construction, particularly in the design of beams and columns. Depending on the assigned construction quality level, the framework modifies key parameters such as stirrup spacing, concrete cover, concrete compressive strength, and the yield strength of both longitudinal and transverse reinforcement. These adjustments help ensure the final design more accurately reflects real-world, in-situ conditions for use in numerical modeling. Random sampling is used to assign these modification factors, with stirrup spacing sampled from a uniform distribution and the other variables drawn from lognormal distributions.

In addition, the framework integrates nonlinear modeling parameters related to construction quality. For example, it assigns bond-slip factors [30] (ranging from 0 to 1) that affect the plastic hinge behavior of structural elements and determines the type of beam-column joint model to be used, whether *rigid*, *elastic*, or *inelastic*. For each quality level (low, moderate, or high), the bond-slip values, joint model type, and associated distribution parameters are defined within the corresponding DCC. These quality-based modeling adaptations are implemented through the DCCs, drawing on shared methods from the base library. Unless there is a need to introduce modifications to additional properties or change the types of distributions used, the default inherited functions from the base library are applied without modification.

6 NUMERICAL MODEL GENERATION

After applying construction quality adjustments, the framework converts the finalized building designs stored in the BDIM into fully defined 3D nonlinear structural models compatible with analysis in *OpenSees* [25]. This task is handled by the `bnsm` package, which structures each component of the building, such as beams, columns, floors, joints, and foundations, as individual objects containing all necessary parameters for numerical modeling. In addition to model creation, the package also supports modal analysis for evaluating dynamic properties and nonlinear static pushover analysis for assessing seismic performance.

The nonlinear response of frame members is represented using a lumped plasticity approach. Plastic hinges are modeled at the ends of beams and columns through *zeroLength* elements, with rigid joint offsets considered. For beams, one rotational spring is assigned to simulate in-plane bending behavior, while columns are modeled with two rotational springs, one for each horizontal direction. These springs utilize the *Hysteretic* uniaxial material model in *OpenSees*. Yield moment and rotation capacity values are determined using methodologies by Panagiotakos and Fardis [30] and Eurocode 8 – Part 3 [13], while additional parameters are calculated using guidance from Haselton et al. [31] and ASCE/SEI – 2017 [32]. The effect of construction quality is incorporated through a bond-slip factor [30,31], which adjusts the plastic rotation capacity to reflect potential material or detailing deficiencies. Furthermore, each plastic hinge element is placed in series with a linear elastic internal member whose stiffness is modified using the approach by Zareian and Medina [33] to mitigate artificial damping effects during dynamic simulations.

For columns not designed using capacity principles, shear hinges are added to the *zeroLength* elements to represent potential shear failures. These are modeled using the *LimitState* material with a *ThreePoint* limit curve [34]. In particular, the Sezen and Moehle [35] degradation model is applied, which uses a trilinear envelope based on displacement ductility to characterize shear strength reduction. The initial shear capacity is calculated per ASCE/SEI – 2017 [32], while initial and degraded stiffnesses are derived using formulas by LeBorgne and Ghannoum [36] and Shoraka and Elwood [37], respectively.

Beam-column joints are modeled through additional *zeroLength* elements positioned between two coincident nodes: a central joint node, which contains the structural mass and connects beams and columns, and a floor node, which is linked through a rigid diaphragm to simulate the floor slab effect. Joint flexibility is considered only in the rotational degrees of freedom along the two horizontal directions. The joint moment-rotation behavior depends on its assigned type, *rigid*, *elastic*, or *inelastic*, as defined by the quality level in the model. For inelastic joints, the *Hysteretic* material is again used, with parameters based on formulations from O'Reilly and Sullivan [38] that account for joint location (e.g., roof, interior, exterior). For elastic joints, stiffness values are derived from the initial slope of their corresponding backbone curves.

7 EXAMPLE APPLICATIONS

To illustrate how the framework can be applied in practice, a sample set of 30 buildings was generated. These RC frames were assumed to have four storeys, fall under the CDL design category, and be designed for a β value of 0.1. The sampled BCIM dataset reflected substantial variation in both secondary attributes and geometric features, which in turn led to notable differences in structural design and seismic performance. For example, nonlinear static pushover analyses were carried out for each building using a load distribution based on the first mode shape. As seen in Figure 5, the resulting normalized capacity curves demonstrated significant variation across the building set, emphasizing the extent of building-to-building variability within the building class. Although dynamic analysis using ground motion records was beyond the scope of this demonstration, such analyses could be incorporated in future work to support the development of fragility curves and vulnerability models for seismic risk evaluation.

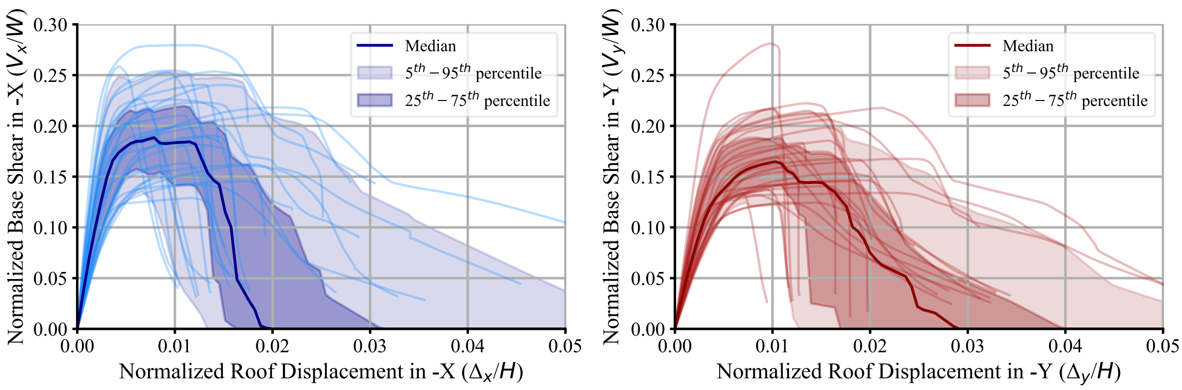


Figure 5. Capacity curves obtained for the sampled building portfolio.

To further showcase the framework's simulated design capabilities, a set of identical BCIM data, differing only in material grades according to each design class, was processed using the four design classes introduced in Crowley et al. [11]. These correspond to distinct periods in European seismic design evolution: CDN (pre-1960s), CDL (1960s–1970s), CDM (1970s–2000s), and CDH (2000s onward). For each design class and varying seismic hazard levels (i.e., different β values), the corresponding BDIM datasets were generated. After completing the simulated design process, nonlinear static pushover analyses were conducted for each building, and the resulting normalized pushover curves, presented in Figure 6, demonstrate how structural capacity evolves across different design eras.

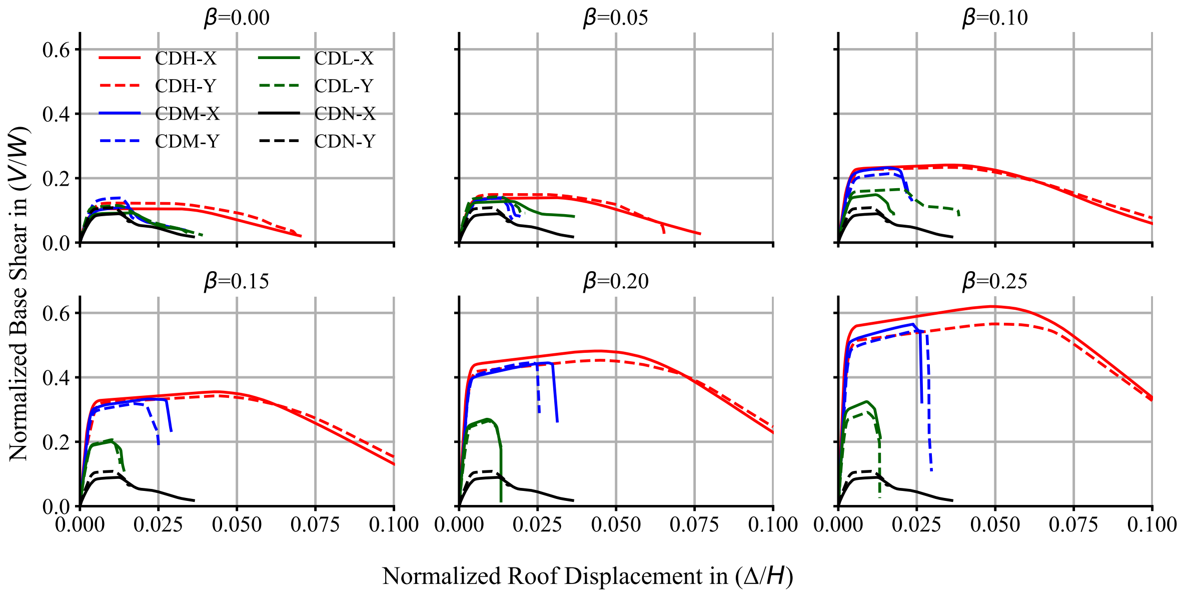


Figure 6. Capacity curves of buildings designed with different seismic design practices and hazard levels.

An important observation is that the capacity curves for CDN remain unchanged across different β values, as this class represents gravity-only design without seismic considerations. In contrast, the normalized base shear (or strength ratio) for the other design classes increases consistently with higher β values, highlighting the influence of seismic design. Furthermore, among the seismic design categories ($\beta > 0$), the strength ratio progressively increases from CDN to CDH, illustrating the advancement of seismic design practices over time.

In terms of ductility, CDH buildings display pronounced ductile behavior across all seismic intensities, consistent with modern capacity design principles. On the other hand, structures in the CDN, CDL, and CDM categories show limited ductility when designed without seismic considerations. As β increases, both CDL and CDM buildings tend to exhibit more brittle responses, particularly in CDL, where failure modes such as shear and joint failures become more prevalent. These results underline the framework's ability to represent key differences in seismic design philosophy, enabling these distinctions to be reflected within the generated building portfolios.

8 CONCLUSIONS

This paper introduces a novel simulated design framework that provides a systematic and flexible approach for modeling variability among buildings and capturing the evolution of seismic design practices across different regions and time periods. By combining probabilistic sampling techniques with a simulated design methodology, the framework produces realistic structural designs and their corresponding numerical models, all tailored to regional or national design contexts. These models serve as the foundation for developing vulnerability functions that more accurately reflect the variability within building classes, thereby improving the reliability of large-scale seismic risk assessments.

The framework is implemented in Python using an object-oriented programming structure, which ensures a modular, extensible design. This makes it easy for researchers and practitioners in earthquake engineering to adapt the framework to their specific needs, integrate it into existing analysis pipelines, and extend it to support additional seismic design codes and modeling approaches. The framework’s functionality was demonstrated through a case study that explored the role of taxonomy attributes and geometric variability in shaping structural performance. The diversity observed in the resulting capacity curves highlights clear differences between historical and modern design philosophies, reinforcing the framework’s effectiveness in generating representative and realistic building portfolios.

REFERENCES

[1] G.M. Calvi, R. Pinho, G. Magenes, J.J. Bommer, L.F. Restrepo-Vélez, H. Crowley, Development of seismic vulnerability assessment methodologies over the past 30 years. *ISET Journal of Earthquake Technology* 2006; **43**(3): 75–104.

[2] G.M. Calvi, A displacement-based approach for vulnerability evaluation of classes of buildings. *Journal of Earthquake Engineering* 1999; **3**(3): 411–438. DOI: 10.1080/13632469909350353.

[3] H. Crowley, R. Pinho, Period-height relationship for existing European reinforced concrete buildings. *Journal of Earthquake Engineering* 2004; **8**: 93–119. DOI: 10.1080/13632460409350522.

[4] FEMA, *HAZUS-MH MR5, Technical manual, Department of Homeland Security - Federal Emergency Management Agency*. Washington, DC: 2014.

[5] M.A. Erberik, Fragility-based assessment of typical mid-rise and low-rise RC buildings in Turkey. *Engineering Structures* 2008; **30**(5): 1360–1374. DOI: 10.1016/J.ENGSTRUCT.2007.07.016.

[6] B. Borzi, H. Crowley, R. Pinho, Simplified pushover-based earthquake loss assessment (SP-BELA) method for masonry buildings. *International Journal of Architectural Heritage* 2008; **2**(4): 353–376. DOI: 10.1080/15583050701828178.

[7] V. Silva, H. Crowley, H. Varum, R. Pinho, L. Sousa, Investigation of the characteristics of Portuguese regular moment-frame RC buildings and development of a vulnerability model. *Bulletin of Earthquake Engineering* 2015; **13**(5): 1455–1490. DOI: 10.1007/s10518-014-9669-y.

[8] P. Mouroux, B. Le Brun, Presentation of RISK-UE project. *Bulletin of Earthquake Engineering* 2006; **4**(4): 323–339. DOI: 10.1007/S10518-006-9020-3/METRICS.

[9] G.M. Calvi, R. Pinho, LESSLOSS: A European Integrated Project on Risk Mitigation for Earthquakes and Landslides 2004(July).

[10] M. Villar-Vega, V. Silva, H. Crowley, C. Yepes, N. Tarque, A.B. Acevedo, *et al.*, Development of a fragility model for the residential building stock in South America. *Earthquake Spectra* 2017; **33**(2): 581–604. DOI: 10.1193/010716EQS005M.

[11] H. Crowley, V. Despotaki, D. Rodrigues, V. Silva, D. Toma-Danila, E. Riga, *et al.*,

Exposure model for European seismic risk assessment. *Earthquake Spectra* 2020; **36**(1_suppl): 252–273. DOI: 10.1177/8755293020919429.

[12] H. Crowley, V. Despotaki, V. Silva, J. Dabbeek, X. Romão, N. Pereira, *et al.*, Model of seismic design lateral force levels for the existing reinforced concrete European building stock. *Bulletin of Earthquake Engineering* 2021; **19**(7): 2839–2865. DOI: 10.1007/s10518-021-01083-3.

[13] CEN, *Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings*. Brussels, Belgium: 2005.

[14] G.M. Verderame, M. Polese, C. Mariniello, G. Manfredi, A simulated design procedure for the assessment of seismic capacity of existing reinforced concrete buildings. *Advances in Engineering Software* 2010; **41**(2): 323–335. DOI: 10.1016/j.advengsoft.2009.06.011.

[15] A. Masi, S. Lagomarsino, M. Dolce, V. Manfredi, D. Ottonelli, Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling. *Bulletin of Earthquake Engineering* 2021; **19**(8): 3253–3286. DOI: 10.1007/s10518-021-01065-5.

[16] C. Del Gaudio, P. Ricci, G.M. Verderame, G. Manfredi, Development and urban-scale application of a simplified method for seismic fragility assessment of RC buildings. *Engineering Structures* 2015; **91**: 40–57.

[17] B. Borzi, R. Pinho, H. Crowley, Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings. *Engineering Structures* 2008; **30**(3): 804–820. DOI: 10.1016/j.engstruct.2007.05.021.

[18] H.M. Crowley, J. Dabbeek, V. Despotaki, D. Rodrigues, L. Martins, V. Silva, *et al.*, European Seismic Risk Model (ESRM20). *EFEHR Technical Report* 2021; **002**.

[19] F. Pavel, H. Crowley, X. Romão, R. Vladut, N. Pereira, V. Ozsarac, Evolution of national codes for the design of RC structures in Romania. *Bulletin of Earthquake Engineering* 2024; **22**(3): 911–949. DOI: 10.1007/s10518-023-01791-y.

[20] A.M.B. Nafeh, G.J. O'Reilly, Fragility functions for non-ductile infilled reinforced concrete buildings using next-generation intensity measures based on analytical models and empirical data from past earthquakes. *Bulletin of Earthquake Engineering* 2024; **22**(10): 4983–5021. DOI: 10.1007/S10518-024-01955-4/METRICS.

[21] G.M. Calvi, G. Magenes, S. Pampanin, Relevance of beam-column joint damage and collapse in RC frame assessment. *Journal of Earthquake Engineering* 2002; **6**(SPEC. ISS. 1): 75–100. DOI: 10.1142/S1363246902000693.

[22] S. Pampanin, G.M. Calvi, M. Moratti, Seismic behaviour of R.C. beam-column joints designed for gravity loads. *12th European Conference on Earthquake Engineering* 2002; **726**: 1–10.

[23] H. Sezen, A.S. Whittaker, K.J. Elwood, K.M. Mosalam, Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey. *Engineering Structures* 2003; **25**(1): 103–114. DOI: 10.1016/S0141-0296(02)00121-9.

[24] P. Ricci, F. de Luca, G.M. Verderame, 6th April 2009 L'Aquila earthquake, Italy: Reinforced concrete building performance. *Bulletin of Earthquake Engineering* 2011; **9**(1): 285–305. DOI: 10.1007/S10518-010-9204-8/METRICS.

[25] F. McKenna, M.H. Scott, G.L. Fenves, Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering* 2010; **24**(1): 95–107. DOI: 10.1061/(asce)cp.1943-5487.0000002.

[26] M. Zhu, F. McKenna, M.H. Scott, OpenSeesPy: Python library for the OpenSees finite element framework. *SoftwareX* 2018; **7**: 6–11. DOI: 10.1016/j.softx.2017.10.009.

[27] G. van Rossum, *Python tutorial*. Amsterdam, Netherlands: 1995.

[28] S. Brzev, C. Scawthorn, A.W. Charleson, L. Allen, M. Greene, K. Jaiswal, *et al.*, *GEM Building Taxonomy Version 2.0*. vol. 02. GEM Foundation; 2013. DOI: 10.13117/GEM.EXP-MOD.TR2013.02.

[29] X. Romão, J.M. Castro, N. Pereira, H. Crowley, V. Silva, L. Martins, *et al.*, *Deliverable Report D26.5 European physical vulnerability models. SERA - Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe*. vol. 26. 2019.

[30] T.B. Panagiotakos, M.N. Fardis, Deformations of reinforced concrete members at yielding and ultimate. *ACI Structural Journal* 2001; **98**(2): 135–148. DOI: 10.14359/10181.

[31] C.B. Haselton, A.B. Liel, S.C. Taylor-Lange, G.G. Deierlein, Calibration of model to simulate response of reinforced concrete beam-columns to collapse. *ACI Structural Journal* 2016; **113**(6): 1141–1152. DOI: 10.14359/51689245.

[32] ASCE, *Seismic Evaluation and Retrofit of Existing Buildings (ASCE/SEI 41-17)*. vol. 41. Reston, Virginia, USA: American Society of Civil Engineers; 2017.

[33] F. Zareian, R.A. Medina, A practical method for proper modeling of structural damping in inelastic plane structural systems. *Computers and Structures* 2010; **88**(1–2): 45–53. DOI: 10.1016/j.compstruc.2009.08.001.

[34] K.J. Elwood, Modelling failures in existing reinforced concrete columns. *Canadian Journal of Civil Engineering* 2004; **31**(5): 846–859. DOI: 10.1139/L04-040.

[35] H. Sezen, J.P. Moehle, Shear Strength Model for Lightly Reinforced Concrete Columns. *Journal of Structural Engineering* 2004; **130**(11): 1692–1703. DOI: 10.1061/(asce)0733-9445(2004)130:11(1692).

[36] M.R. LeBorgne, W.M. Ghannoum, Calibrated analytical element for lateral-strength degradation of reinforced concrete columns. *Engineering Structures* 2014; **81**: 35–48. DOI: 10.1016/j.engstruct.2014.09.030.

[37] M.B. Shoraka, K.J. Elwood, Mechanical model for non ductile reinforced concrete columns. *Journal of Earthquake Engineering* 2013; **17**(7): 937–957. DOI: 10.1080/13632469.2013.794718.

[38] G.J. O'Reilly, T.J. Sullivan, Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures. *Journal of Earthquake Engineering* 2019; **23**(8): 1262–1296. DOI: 10.1080/13632469.2017.1360224.