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Citation (APA)
Kazemi, P., Turrin, M., Andriotis, C., Entezami, A., Mariani, S., & Ghisi, A. (2025). Integrating Dynamic Seismic Simulation in Architectural Design: A Parametric Approach for Tall Buildings with Outer Diagrids. In S. Aşut, & S. Bianchi (Eds.), *A Perspective in Interdisciplinary Built Environment Education: Computation for Earthquake Resilience* (pp. 263-290). TU Delft OPEN Publishing.

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Colophon

A Perspective in Interdisciplinary Built Environment Education:
Computation for Earthquake Resilience

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Keywords:
Built environment education, Interdisciplinary education, Computation,
Earthquake resilience, Curriculum development

Published by:
TU Delft OPEN Publishing | Delft University of Technology, The Netherlands

DOI: https://doi.org/10.59490/mg.116

ISBN: 978-94-6518-174-5

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Integrating Dynamic Seismic Simulation in Architectural Design: A Parametric Approach for Tall Buildings with Outer Diagrids

Pooyan Kazemi[1*], Michela Turrin[2], Charalampos Andriotis[2], Alireza Entezami[1], Stefano Mariani[1], Aldo Ghisi[1]

This paper presents a comprehensive computational workflow to generate, evaluate, and compare different outer diagrid designs for tall buildings, focusing on their structural efficiency under various load conditions, including seismic actions. Such diagrid systems not only enhance both structural resilience and architectural flexibility but also provide primary resistance to lateral loads, allowing for smaller internal core structures. Despite their advantages, widely used architectural design software, such as Grasshopper®, offer limited support for the seismic simulations essential for such complex structures. To address this limitation, a novel integration of the Alpaca4d plug-in, based on OpenSees software, is developed to facilitate seismic simulations for architects and engineers.

The methodology generates a diverse dataset of tall buildings by varying critical design parameters, including the geometries of the top and bottom floors, floor heights, and vertical transformations such as tapering or twisting. From over 61,200 theoretical combinations, the Latin hypercube sampling technique is adopted to select 1000 models to ensure a representative diversity. Each model is subject to cross-section optimisation based on Eurocode load combinations, incorporating both permanent and live loads according to code specifications. Dynamic analyses are then performed under seven ground motions selected from the PEER NGA-West2 database, to capture structural responses under realistic conditions.

The computational workflow generates key outputs, including inter-storey drifts, base reaction forces and moments, and acceleration distributions, recorded at critical nodes and elements to optimise data collection and computational efficiency. These outputs provide a detailed understanding of the seismic performance of each model and serve as the basis for

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further structural/materials optimization. By leveraging these results, the workflow will support in the future early decision-making in structural and architectural design, also in view of the progresses in the artificial intelligence field. Overall, this approach offers a streamlined and adaptable method for systematically evaluating and optimising the seismic design of tall buildings for architectural design.

Keywords: Computational design, Tall buildings, Architectural form generation, Seismic simulations, Design exploration, Early-stage design

Introduction

The successful design of tall buildings increasingly relies on integrating architectural creativity with structural functionality[1]. Early design decisions have a profound impact on resource utilization, financial outcomes, and the ultimate form and functionality of a building[2,3]. Performance-driven design approaches emphasize the need for collaboration between architects and engineers from the beginning, enabling innovative solutions that balance aesthetics, structural efficiency, and sustainability.

Tall buildings present unique design challenges due to their complex structural and functional requirements. Architects often prioritise visually striking forms, which may clash with structural efficiency and safety requirements. To address these conflicting priorities, early-stage collaboration between architects and engineers is essential to develop designs that harmonize architectural vision and structural performance. Traditional sequential design processes, where architects lead the design and engineers support structural requirements, often lead to inefficiencies and major deviations from the original concepts[4,5]. This highlights the need for integrated design workflows that align aesthetic and structural goals from the outset.

Design of tall buildings is a case that underscores the benefits of integrating architectural and structural considerations from the start. Unlike intuition-based design approaches, this method employs quantitative assessments to guide early design decisions. Metrics such as lateral displacement, total weight, and stiffness are essential for assessing the efficiency and feasibility of proposed designs. Structural stiffness, in particular, is a critical parameter in tall building design, as it directly influences lateral stability and material utilisation. The integration of such performance metrics within a multi-objective optimisation framework has facilitated a shift toward structurally-informed design philosophies, wherein structural requirements drive rather than constrain creative exploration[6].

Among the various structural systems developed for tall buildings, outer diagrid structures have gained significant attention due to their ability to harmonize architectural flexibility with structural efficiency[7]. The diagrid typology, characterized by an external skeleton composed of diagonal elements, is uniquely suited to resist horizontal forces such as seismic and wind loads. By doing so, it reduces or strategically complements internal core structures, such as shear walls, enabling lighter and more open architectural forms. Moreover, the geometric clarity of diagrid structures often contributes to their aesthetic appeal, blending strength with elegance[8].

The benefits of diagrid systems have been validated by experimental and analytical studies. Recent experimental tests on diagrid systems have underscored the suitability of this typology for tall buildings: studies have explored the failure probabilities under cyclic displacement-controlled loading that simulate seismic actions providing insights into stiffness reductions and other performance

metrics[9]. Analytical research has further explored the relationship between lateral deformation and stiffness, particularly for polygonal plans with 3 to 12 sides connected by vertical diagrids. These findings highlight the effectiveness of diagrids in tall building design but also reveal a gap in existing methodologies[10].

Parametric architectural design, whether directed by human or powered by artificial intelligence, has emerged as a significant area of interest[11,12,13]. The goal is to exploit both the automated generation of diverse building forms and the integration of extensive outputs via artificial intelligence or optimisation tools[14,15,13]. This approach necessitates the streamlined production of extensive design databases to support the generation of innovative solutions[12,13,15]. Parametric tools further enhance collaboration by providing real-time feedback on structural performance, enabling iterative refinement of architectural concepts.

This research emphasizes the schematic (conceptual) design phase, recognizing its pivotal role in the overall design process. Choosing the optimal design option during this phase sets the foundation for subsequent development stages. The significance of initial design decisions is paramount, as they greatly influence the project's ultimate form, functionality, and financial feasibility. If not carefully considered, these decisions can lead to suboptimal outcomes[16]. Construction costs, which represent a substantial portion of the project budget, are profoundly affected by early design choices[17]; therefore, a proactive approach in the initial stages can yield substantial cost savings and more efficient structural solutions[18], including structural configurations, vertical transportation systems, and mechanical installations[19,20]. Moreover, proactive design reduces downstream engineering challenges, streamlining the transition from conceptual models to practical implementation.

The use of Computer-Aided Architectural Design (CAAD) technologies, particularly those utilizing data-driven and parametric methodologies, can significantly speed up the ability to explore and evaluate design alternatives at the outset. It allows designers to rapidly assess a diverse range of design solutions while addressing various aspects[19,21,22]. Advanced computational workflows enable simultaneous evaluation of structural, aesthetic, and environmental performance, fostering a more holistic approach to tall building design. By going beyond traditional constraints, designers can broaden their creative horizons perform more diverse, design exploration[23]. Therefore, the integration of CAAD methodologies significantly enhances rapid exploration and performance-driven form-finding strategies[19, 24].

Existing works have studied the effects of alternative architectural choices made in the early design phase, e.g. in terms of tall building geometry, on the seismic response through numerical simulation, including the generation and the enrichment of a database explored by artificial intelligence tools[14,15,24]. These studies were carried out by means of a simplified approach, i.e. exploiting

a statically equivalent seismic loading and a limited option of architectural forms[25]. In contrast, a computational workflow is presented here to assess the seismic behaviour of tall buildings with outer diagrids, using spectrum-compatible real accelerograms extracted from the PEER NGA-West2 database in dynamic seismic simulation. This workflow improves existing methodologies by incorporating realistic ground motion data and enabling the systematic evaluation of diverse configurations under varying seismic conditions. The workflow allows for a variety of architectural forms, thereby broadening the design space available to designers.

To do this, we use Alpaca4d, a Grasshopper plugin built upon OpenSees. As an open-source and Python-based tool, Alpaca4d includes custom enhancements for performing time history simulations, making it particularly useful given the complexities associated with open finite element (FE) tools, which often lack user-friendly interfaces. This accessibility makes dynamic seismic simulation more

Table 1. List of software and plugins used in this study, including their descriptions, versions, and dates.

Software or Plugin name	Description	Version	Release Date
Rhinoceros®	A commercial 3D computer graphics and computer-aided design application used for modelling, rendering, and analysing complex shapes and surfaces.	7.37.24107.15001	16-04-2024
Grasshopper	A visual programming language and environment integrated with Rhinoceros, used for parametric design and algorithmic modelling.	Build 1.0.0007	16-04-2024
Alpaca4D	A Grasshopper plugin developed on top of OpenSees, enabling the analysis of beam, shell, and brick elements through static, modal, and ground motion analysis.	0.7.1	19-11-2024
Karamba	An interactive, parametric engineering tool within Grasshopper for finite element analysis on complex structures.	2.2.0.17	07-10-2022
Colibri	A plugin for Grasshopper that facilitates design space exploration and optimisation by managing and visualizing large sets of design alternatives.	2.2.0	30-11-2022
OpenSeesPy	A Python library for performing finite element analysis using the OpenSees framework, allowing for advanced simulations of structural and geotechnical systems.	3.5.0	11-05-2023

feasible for architects and engineers, facilitating the creation of a database of alternative architectural forms. Furthermore, this integration empowers designers to incorporate structural insights directly into the design process, bridging the gap between architectural vision and structural feasibility. All of the software (and plug-ins) used, including their descriptions, versions, and dates, are listed in Table 1.

The approach offers valuable insights into the structural performance of diverse architectural forms and provides a time-efficient alternative to conventional FE simulations, which are typically more labour-intensive for tall buildings in practice. This paper outlines the essential features of the workflow and its efficacy for early-stage design exploration. The goal is to help designers in an early-design phase pursue a multi-objective search for a “good” choice that integrates not only aesthetics, mechanical behaviour, and, in future developments, economic cost, but also sustainability[26]. Furthermore, the findings emphasize the importance of considering lateral load considerations, particularly seismic actions, into tall building designs. These results can be extended to include other research areas, such as wind load analysis, and fluid-structure interaction[27].

Methodology

The successful design of tall buildings relies on the seamless integration of architectural creativity and structural functionality, particularly when addressing the complex demands of seismic performance. To meet these challenges, this study presents a computational workflow designed to systematically explore diverse architectural and structural configurations. This workflow ensures that critical performance criteria are addressed from the earliest design stages, streamlining the evaluation and optimization of tall building designs. The following main steps outline the methodology, serving as a foundation for the detailed analyses presented in this work.

- Generation of the model geometry. This step includes: i) a Latin hypercube sampling (LHS) strategy[28-29] to define a manageable number of cases for the computational resources at hand; ii) usage of the design parametric tools to provide an architectural form, first as a solid model, next as a discretized set of nodes and elements; iii) pre-dimension phase to initialise the element cross-sections to the correct sizes. This step is described in Section "Definition of the tall building geometry", see below.
- Definition of the seismic loads according to suitable earthquake databases, as shown in "Definition of the dynamic loading", see below.
- Setting of required output variables according to architectural, structural, environmental, economic priorities. In this work, as shown in "Sampled response output", see below, the emphasis is on architectural and structural variables, but ongoing research is already considering also the other ones.
- Exploitation of the database. The output can be either inspected directly by generating some figures of merit according to (possibly weighted) quantities of interest, including artificial intelligence algorithms[14-15], or used to surrogate alternative architectural forms (ongoing research). This step is exemplified in "Exploitation of building database", see below.

Definition of the tall building geometry (parametric model)

The development of a parametric model for tall buildings is critical to integrate architectural and structural considerations into the seismic design. This section outlines the creation of a comprehensive database of tall building geometries, focusing on the outer diagrid structure. By leveraging parametric design tools, the study explores a wide range of architectural forms and their structural performance under seismic actions. The methodology incorporates key design parameters and employs advanced sampling and computational techniques, to ensure an efficient yet thorough exploration of the design space.

Overview of the parametric model

The goal is to develop a comprehensive database of tall buildings geometries with outer diagrids, evaluated under a range of seismic loading conditions to assess their structural performance and inform design optimisation. This database provides detailed structural performance metrics for a variety of loading conditions, focusing particularly on seismic responses.

This section elaborates on constructing a parametric model that enables the automatic generation of tall building models, including both architectural and structural components, using Grasshopper. Ten parameters were used to describe the architectural form of a tall building, based on geometric and architectural form choices; these variables are listed and detailed in Table 2, where also their names, descriptions, and value ranges are shown (Figure 3, Stage A). The choices made are summarised in the following.

- Top and bottom geometry and orientation. The geometry of the top plan is independent of the geometry of the bottom plan, and both are assumed to be polygons with a number of sides between 3 and 12. The top and bottom plans can be aligned along one of their corners or along one of their edges (Figure 3, Stage A.1).
- Number of stories and floor height. The building can have a number of floors between 40 and 60 with an increasing step of 4 floors in between. The distance h_{floor} between floors is set to be 3.5, 4.0 or 4.5m.
- Vertical transformation rule: tapering or twisting or curvilinear transition. These options control the form of the building along its vertical development, and some examples of the variety achieved by way of the morphing parameters are shown in Figure 1 (in the same picture, the relevant values of design parameters are also included). While tapering allows to connect the top and bottom plan via straight lines, twisting and curvilinear transformations modify the form via smooth curves. Additional details for the transformation rules here adopted can be found in[28] (Figure 3, Stage A.2).

Parametric model generation and sampling strategy

The theoretical design space includes 61,200 combinations, offering a diverse range of architectural forms. This number is computed by multiplying the number of possible values for each design variable. For instance, the design variable n_{top} has 10 possible values, and similarly, n_{bot} also has 10 possible values. To effectively exploit available computational resources and manage complexity, 1000 models were chosen in the design space according to a LHS rule, a technique derived from the concept of a 'Latin square' in combinatorial mathematics. A Latin square is an $n \times n$ matrix populated with n distinct elements , such that each element appears exactly once in each row and column[30]. More importantly, this method ensures diversity without bias in the dataset, particularly avoiding an overrepresentation

Table 2. Design variables and description for the parametric model of tall buildings.

Design Variable	Symbol	Description	Ranges
Edge count of top plan geometry	n_{top}	Number of edges in the top plan geometry	[3,4,...,12]
Edge count of bottom plan geometry	n_{bot}	Number of edges in the bottom plan geometry	[3,4,...,12]
Orientation of top and bottom plans	θ_{rel}	Relative positioning of top and bottom plans (corner to corner =0, corner to edge =1)	[0,1]
Total floor count	n_{floor}	Total number of floors in the structure	[40,44,48,...,60]
Floor-to-floor height	h_{floor}	Height between consecutive floors (meters)	[3.5,4,4.5]
Method of vertical transformation	t_{vert}	Method of connecting top and bottom plans (tapered/twisted/curvilinear)	[0,1,2]
Tapering intensity	i_{taper}	Area scale factor of top plan compared to bottom plan	[50%,60%,...,90%, 100%]
Twisting intensity	i_{twist}	Rotation angle of the top plan (degrees)	[30,45,60,75,90]
Position parameter for curvilinear control floor	p_{curv}	Position parameter for curvilinearity	[0.25,0.5,0.75]
Intensity parameter for curvilinear control floor	i_{curv}	Intensity parameter for curvilinearity	[0.85,1.15]

of extremes in buildings highs or discrepancies in the number of edges between top/bottom plans. Each individual tall building model generation in Grasshopper requires approximately 1 minute on average, while each FE simulation takes around 30 minutes on a regular workstation, depending on the number of floors. Furthermore, the storage requirement for each FE simulation is approximately 1.2 GB. Although in this work the use of a Linux cluster and parallelization have significantly reduced the computational time, it is still infeasible to generate and simulate all 61,200 models in the design space due to the extensive time and storage demands. Therefore, the aforementioned sampling technique has been employed to select 1000 representative samples that adequately capture the characteristics of the entire design space.

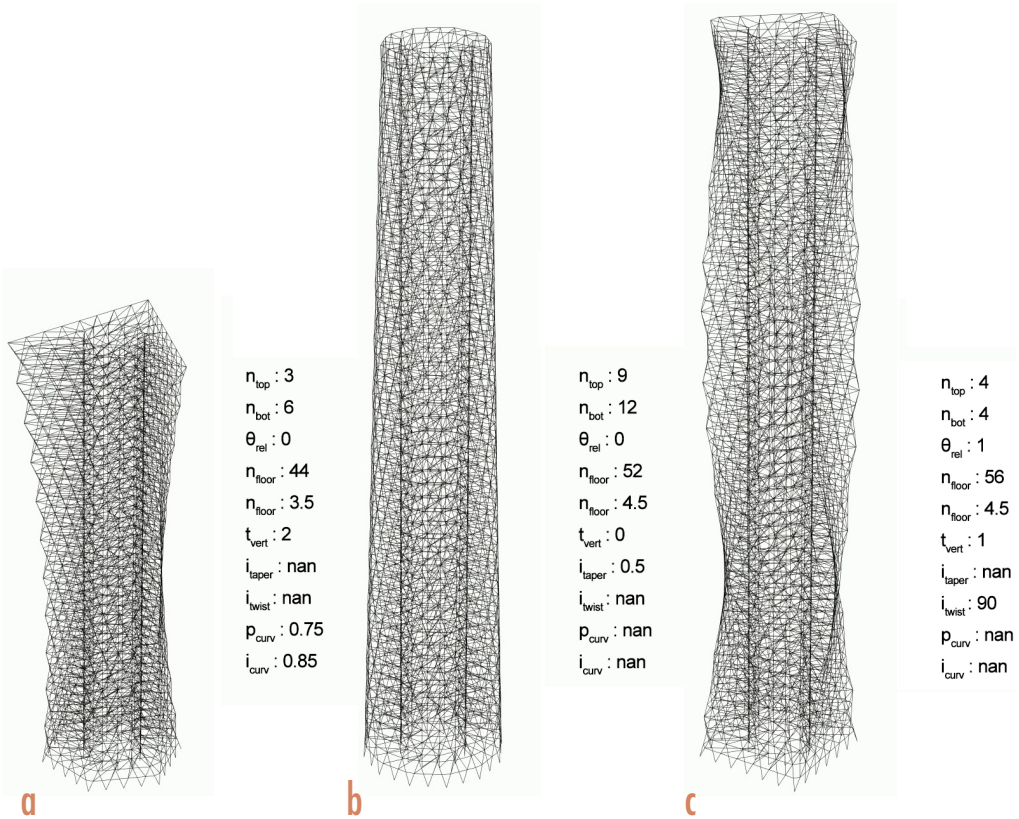


Figure 1. Examples of tall building models with different vertical transformations: (a) curvilinear, (b) tapered, and (c) twisted forms.

Diagrid integration and structural features

Once the architectural models are generated, the diagrid pattern is mapped onto the building façade by dividing the perimeter of all floor plans (Figure 3, Stage B.1). This process generates a grid of points, and polylines are then created to connect selected nodes following a specific pattern, forming the diagrid structure. Each diagrid module spans four floors. The structural components of an exemplary tall building model are highlighted in Figure 2. This figure depicts the diagrid diagonals, horizontal members, core columns, beams, bracing, and radial floor beams.

The workflow related to the model generation is detailed in Figure 3: the flowchart outlines several steps utilizing a combination of software tools. The procedure begins with a graphical parametric design script implemented in Grasshopper; which employs simulation plug-ins such as Colibri and Alpaca4d[29]. The former plug-in has been used to produce, for every case, the architectural and structural model files, a file collecting the seismic data useful for post-processing, an image of the building model with its generative information stored in a CSV file. The latter plug-in has been enhanced to support dynamic simulations by introducing features such as uniform excitation at the basement of the structure along the horizontal direction, representing a prescribed earthquake.

Efficient workflow management is crucial, especially considering the need to leverage high-performance computing capabilities. While workflow management should be independent of the software choice, the Python version of OpenSees facilitates easy integration with Grasshopper, enabling efficient automation of

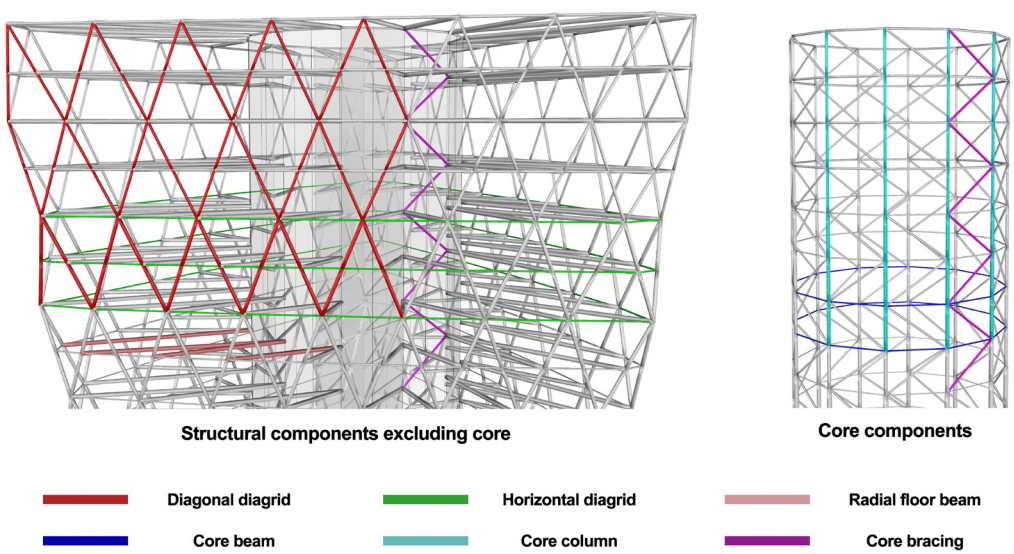


Figure 2. Design variables and description for the parametric model of tall buildings.

FE simulation files. Additionally, it supports parallelization of simulations on Linux clusters, further enhancing automation and computational efficiency. Therefore, OpenSeesPy, a Python-based scripting language designed to operate OpenSees—a well-known earthquake engineering software[31]—has been selected as the programming standard. OpenSeesPy excels in its robustness and offers flexibility for future expansion to nonlinear material behaviour or alternative analysis methods, such as modal analysis. Below is a summary of the file organisation approach:

- folders, labelled 1 to 1000 containing a Python script for Linux cluster execution, have been created (Figure 3, Stages D and E);
- four CSV files useful for the post-processing phase are included in each folder;
- an image file containing a picture of each model (1 to 1000) is also generated;
- another CSV file containing the list of the design variables corresponding to each model together with additional information inferable from the geometry only has been also produced.

Moreover, the buildings present a core connected through radial beams to the outer diagrids: the ratio between the core and the floor areas varies with height, ranging from just under 20% at lower levels to just over 20% at higher levels. All structural elements are assumed to be made of construction steel, while the floor slabs are modelled through rigid diaphragms.

The dynamic seismic simulation starts with a pre-dimensioning phase where static loads are applied as distributed loads on the beams of each floor. These include the dead weight of structural elements and other floor-specific loads like permanent or live loads for the office function, ranging from 7.5 kN/m^2 to 14.5 kN/m^2 for dead loads and assumed 2.5 kN/m^2 for live loads, without reduction in height. Eurocode load combinations are considered for this phase, incorporating a simplified seismic action with a statically equivalent method detailed in the reference[14].

This phase employs a cross-section optimiser from the Karamba, plug-in within Grasshopper, utilizing a database of over 2000 sections that vary every four floors. The optimizer aims to find the best solution by limiting horizontal displacement to h/500 of the building height and maintaining a utilisation factor of 95%, which represents the ratio between the maximum computed stress and the design stress in the structural members (Figure 3, Stage B.2).

This detailed procedure facilitates the creation of more realistic tubular sections for the outer diagrids, core columns, bracing, and both horizontal and radial beams, serving as a starting point for the construction of the building database that will undergo subsequent dynamic seismic simulation. Figure 4 illustrates a

sample tall building model featuring dimensioned tubular sections for the outer diagrids. It clearly identifies different floor groups, denoted by colour gradients that indicates the diameter of the cross sections: blue signifies smaller diameters, red indicates larger diameters, and green represents values in between. A total

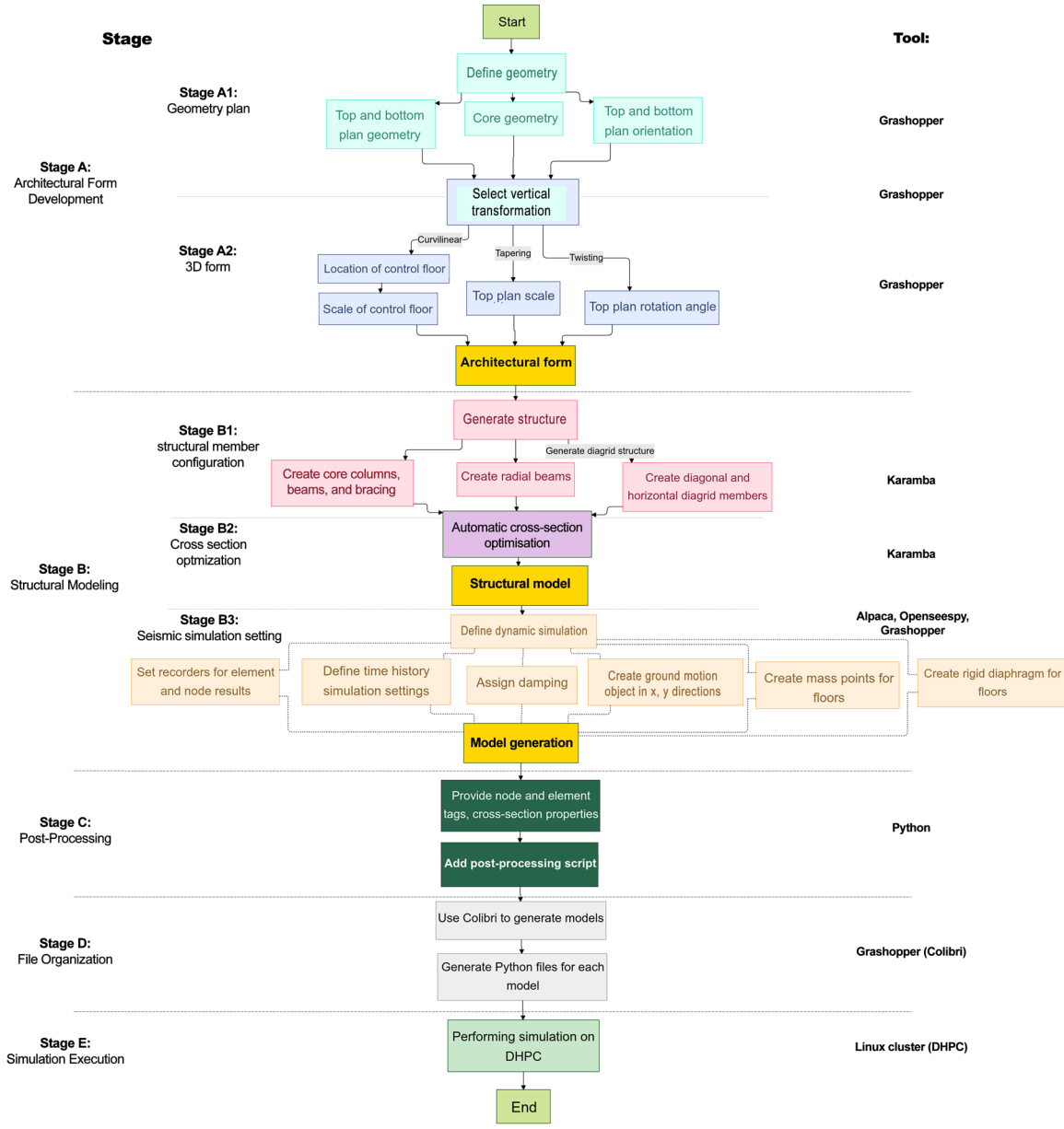


Figure 3. Detailed workflow for the generation of the building database.

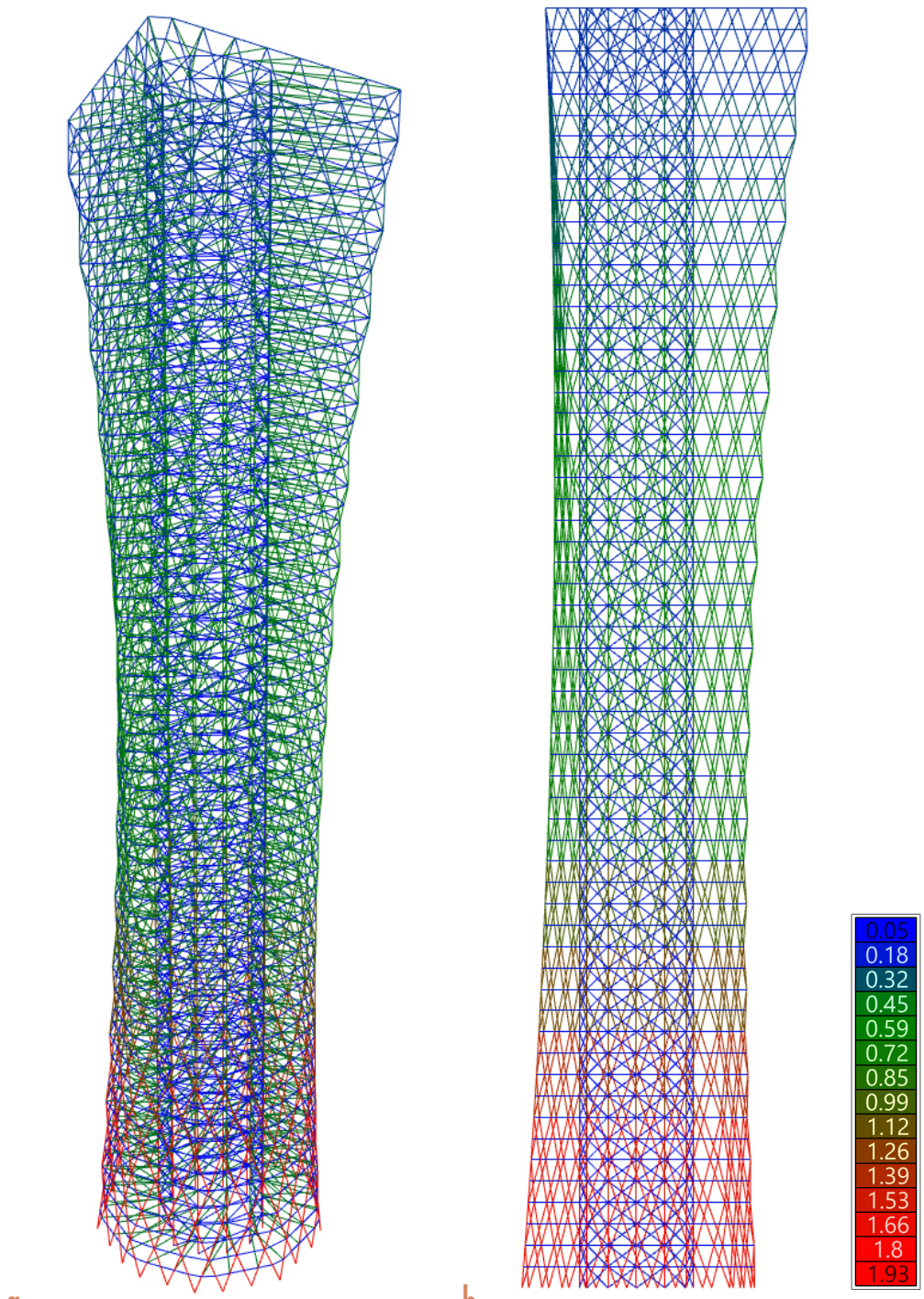


Figure 4. Example of a tall building subjected to the automated cross-section optimisation; (a) perspective, and (b) side view. The legend shows the diameter of the tubular cross section in meters.

of 65 unique cross-sections have been assigned throughout the model, ensuring an optimised distribution of material and structural efficiency tailored to the load-bearing requirements of the building.

Definition of the dynamic loading

The PEER NGA-West2 seismic database[32] has been selected to define seven different ground motions. At variance with other commonly used seismic databases, which are typically limited to periods of 4 s, it considers design spectra based on periods of up to 10 s, which are necessary to correctly define seismic inputs for tall buildings which tend to have fundamental vibration periods higher than common buildings or infrastructure (Figure 3, Stage B.3).

To ensure meaningful comparison between alternative architectural forms, the selection of seismic events has primarily focused on moderate earthquakes. Should the inclusion of more severe earthquakes be necessary due to the geo-location of the building site, the results must be interpreted with caution, as they may necessitate accounting for nonlinear constitutive behaviours in the analyses.

Figure 5 displays the seven selected motions relative to the design spectrum. A critical aspect of the seismic simulation for tall buildings in OpenSees is the integration of ground motion data into the analysis workflow. Thus, a uniform excitation at all nodes restrained to the ground, both in X- and Y-directions, has been added as a parametric design capability in Alpaca4d. For the sake of simplicity and assuming moderate excitations, the Z-vertical excitation has not been considered in this work, but it can easily be included in a future development. For the transient analysis, a Rayleigh damping with a 5% damping ratio is adopted in relation to the fundamental modes, adhering to the methodology outlined in [33]. In this study, the first ten vibration modes of each tall building model are identified and documented in a separate file. These fundamental modes include the expected cantilever-like behaviour dominated by bending along the height of the building, purely torsional modes, and also coupled bending torsional modes.

Sampled response output

Collecting data for all nodes and elements at every time step is both impractical and computationally intensive. Therefore, strategic decisions are required before initiating the analyses to determine which nodes and elements are critical for capturing the required output, and what data should be recorded during the transient analysis. In this study, OpenSeesPy's output commands are utilized as tools to store specific response data of interest, such as displacements, accelerations, and forces, during the simulation. The utilization of structural members, defined as the ratio of computed stress or force to design capacity, is calculated for key elements like diagrids, core columns, and bracing. This aids in

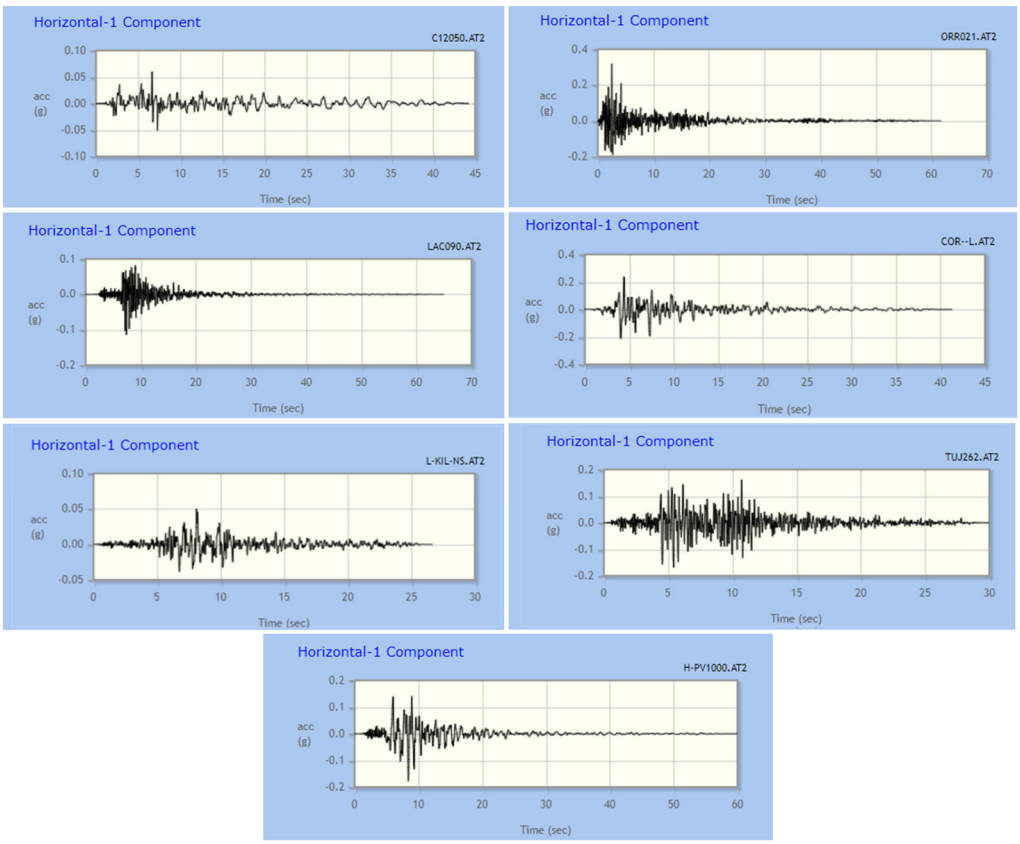


Figure 5. Selected ground motions (unscaled) used in dynamic seismic simulations.

identifying overstressed or underutilized components, optimizing cross-sections, and enhancing design efficiency during post-processing, while providing insights into load distribution for early-stage optimization.

The total number of nodes present in each model depends significantly on the building's design variables, particularly the number of stories, which ranges from 40 to 60. While a typical model with 50 floors has around 10,000 nodes, this number varies, increasing for taller buildings and decreasing for shorter ones. For instance, a model with 40 floors may have approximately 8000 nodes, while a model with 60 floors may exceed 12,000 nodes. This variability reflects the parametric nature of the models and the range of design configurations considered.

Out of this total amount, the following nodes are deemed relevant for characterizing the earthquake response: the core and outer diagrid restrained nodes, the

centroid node at each floor, and the corner nodes at each floor. These nodes have been selected based on their ability to represent the dynamic behaviour of the building effectively, while minimizing computational effort. The core and outer diagrid restrained nodes are critical for capturing the structural behaviour at the building supports, where maximum reaction forces and moments occur due to seismic excitation. The centroid nodes at each floor reliably represent the average translational displacement and acceleration for the entire floor, aiding in the computation of inter-storey drift and other floor-specific metrics. The corner nodes at each floor, chosen for their maximum distance from one another, ensure the dynamic response is captured across the full extent of the floor, accounting for potential torsional effects and lateral deformations that may vary across the floor geometry.

The selection of these nodes was validated through empirical testing on a sample tall building model. This process involved conducting preliminary simulations on a single tall building with a representative design configuration (e.g. 50 floors, curvilinear transformation, and mid-range tapering). During these tests, the dynamic response was recorded for all nodes and compared against the results obtained from the reduced set of selected nodes. The comparison showed minimal discrepancies (within 5%) for key structural metrics such as inter-storey drift, floor acceleration, and reaction forces, confirming the efficacy of the node selection approach.

The data recorded for these selected nodes include the three components of the translational displacements plus three components of the translational acceleration for each time step. Reaction forces (including moments) are also added for the restrained nodes at the base of the building. Other quantities of interest, such as the inter-storey drift, are computed during the post-processing phase based on these recorded outputs (Figure 3, Stage C).

For the structural elements, a similar selection process balances meaningfulness and computational effort. The core support columns, bracing elements, diagrid diagonal elements at the supports, and diagrid diagonal and horizontal members corresponding to the corner nodes are included in the output files. To capture the full structural response, OpenSeesPy's output commands are used to store data at each end of the selected elements. Specifically, by assuming x as the axis of the beam element, the following response data are recorded: the axial force N; the two components of the shear force Vy and Vz; three components of the moment (two components, My and Mz, for the bending moment and one component Mx for the torque). All the variables are computed and stored in correspondence of each end of the considered element.

Structural analysis via high performance computing

The analysis duration is set to 30 s for all cases, with a time step of 10 ms set for writing the output variables. Both duration and time step are aimed at limiting the computational burden and are deemed suitable given the D5-95 duration of all ground motions used, which is always below this limit. The time step number is therefore set to 3000, and an implicit Newmark time integration method has been adopted. The UmfPack solver, known for its efficiency in factorizing large, sparse matrices, is employed to enhance computational speed and accuracy in handling the complex structural systems modelled in this study.

Each of the 1000 models defined in the pre-processing must be subjected to the seven ground motions obtained from the PEER NGA-West2 seismic database, amounting to a total of 7000 three-dimensional analyses. For this task, the Delft Blue supercomputer was utilized, featuring 218 computing nodes each with 48 cores 2 x Intel Xeon E5-6248R and 192 GB RAM (out of 338 total cores with alternative hardware architecture). The computations were executed on CPU cores using a job array organisation of the scheduler.

Following the solver phase, a post-processing phase is conducted on the same cluster, using Python libraries such as VFO and Opsvis to facilitate visualisation of node and element recorders. This step has been necessary for navigating the extensive data collected and involves a strategic organisation of file names, locations and other properties, automated through Python scripts and GhPython components within Grasshopper.

In the post-processing phase, inter-storey drift, normal and shear stresses, von Mises stresses, total base shear forces, and bending moments were computed for each building model and stored in designated folders.

Exploitation of the building database

Several analyses can be conducted using the resulting database. Here, to pinpoint the models of interest for designers, a specific ground motion is assumed, and models are assessed based on their performance in this context. Further investigations incorporating artificial intelligence tools to analyse the database are in progress, including proper consideration of a larger suite of earthquakes, see e.g. [28]. Models with the lowest response values for specific structural metrics are summarized in Table 3. Furthermore, all selected models are visually depicted in Figure 6, allowing a comparative analysis of their unique geometric and structural characteristics.

Model #63 (Figure 6a) outperforms others with the smallest average normalised response, achieving the best index value (0 for the best and 1 for the worst) determined by aggregating the relative positions across all considered responses. This model presents a curvilinear design with the minimum number

of floors (40) and a floor-to-floor height of 3.5m, featuring a six-sided polygon at the top plan and a three-sided polygon at the bottom plan. Model #115 (Figure 6b), in contrast, demonstrates the best torsional response but with a relatively low absolute value: it is a tapered model without a change in plan area between the top and bottom, maintaining equal area at both ends. Model #302 (Figure 6c) achieves the lowest overall acceleration and is also a curvilinear model. In this way, each model listed in the table represents the best-performing design in terms of a specific seismic response. While in some cases, such as the mentioned model #63 above, the outcome confirms the designers' intuition, in other cases, such as for model #531 (Figure 6d), which has the lowest von Mises stress in the observed elements, the output leads to unexpected results. Model #531 is a building with a significant height and an interesting curvilinear form, but, evidently, it also features a well-distributed diagrid system, efficiently distributing the workload among each member. Model #725 (Figure 6f) presents the lowest mass/weight, only 6290 tons, and it is very regular, but its (relatively) low height is comparable with other cases, such as #63 or #641 (Figure 6e); so, also this case shows that the automated procedure can offer interesting insights to designers.

Table 3. Features and response values for the top-performing models among a total of 1000 considered tall building models.

Model ID	Mini-mized response	Overall max acceleration (m/s^2)	Overall max drift (mm)	Overall max von Mises stress (MPa)	Overall max torque (N·m)	Total max base shear force (kN)	Total mass of steel (ton)	Average normal-ised response
63	Average normalised response	2.219	1.670	141.55	0.000028	826,420	12,400	0.153
115	Overall max torque	2.271	1.730	108.11	0.000022	1,326,200	24,100	0.236
302	Overall max accel-eration	1.528	2.357	161.45	0.000144	2,128,200	44,300	0.438
531	Overall max von Mises stress	1.570	2.310	78.80	0.000114	1,123,900	27,100	0.235
641	Overall max drift	2.339	1.571	152.62	0.000042	971,570	13,500	0.188
725	Total mass of steel	2.937	3.120	120.75	0.000113	656,000	6290	0.360
841	Total max base shear force	2.847	2.946	123.54	0.000180	623,850	9830	0.380

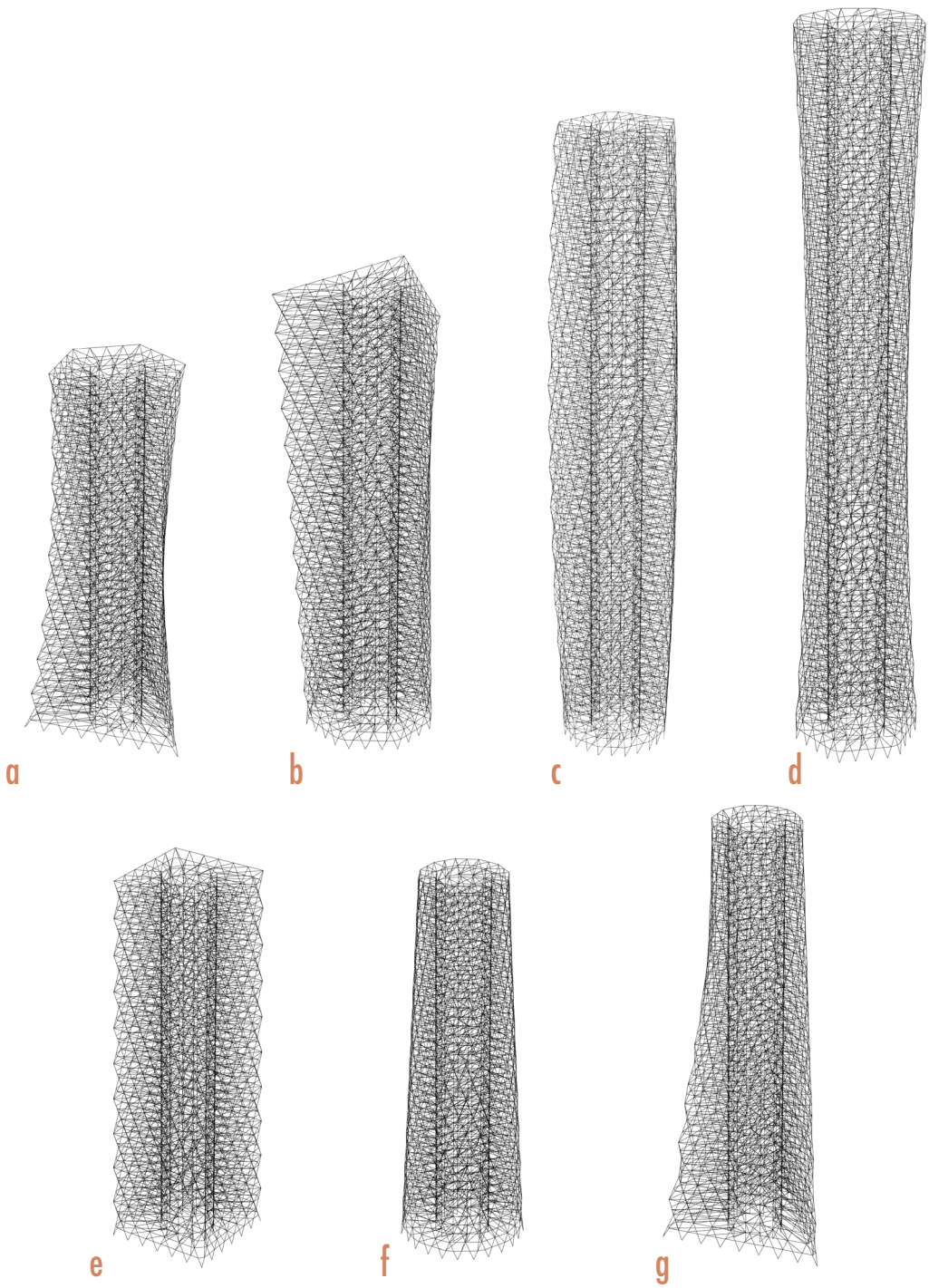


Figure 6. Visualisation of the best performing models, displaying the minimum value for specific responses outlined in Table 2: (a) model 63, (b) model 115, (c) model 302, (d) model 531, (e) model 641, (f) model 725, and (g) model 841.

Model #841 (Figure 6g) exhibits the lowest base shear force due to its minimum number of floors and tapered form, with a maximum of tapering amount of 50%. Model #725 demonstrates a comparable base shear force, featuring the same number of floors (40) and tapering; however, its top and bottom plan geometries differ from those of Model #841. Additionally, it is important to note that Model #63 also comprises 40 stories, but since it is not tapered, its base shear force is greater than that of the two aforementioned models.

Conclusion

A computational workflow has been developed to assist designers in the early stages of designing tall buildings with outer diagrid structures. This method facilitates the exploration of diverse architectural forms by providing a parametric design platform that allows systematic variation of key geometric parameters such as: number of polygonal sides for the top and bottom floors; inter-storey heights; total number of stories; vertical transformations (tapering, twisting, or curvilinear adjustments) throughout the height of the building. By defining these parameters as inputs within the parametric model, a broad spectrum of building forms can be automatically generated and analysed, offering an intuitive approach for evaluating design alternatives.

An automated process has been created to generate simulation files utilizing Grasshopper and Python, with enhancements in the Alpaca4D plug-in built on OpenSees software. This enables dynamic seismic simulations of tall buildings with outer diagrids. This workflow includes both pre- and post-processing stages, that allow raw simulation data, such as node and element outputs, to be transformed into meaningful structural indices such as inter-storey drift, base shear, and other critical metrics.

For this study, 1000 simulation files, each representing a unique building configuration, have been generated and run across seven different ground motion records, resulting in 7000 simulations. To efficiently handle this computational demand, the analyses were run on the Delft Blue Linux high-performance cluster, allowing parallel processing, and storage of all time-history results.

One of the primary motivations for building this database is its potential for training surrogate models, which could provide a rapid and computationally efficient alternative to detailed finite element simulations. This capability highlights the database value as a foundational resource for machine learning applications in architectural and structural design. Such a surrogate model, incorporating structural, economic, and environmental response parameters, can facilitate informed decision-making in the early design stages of tall buildings. Additionally, the database offers an opportunity for interactive visualization, enabling designers to explore design options dynamically and intuitively. This feature can represent an exciting direction for future development as it allows users to examine how design variations impact structural performance metrics, providing a more user-

friendly and iterative approach to design exploration. Moreover, while the issue is not discussed here, the database could also be augmented a posteriori through several techniques[15,25]. However, it should be noted that the surrogate model cannot extend its predictions outside the parameter design space with which it was built, and therefore the choice of parameters cannot be underestimated.

As this research integrates 91 diverse response variables, including structural, economic and environmental factors, the resulting surrogate model provides a foundation for improving decision-making during the conceptual design stage. Future research could also prioritize the development of interactive visualization systems that allow the database to be leveraged as a design exploration tool, promoting a more hands-on approach to optimizing tall building designs. Furthermore, future work could extend this database with additional design features and responses while incorporating generative AI algorithms to identify high-performing designs within the parameter space. These algorithms can enable automated design generation and optimisation, significantly enhancing the exploration of innovative structural and architectural configurations.

Author Contributions

Original concept and methodology, original draft: P.K., A.G.; software and investigation—: P.K.; computational resources: C.A., M.T. Writing and editing: all authors. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Conflict of Interest

The authors declare no conflicts of interest.

Ethical Compliance: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data Access Statement: Research data supporting this publication are available from the corresponding author.

References

1. C. M. Herr, "Creativity in cross-disciplinary collaborations between architects and structural engineers in China," Proceedings of IASS Annual Symposia, vol. 2018, no. 4, pp. 1-8, International Association for Shell and Spatial Structures (IASS), July 2018.
2. R. Hyde, "Computer-aided architectural design and the design process," *Architectural Science Review*, vol. 59, no. 4, pp. 255-256, July 2016, doi: 10.1080/00038628.2016.1194516.
3. H. Sun, H. V. Burton, and H. Huang, "Machine learning applications for building structural design and performance assessment: State-of-the-art review," J*ournal of Building Engineering*, vol. 33, p. 101816, 2021, doi: 10.1016/j.jobe.2020.101816.
4. M. Elnimeiri and B. S. Taranath, Tall Buildings and Urban Habitat, Council on Tall Buildings and Urban Habitat (CTBUH), 2012.
5. B. S. Taranath, *Tall building design: Steel, concrete, and composite systems*, CRC Press, 2016, doi: 10.1201/9781315374468
6. L. L. Beghini, A. Beghini, N. Katz, W. F. Baker, and G. H. Paulino, "Connecting architecture and engineering through structural topology optimization," *Engineering Structures*, vol. 59, pp. 716-726, 2014, doi: 10.1016/j.engstruct.2013.10.032.
7. K. S. Moon, "Sustainable structural engineering strategies for tall buildings," *The Structural Design of Tall and Special Buildings*, vol. 17, no. 5, pp. 895-914, 2008, doi: 10.1002/tal.475.
8. M. Ali and K. Moon, "Advances in structural systems for tall buildings: Emerging developments for contemporary urban giants," *Buildings*, vol. 8, no. 8, pp. 104, 2018, doi: 10.3390/buildings8080104.
9. C. Liu et al., "Study on flexural stiffness of diagrid non-stiffened node based on four-spring assemblage model," *Engineering Structures*, vol. 198, p. 109500, 2019, doi: 10.1016/j. engstruct.2019.109500.
10. D. Fang and C. Liu, "Mechanical characteristics and deformation calculation of steel diagrid structures in high-rise buildings," *Journal of Building Engineering*, vol. 42, p. 103062, 2021, doi: 10.1016/j.jobe.2021.103062.
11. C. Preisinger, "Linking Structure and Parametric Geometry," *Architectural Design*, vol. 83, 2013, doi: 10.1002/ad.1564.
12. L.M. Mueller et al., "Data and Parameterization Requirements for 3D Generative Deep Learning Models," Proceedings of 42nd eCAADe Conference, Nicosia, Cyprus, 9-13 September, pp. 615-624, 2024.
13. M. Turrin et al., "Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms," *Advanced Engineering Informatics*, vol. 25, no. 4, pp. 656–675, 2011, doi: 10.1016/j.aei.2011.07.009.

14. P. Kazemi et al., “Classification of the structural behavior of tall buildings with a diagrid structure: A machine learning-based approach,” *Algorithms*, vol. 15, no. 10, p. 349, 2022, doi: 10.3390/a15100349.

15. P. Kazemi et al., “Machine learning techniques for diagrid building design: Architectural-structural correlations with feature selection and data augmentation,” *Journal of Building Engineering*, vol. 86, p. 108766, 2024, doi: 10.1016/j.jobe.2024.108766.

16. H. Zheng, V. Moosavi, and M. Akbarzadeh, “Machine learning assisted evaluations in structural design and construction,” *Automation in Construction*, vol. 119, p. 103346, 2020, doi: 10.1016/j.autcon.2020.103346.

17. N. Brown and C. Mueller, “Early-stage integration of architectural and structural performance in a parametric multi-objective design tool,” 3rd Annual Conference on Structures and Architecture, Guimarães, Portugal, 27-29 July 2016.

18. A. S. Ramdasi and S. N. Tande, “Lateral load analysis of high rise structures,” *International Journal of Engineering Science and Technology*, vol. 6, no. 6, pp. 268, June 2014.

19. Z. Yu, H. Dai, and Z. Shi, “Structural form-finding of bending components in buildings by using parametric tools and principal stress lines,” *Frontiers of Architectural Research*, vol. 10, pp. 1-11, 2021. doi: 10.1016/j.foar.2021.11.004.

20. N. C. Brown and C. T. Mueller, “Design variable analysis and generation for performance-based parametric modeling in architecture,” *International Journal of Architectural Computing*, vol. 17, no. 1, pp. 36-52, Mar. 2019. doi: 10.1177/1478077118799491.

21. A. Bidgoli and P. Veloso, “DeepCloud. The application of a data-driven, generative model in design,” ACADIA // 2018: Recalibration. On imprecision and infidelity. Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Mexico City, Mexico, 18-20 Oct. 2018, pp. 176–185, doi: 10.52842/conf.acadia.2018.176.

22. S. B. Abdalla, M. Rashid, and D. R. Ara, “Plausibility of CAAD in conceptual design: Challenges in architectural engineering for early-stage digital design tools,” J*ournal of Architectural Engineering*, vol. 27, no. 2, pp. 04021004, Jun. 2021. doi: 10.1061/(ASCE)AE.1943-5568.0000457.

23. K. Saldana Ochoa, P. O. Ohlbrock, P. D’Acunto, and V. Moosavi, “Beyond typologies, beyond optimization: Exploring novel structural forms at the interface of human and machine intelligence,” *International Journal of Architectural Computing*, vol. 19, no. 3, pp. 466-490, 2021, doi: 10.1177/1478077120943062.

24. B. Ekici, Z. T. Kazanasmaz, M. Turrin, M. F. Tasgetiren, and I. S. Sariyildiz, “Multi-zone optimisation of high-rise buildings using artificial intelligence for

sustainable metropolises. Part 1: Background, methodology, setup, and machine learning results," *Solar Energy*, vol. 224, pp. 373-389, 2021, doi: 10.1016/j.solener.2021.05.083.

25. P. Kazemi et al., "Artificial intelligence-powered computational strategies in selecting and augmenting data for early design of tall buildings with outer diagrids," *Buildings*, vol. 14, no. 4, p. 1118, 2024, doi: 10.3390/buildings14041118.
26. D. Fang et al., "Reducing embodied carbon in structural systems: A review of early-stage design strategies," *Journal of Building Engineering*, vol. 76, p. 107054, 2023, doi: 10.1016/j.jobe.2023.107054.
27. E. Estrado et al., "Optimization of complex-geometry high-rise buildings based on wind load analysis," *Simulation*, vol. 99, no. 11, pp. 1133-1146, 2023, doi: 10.1177/00375497221109577.
28. P. Kazemi et al., "Deep learning approach to structural performance prediction of tall buildings in seismic areas," Proceedings of the IASS 2024 Symposium Redefining the Art of Structural Design, August 26-30, Zurich, Switzerland, 2024.
29. "Alpaca4d - OpenSees wrapper for Grasshopper," [Online]. Available: https://alpaca4d.gitbook.io/docs, Accessed: Oct 30, 2024.
30. R. Sheikholeslami and S. Razavi, "Progressive latin hypercube sampling: An efficient approach for robust sampling-based analysis of environmental models," *Environmental Modelling & Software*, vol. 93, pp. 109-126, 2017, doi: 10.1016/j.envsoft.2017.03.010.
31. F. McKenna et al., "Nonlinear finite-element analysis software architecture using object composition," *Journal of Computing in Civil Engineering*, vol. 24, pp. 95–107, 2010, doi: 10.1061/(ASCE)CP.1943-5487.0000002.
32. E. Seyhan et al., "NGA-West2 site database," *Earthquake Spectra*, vol. 30, no. 3, pp. 1007-1024, 2014, doi: 10.1193/062913EQS180M.
33. J. Hall, "Problems encountered from the use (or misuse) of Rayleigh damping," *Earthquake Engineering & Structural Dynamics*, vol. 35, pp. 525-545, 2006, doi:10.1002/eqe.541.

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