



Available online at
<https://jurnalteknik.unisla.ac.id/index.php/CVL>
<https://doi.org/10.30736/cvl.v2i2>



Effects of Finite Element Modeling Parameters on Seismic Response of a Hospital Building

Muhammad Puja Fathurrachman^{1*}, Syahrul Satar², Multasam³, Adhriyansyah Effendy Saputra⁴

^{1*,2,3,4}Department of Civil Engineering, Institut Teknologi Bacharuddin Jusuf Habibie

Email : ^{1*}pujafat@ith.ac.id ²rulsatar@ith.ac.id ³multasam18@ith.ac.id

⁴saputraae.251101039@mahasiswa.ith.ac.id

ARTICLE INFO

Article History :

Article entry : 23-06-2026

Article revised : 06-07-2026

Article received : 18-08-2026

Keywords :

Structural Modeling, Seismic Response, Mesh Convergence, Insertion Point, End Length Assumption, Equivalent Lateral Force

IEEE Style in citing this article :

M. P. Fathurrachman, S. Satar, Multasam, and A. E. Saputra, "Effects of Finite Element Modeling Parameters on Seismic Response of a Hospital Building", CVL, vol. 11, no. 2, pp. 142–151.

ABSTRACT

Accurate structural modeling is essential for reliable seismic performance evaluation, yet default software settings in finite element analysis tools are frequently adopted without adequate calibration. This study investigates the sensitivity of seismic response in a five-story reinforced concrete hospital building to three key modeling parameters: shell element mesh size, insertion point configuration, and beam end length assumption. A mesh convergence study was first conducted across six discretization levels to identify an optimal mesh size. Subsequently, four structural models were developed using a Design of Experiment (DoE), with M1 (top insertion point, clear length) serving as the reference baseline. Linear seismic analysis was performed using the Equivalent Lateral Force (ELF) method in accordance with SNI 1726:2019, with natural period, base shear force, and story displacement adopted as response indicators. Results show that a 1 m mesh size provides an optimal balance between accuracy and computational efficiency. Insertion point configuration was identified as the dominant parameter, with centroid-based models producing up to 21% longer natural periods and 46% greater story displacements compared to M1. Base shear was exclusively governed by the end length assumption, as the ELF method renders it insensitive to stiffness-related parameters.

1. Introduction

Structural performance evaluation is fundamentally governed by the assumptions adopted during the modeling process, including material properties, loading conditions, and numerical analysis approaches [1], [2]. In practice, these decisions are frequently made under uncertainty, and even seemingly minor modeling choices have been shown to produce significant discrepancies in predicted seismic responses [3], [4]. This concern is especially critical for hospital buildings, which are classified as essential facilities under seismic design provisions and must remain operational following seismic events, thereby imposing a higher standard of accuracy and reliability on structural evaluation [5], [6].

The reliability of seismic response predictions is directly affected by the accuracy of stiffness representation in numerical models — a quality that is itself governed by modeling parameter choices such as element discretization, insertion point assignment, and member end length assumption [7].



Copyright © 2026 Muhammad Puja Fathurrachman, et al This work is licensed under a [Creative Commons Attribution-ShareAlike 4.0 International License](https://creativecommons.org/licenses/by-sa/4.0/). Allows readers to read, download, copy, distribute, print, search, or link to the full texts of its articles and allow readers to use them for any other lawful purpose.

Kwon and Ghannoum [8] found that code-based stiffness estimates frequently deviate from actual structural behavior, underscoring the necessity of deliberate stiffness calibration in numerical models. Raheem et al. [3], [9] further demonstrated that modeling choices involving beam placement, rigid end offsets, and joint connectivity produces measurable variations in global stiffness, story drift, and base shear demand across buildings of varying height. Kumbhar and Kumar [4] confirmed similar sensitivity in regular RC frames, linking slab participation and end offset assumptions to stiffness distribution and seismic force demand.

With specific regard to shell element discretization, Sazzad et al. [10] examined the effect of slab mesh size on lateral load response in ETABS and demonstrated that coarser mesh configurations underestimate stiffness contributions from slab elements, leading to overestimated natural periods. This finding establishes mesh convergence studies as a standard prerequisite for parametric investigations involving shell elements [11]. Beyond mesh size, the insertion point and end length configurations of frame elements were selected as the focus of this study because they represent the most commonly applied default settings in CSI software that practitioners rarely adjust, yet both directly govern the effective stiffness and tributary mass of the structural model — the two quantities that control all seismic response indicators. These parameters are also recognized as influential in the existing literature [12], [13], [14], [15]. Fathurrachman et al. [16] further demonstrated that stiffness-related modeling assumptions produce significant differences in seismic evaluation outcomes in buildings with complex configurations, establishing a direct precedent for the present investigation. In the context of hospital building seismic performance, Imran et al. [6] evaluated the seismic behavior of a five-story reinforced concrete hospital building in Indonesia and highlighted the critical role of structural period and lateral stiffness in determining seismic vulnerability and retrofit requirements, reinforcing the need for accurate numerical modeling in essential building design. Zebua et al. [5] similarly underscored that hospital buildings require rigorous seismic performance evaluation due to their operational criticality, particularly in regions of high seismicity. Septiarsilia et al. [17] further evaluated the seismic behavior of a building modified with a Special Concentrically Braced Frame system and confirmed the sensitivity of dynamic response indicators to structural system configuration under SNI 1726:2019.

Despite these findings, most prior studies have examined modeling parameters in isolation — for example, Sazzad et al. [10] investigated mesh size without varying insertion point, while Raheem et al. [3], [9] focused on joint connectivity and offset assumptions without concurrent mesh sensitivity evaluation — and have largely relied on idealized regular frame geometries rather than realistic essential facility models [18], [19]. To address this gap, this study makes an explicit contribution by simultaneously investigating three modeling parameters — mesh size, insertion point, and beam end length — within a finite element model derived from an actual hospital building, providing integrated and case-grounded modeling recommendations that prior studies have not offered. This study addresses the gap through a two-stage approach. First, a mesh convergence study is conducted to identify the optimal shell element size. Second, a parametric study is conducted using a Design of Experiment (DoE) that systematically varies insertion point configuration and beam end length assumption across four structural models. Linear seismic analysis per SNI 1726:2019 [20] is then applied to quantify the influence of each parameter on natural period, base shear force, and story displacement. The findings are expected to yield specific recommendations on the preferred insertion point configuration and beam end length assumption for reinforced concrete hospital building models in seismic-prone regions.

2. Research Method

This study employs a linear static seismic analysis approach — specifically the Equivalent Lateral Force (ELF) method per SNI 1726:2019 — to evaluate the influence of finite element modeling parameters on the seismic response of a building structure. The methodology is structured into two main stages: (1) mesh convergence analysis and (2) parametric study using a Design of Experiment (DoE). The DoE approach was selected because it enables systematic and simultaneous variation of multiple parameters across a structured set of models, allowing the independent and combined effects of each parameter to be identified efficiently. The overall objective is to quantify how selected modeling parameters affect key structural response indicators, including natural period, base shear force, and story displacement.

3. Description and Technical

3.1 Population and Samples

The object of this study is a five-story reinforced concrete hospital building located in Parepare, South Sulawesi, Indonesia. The building is modeled numerically using ETABS and serves as the basis for all parametric variations conducted in this study.

The structural system adopted is a dual system, consisting of a moment-resisting frame combined with shear walls, where both systems contribute to lateral load resistance. The building represents a mid-rise essential facility requiring reliable seismic performance evaluation. A dual system was adopted as it represents the most commonly applied lateral load-resisting configuration in mid-rise hospital buildings in Indonesia, and is the structural system specified in the original building design documents used as the basis for this study.

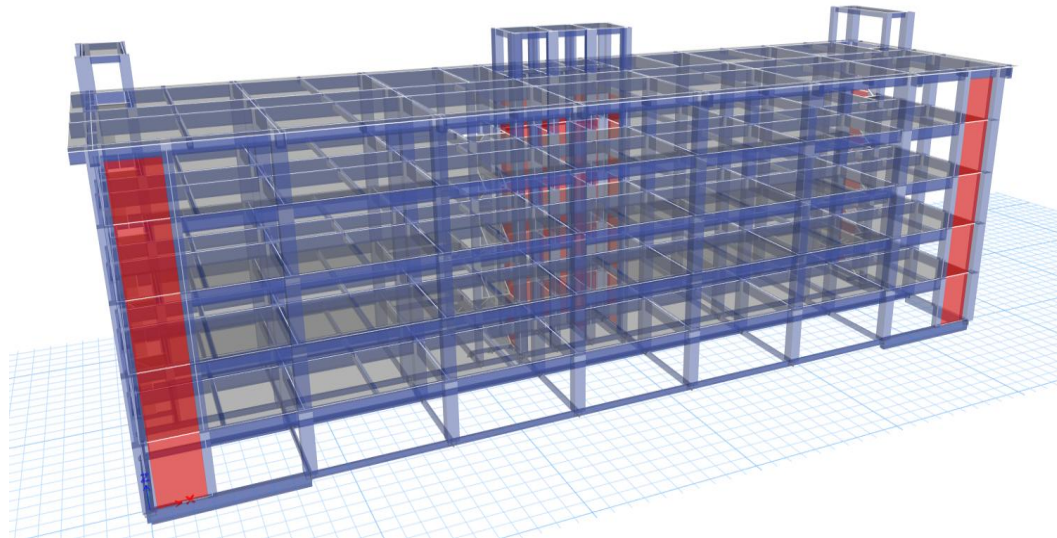


Figure 1. 3D numerical model of the five-story hospital building (Source: Research Data).

3.2 Sampling Techniques

A parametric sampling approach using a design of experiment (DoE) method is employed. Two key modeling parameters are selected: insertion point configuration (Top and Center) and beam end length assumption (Clear Length and Full Length). These parameters are systematically combined to generate four structural models (M1–M4), while all other modeling aspects are kept constant. The combination of these parameters is summarized in **Table 1**.

Table 1. Design of Experiment (DoE) Matrix — Structural Model Configurations (Source: Research Data).

Model	Mesh	Insertion Point	End Length
M1	1 m	Top	Clear Length
M2	1 m	Top	Full Length
M3	1 m	Center	Clear Length
M4	1 m	Center	Full Length

Model M1 is designated as the reference model because it employs the top insertion point — which accounts for the physical T-beam eccentricity between beam and slab — and the clear span length, which excludes the rigid joint overlap zone. These two assumptions most closely replicate the actual geometric and mass conditions of the as-built structure.

3.3 Operational Definition of Variables.

The study involves three categories of variables. The input parameters are insertion point configuration and beam end length assumption, which are systematically varied across the four structural models. The shell element mesh size serves as the controlled parameter, fixed at 1 m for all models following the convergence study. The response variables — natural period (T), base shear force (V), and story displacement (δ) — are the seismic response indicators used to evaluate the effect of each input parameter.

The mesh size is first optimized through a convergence study, where multiple discretization levels are evaluated to identify an efficient and stable solution. The selected mesh size is then used consistently in all parametric models.

3.4 Instrument Analysis Tool

The structural modeling and analysis are performed using ETABS. Floor slabs are modeled as shell elements, while beams and columns are represented as frame elements. Seismic analysis is conducted using the Equivalent Lateral Force (ELF) method in accordance with SNI 1726:2019. The method determines base shear based on structural mass, fundamental period, and site-specific spectral acceleration, which is then distributed along the building height. The ELF method was selected not as a performance assessment tool, but as a controlled analytical framework to isolate and compare the effect of modeling parameters across models under identical loading conditions. Since the primary objective is sensitivity analysis rather than seismic performance evaluation, ELF provides a consistent and reproducible basis for comparison.

3.5 Data Analysis Techniques

Data analysis is conducted in two sequential stages. In the first stage, a mesh convergence analysis is performed by comparing the fundamental natural period obtained from models with progressively refined mesh sizes. The optimal mesh size is selected based on the stability of results and acceptable computational time. In the second stage, a comparative parametric analysis is carried out by evaluating the responses of the four models (M1–M4) in terms of natural period, base shear force, and story displacement. The analysis examines the relative differences between models, the sensitivity of each response indicator to the modeling assumptions applied, and the identification of dominant parameters affecting structural stiffness and seismic mass.

The results are interpreted to determine the relative influence of each parameter on the three response indicators. Based on this analysis, specific recommendations are formulated regarding the preferred insertion point configuration and end length assumption for reinforced concrete hospital building models, with the goal of improving the representativeness and reliability of numerical models used in seismic design practice.

4. Results and Discussions

4.1 Mesh Convergence Analysis

The initial phase of the study involved a mesh convergence analysis to identify a shell element discretization that ensures numerical stability without excessive computational overhead. Six different mesh sizes—ranging from 8 m down to 0.25 m—were evaluated, as illustrated in **Figure 2**.

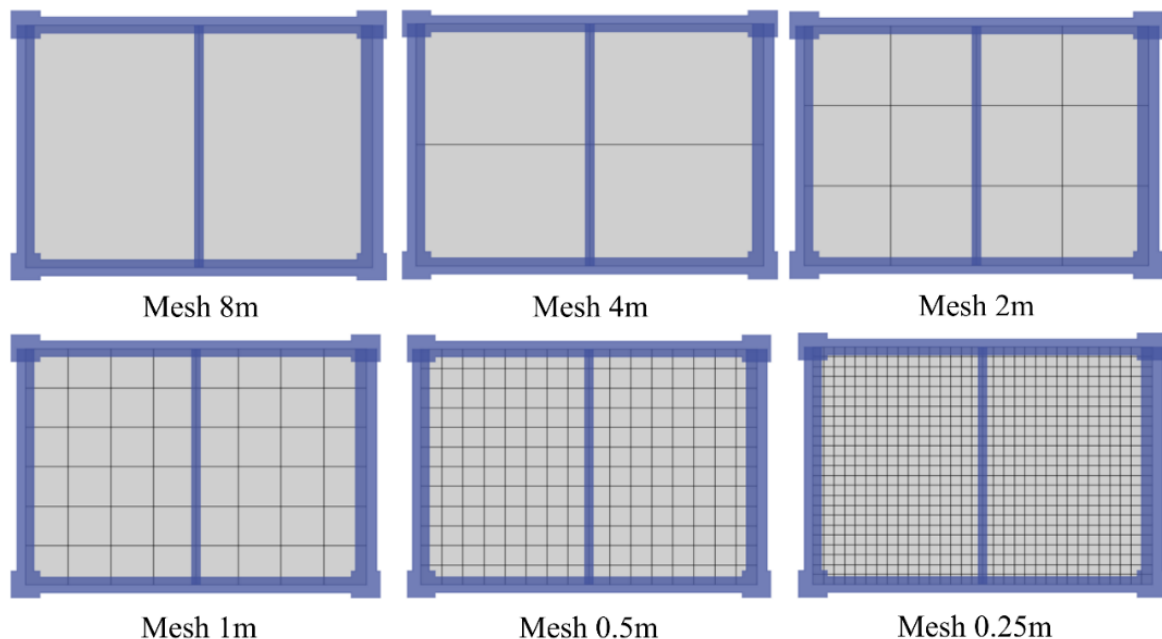


Figure 2. Comparison of element discretization levels for mesh convergence study (Source: Research Data).

The results of the convergence study, comparing the fundamental natural period (T) and the associated computational time, are summarized in **Table 2** and **Figure 3**.

Table 2. Mesh Convergence Results (Source: Research Data).

Mesh Size (m)	Natural Period, T (s)	Relative Change (ΔT)	Time (min)
8.00	0.588	-	0.15
4.00	0.593	0.84%	0.17
2.00	0.615	3.58%	0.27
1.00	0.627	1.91%	0.78
0.50	0.634	1.10%	5.45
0.25	0.636	0.31%	47.52

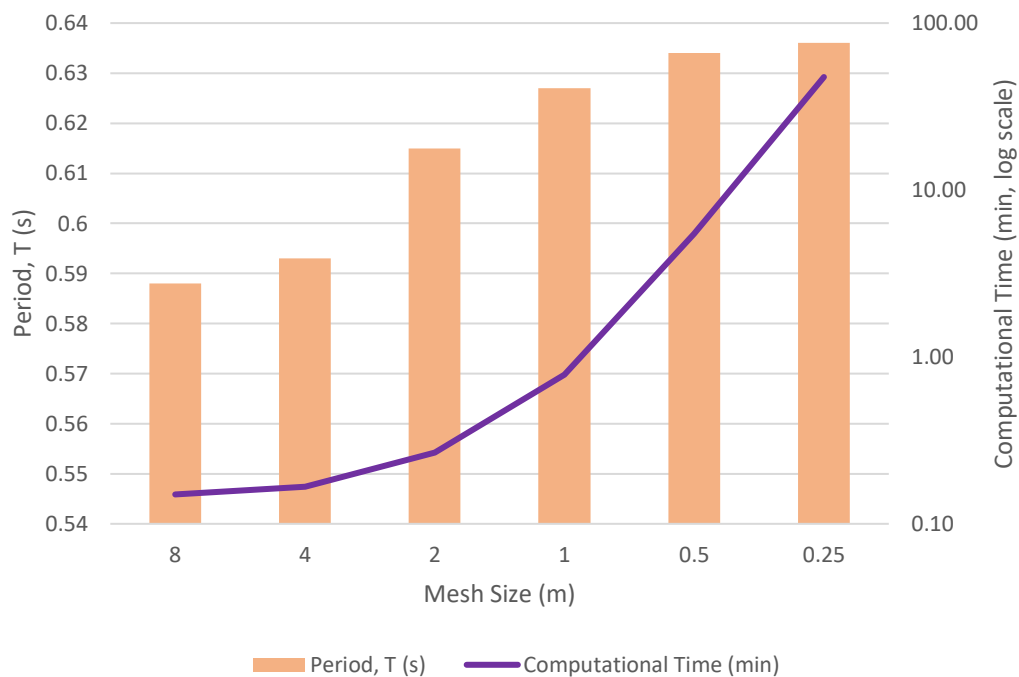


Figure 3. Mesh convergence results (Source: Research Data).

The data indicates that as the mesh size decreases, the natural period increases and eventually approaches a stable asymptotic value. While the 0.25 m mesh provides the highest level of refinement, the improvement in accuracy from 1 m to 0.25 m is negligible (less than 1.5% total change), whereas the computational time increases exponentially from 0.78 minutes to nearly 48 minutes. This drastic increase in time is best visualized using a logarithmic scale, which highlights the point of diminishing returns.

Following the principles of computational efficiency, a 1 m mesh size was selected for the subsequent parametric study. This discretization provides a stable result where the natural period has converged sufficiently to satisfy the accuracy requirements for an essential hospital facility.

4.2 Comparative Parametric Analysis

Following the mesh convergence, a parametric study was conducted using a Design of Experiment (DoE) approach to evaluate the sensitivity of the hospital's seismic response to insertion points and member end lengths. The visual differences in these configurations—specifically the shift from centroid-based to eccentric top insertion points and the variation between clear and full member lengths—are illustrated in **Figure 4**.

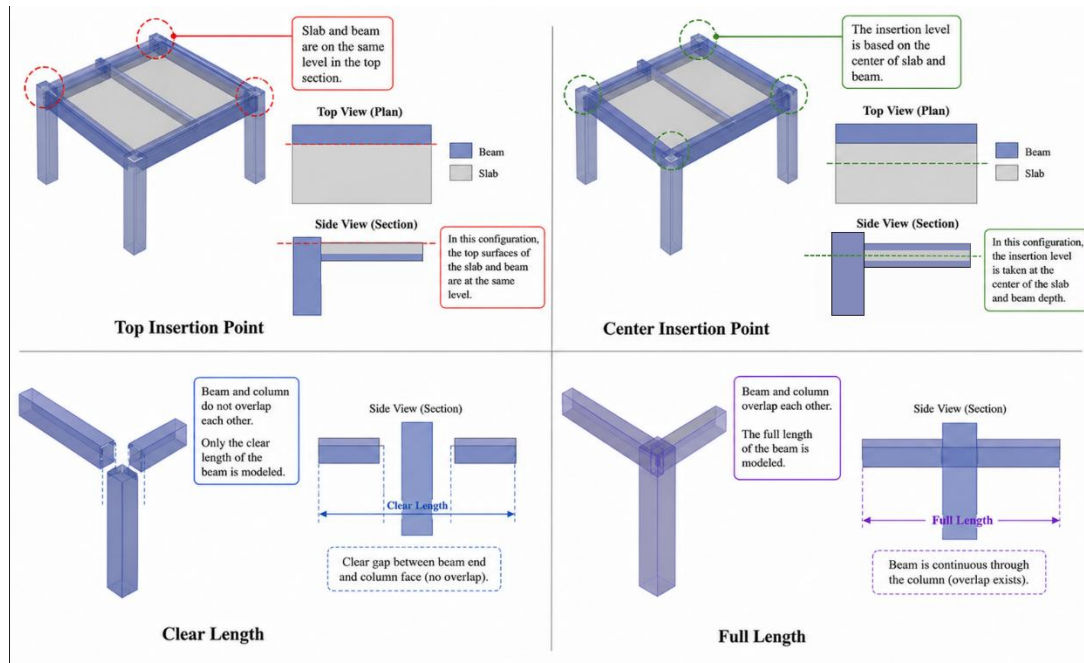


Figure 4. Visual representation of Top vs. Center insertion points and Clear vs. Full member length (Source: Research Data).

4.2.1 Influence on Natural Period (T)

The natural period is a primary indicator of global structural stiffness. The comparison between models is summarized in **Table 3** and **Figure 5**.

Table 3. Natural Period Comparison and Relative Error (Source: Research Data).

Model	Period T (s)	Error vs. M1 (%)
M1 (Ref)	0.527	0%
M2	0.542	3%
M3	0.618	17%
M4	0.636	21%

The transition from "Top" to "Center" insertion points caused the most significant discrepancy in the natural period, resulting in relative differences ranging from 17% to 21% compared to the reference model. This confirms that "Top" insertion points, which account for the eccentric T-beam effect, significantly increase the lateral stiffness of the structural system. Conversely, centroid-based modeling (Models M3 and M4) fails to capture this added stiffness, leading to an overestimation of structural flexibility that reduces the reliability of the seismic response prediction.

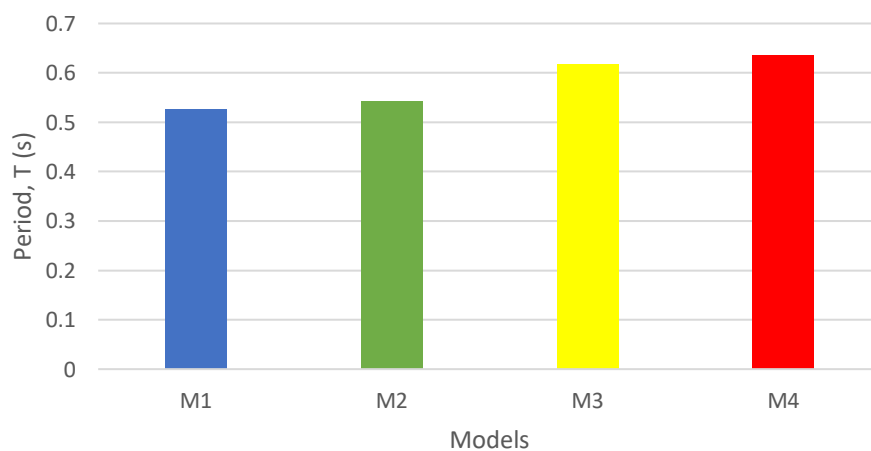


Figure 5. Comparison of fundamental natural periods across structural models (Source: Research Data).

In contrast, the impact of member end length assumptions (Clear vs. Full) was notably less significant for this specific geometry, contributing to only a 3% to 4% variation in the natural period. However, it is important to note that in models with higher frame density or complexity, the mass differences resulting from overlapping joint volumes in "Full Length" assumptions can more substantially impact the fundamental period. For this hospital model, the stiffness gain from "Top" insertion points remains the dominant driver of accuracy, whereas the end length assumption primarily influences force demand, such as base shear.

4.2.2 Influence on Story Displacement (δ)

The story displacement profiles for both X and Y directions, representing the building's lateral drift under seismic loading, are illustrated in **Figure 6**.

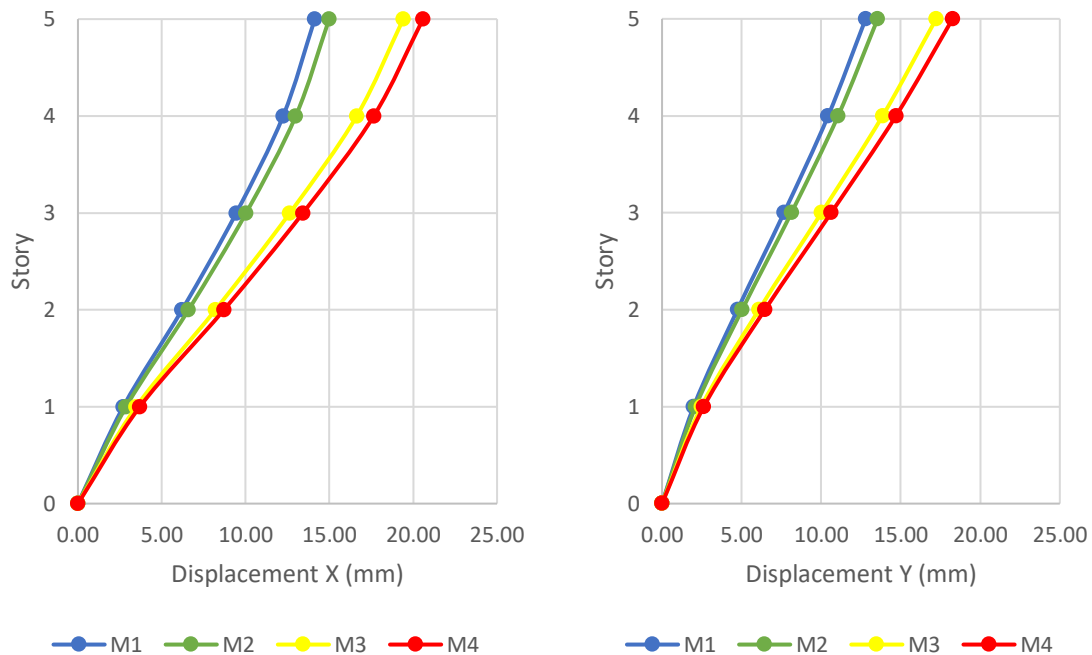


Figure 6. Story displacement profiles for M1–M4 in X and Y directions (Source: Research Data).

The modeling parameters significantly influenced the predicted lateral deformations, with the discrepancies becoming more pronounced at higher floor levels. The numerical comparison of the top-story displacement is summarized in **Table 4**.

Table 4. Top-Story Displacement and Relative Error Comparison (Source: Research Data).

Model	δx (mm)	Error (%)	δy (mm)	Error (%)
M1 (Ref)	14.13	0%	12.80	0%
M2	14.99	6%	13.55	6%
M3	19.41	37%	17.23	35%
M4	20.58	46%	18.26	43%

The results indicate that the insertion point is the primary driver of predicted displacement response. Shifting from "Top" to "Center" (M1 to M3) resulted in a massive 37% increase in predicted displacement. This aligns with the natural period findings, confirming that centroid-based modeling significantly underestimates the lateral stiffness provided by the T-beam effect.

The end length assumption further compounded this error; when "Full Length" was combined with a "Center" insertion point (Model M4), the displacement error reached a peak of 46% in the X-direction and 43% in the Y-direction.

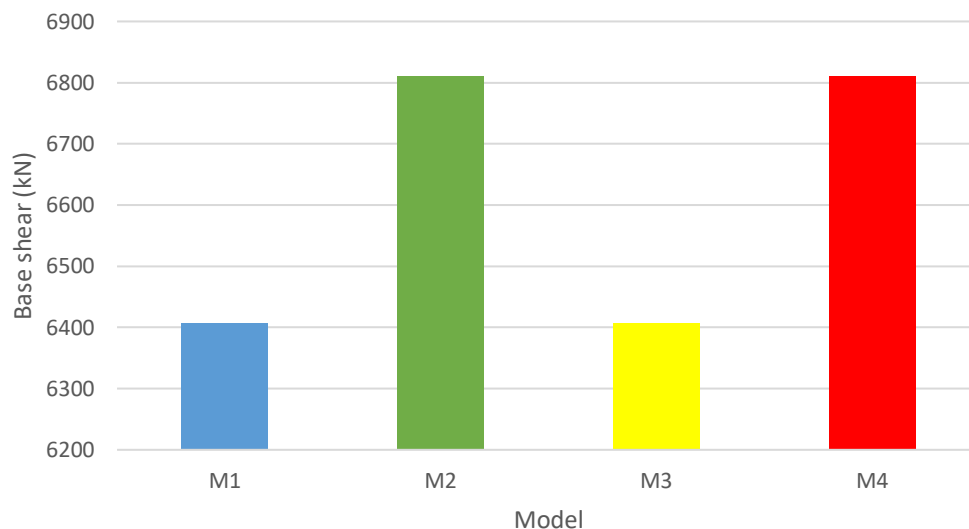
4.2.3 Influence on Base Shear (V)

Table 5 and **Figure 7** present the base shear results for all four models. Models M1 and M3 produced identical values of 6,406.65 kN, as did M2 and M4 at 6,810.77 kN — a 6.31% difference between end length groups. The insertion point parameter did not affect base shear.

Table 5. Base shear comparison across models (Source: Research Data).

Model	Base Shear (kN)	Error Vs. M1 (%)
M1	6406.654	0.00%
M2	6810.772	6.31%
M3	6406.654	0.00%
M4	6810.772	6.31%

The identical base shear between M1 and M3, and similarly between M2 and M4, is attributable to the nature of the ELF method itself. Under ELF, base shear is governed by two quantities: the seismic response coefficient and the effective seismic weight of the structure. The insertion point parameter influences only the geometric positioning of frame elements and, by extension, structural stiffness — it does not alter member mass or tributary weight. Consequently, base shear is determined solely by seismic weight. Since insertion point does not alter member mass, models sharing the same end length assumption carry identical seismic weights and therefore produce equal base shear.

**Figure 7.** Base Shear Results for Each Structural Model (Source: Research Data).

The 6.31% difference between the clear and full-length groups, on the other hand, is a direct consequence of the end length assumption's effect on seismic weight. The full-length model distributes member self-weight over the entire center-to-center span, whereas the clear length model limits this to the net span between column faces, resulting in a lower total seismic weight and correspondingly lower base shear.

It should be noted that this insensitivity of base shear to insertion point is a characteristic specific to ELF analysis. Under RSA, base shear is derived from modal combination and is therefore directly dependent on the natural period of each model. Since insertion point configuration produces natural period differences of up to 21% across the four models — as shown in Section 4.2.1 — RSA would be expected to yield correspondingly different spectral accelerations and, consequently, differentiated base shear values across all models. In particular, centroid-based models (M3, M4), which exhibit longer periods, would likely fall in a lower spectral acceleration region compared to top insertion point models (M1, M2), potentially producing lower base shear values despite carrying the same or greater seismic weight. This interaction between insertion point and base shear under RSA remains unquantified in the present study and is recommended as a direction for future investigation.

5. Conclusion and Suggestion

5.1 Conclusion

This study investigated the sensitivity of seismic response in a five-story hospital building to three finite element modeling parameters: shell element mesh size, insertion point configuration, and beam end length assumption. Based on the mesh convergence study and comparative parametric analysis of four structural models (M1–M4), the following conclusions are drawn:

- The mesh convergence study confirmed that a shell element mesh size of 1 m provides a stable and sufficiently accurate representation of structural behavior, offering an appropriate balance

between solution accuracy and computational efficiency. Further refinement beyond 1 m yields negligible improvement while significantly increasing computation time.

- The insertion point configuration is the most influential modeling parameter on natural period and story displacement. Adopting a centroid-based insertion point, as opposed to a top insertion point that accounts for T-beam eccentricity, substantially underestimates the lateral stiffness of the structural system, leading to overestimated natural periods and lateral displacements.
- The beam end length assumption is the sole parameter affecting base shear force under the ELF method. The full-length assumption increases the computed seismic weight of the structure relative to the clear length assumption, resulting in higher base shear. The insertion point configuration, which affects stiffness but not mass, has no influence on ELF base shear.
- The combination of centroid-based insertion point and full end length assumption (M4) produced the greatest cumulative deviation from the reference model (M1) across all response indicators, confirming that the simultaneous application of non-representative default settings amplifies modeling error significantly.
- Among the parameters studied, insertion point configuration exerts a dominant influence on stiffness-related responses, while end length assumption governs mass-related force demands. These two parameters operate through distinct mechanical pathways and their effects are largely independent and additive.

5.2 Suggestion

Based on the findings and limitations of this study, the following recommendations are proposed for future research:

- Future studies should employ Response Spectrum Analysis (RSA) or Time History Analysis to evaluate the same modeling parameters, as these methods derive lateral forces through modal combination and are inherently period-sensitive. This would allow a more comprehensive assessment of how insertion point configuration affects base shear — an effect that is masked under the ELF method due to its reliance on a fixed approximate period.
- The present study was conducted on a regular five-story reinforced concrete hospital building. Extending the investigation to irregular structural configurations, taller buildings, or buildings with different structural systems would improve the generalizability of the findings across a broader range of design scenarios.
- Nonlinear static (pushover) or nonlinear dynamic analysis should be incorporated in subsequent studies to evaluate the sensitivity of modeling parameters on inelastic structural behavior, which is of critical importance for performance-based seismic design of essential facilities.

The authors gratefully acknowledge the financial support provided by the 2026 Internal Research Grant Program of the Bacharuddin Jusuf Habibie Institute of Technology (ITH).

References

- [1] M. Algamati, A. Al-Sakkaf, E. Mohammed Abdelkader, and A. Bagchi, "Studying and Analyzing the Seismic Performance of Concrete Moment-Resisting Frame Buildings," *CivilEng*, vol. 4, no. 1, pp. 34–54, Jan. 2023, doi: 10.3390/civileng4010003.
- [2] K. Morfidis, A. Athanatopoulou, A. Giaralis, A. Sextos, and I. Avramidis, *Eurocode-Compliant Seismic Analysis and Design of R/C Buildings*. 2015.
- [3] S. Abdel Raheem, A. Abdel Zaher, A. Taha, and M. Omar, "Effects of numerical modeling simplification on seismic design of buildings," *Coupled Systems Mechanics*, vol. 7, pp. 731–753, 2018, doi: 10.12989/csm.2018.7.6.731.
- [4] O. Kumbhar and R. Kumar, "Effect of Modeling Assumptions on Seismic Performance of RC Building," in *Lecture Notes in Civil Engineering*, 2019, pp. 73–84. doi: 10.1007/978-981-13-0362-3_6.
- [5] D. Zebua, A. A. S. Putra, L. S. B. Wibowo, and S. Alfiani, "EVALUATION OF SEISMIC PERFORMANCE OF HOSPITAL BUILDING USING PUSHOVER ANALYSIS BASED ON ATC-40," *Journal of Civil Engineering, Science and Technology*, vol. 14, no. 2, pp. 138–145, Sep. 2023, doi: 10.33736/jcest.5326.2023.

- [6] I. Imran, D. M. Siringoringo, and S. S. Rainayana, "Seismic evaluation and retrofit of a typical reinforced concrete hospital building in Indonesia with DCFP isolation system," *Structures*, vol. 64, p. 106593, Jun. 2024, doi: 10.1016/j.istruc.2024.106593.
- [7] L. Nirmalkar, "Modelling And Analysis the Structures by Finite Element Methods," *INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT*, vol. 09, no. 04, pp. 1–9, Apr. 2025, doi: 10.55041/IJSREM45365.
- [8] J. Kwon and W. Ghannoum, "Assessment of international standard provisions on stiffness of reinforced concrete moment frame and shear wall buildings," *Eng. Struct.*, vol. 128, 2016, doi: 10.1016/j.engstruct.2016.09.025.
- [9] S. E. Abdel Raheem, A. K. Abdel Zaher, and A. M. Taha, "Finite element modeling assumptions impact on seismic response demands of MRF-buildings," *Earthquake Engineering and Engineering Vibration*, vol. 17, no. 4, pp. 821–834, Oct. 2018, doi: 10.1007/s11803-018-0478-1.
- [10] Md. M. Sazzad, Md. S. Azad, Md. T. Islam, and F. Ibna Rahman, "Effect of Mesh Size of Floor Slab against Lateral Loads while using Etabs Program," vol. 06, pp. 40–44, 2017.
- [11] S. Sattar, "Evaluating the consistency between prescriptive and performance-based seismic design approaches for reinforced concrete moment frame buildings," *Eng. Struct.*, vol. 174, pp. 919–931, 2018, doi: 10.1016/j.engstruct.2018.07.080.
- [12] CSI, *CSI Analysis Reference Manual for SAP2000, ETABS, SAFE, and CsiBridge*. 2017.
- [13] Ondrej, "Effect of insertion point on beam reactions," CSI America Wiki. Accessed: Dec. 30, 2025. [Online]. Available: <https://wiki.csiamerica.com/display/tp/Effect+of+insertion+point+on+beam+reactions>.
- [14] Ondrej, "Insertion point," CSI America Wiki. Accessed: Dec. 30, 2025. [Online]. Available: <https://wiki.csiamerica.com/display/kb/Insertion+point>
- [15] Dr. G. H. Powell, *Modeling for Structural Analysis*. Berkeley: CA: Computers and Structures, Inc., 2010.
- [16] M. P. Fathurrachman, I. Satyarno, and D. Sulistyono, "Modeling's Effect of Irregular Building Structure with Vegetated Roof on Seismic Evaluation per ASCE 41-17," *Semesta Teknika*, vol. 27, no. 2, pp. 168–181, Nov. 2024, doi: 10.18196/st.v27i2.22775.
- [17] Y. Septiarsilia, E. Susanti, D. K. Fitriyah, Dewi Pertiwi, and Umbu Miron, "Seismic Performance Evaluation Of Building Structures Modified With Special Concentrically Braced Frames (SCBF)," *Civilla : Jurnal Teknik Sipil Universitas Islam Lamongan*, vol. 11, no. 1, pp. 77–88, Apr. 2026, doi: 10.30736/cvl.v11i1.1617.
- [18] A. Sen *et al.*, "ASCE/SEI 41 assessment of reinforced concrete buildings: Benchmarking linear procedures and FEMA P-2018 with empirical damage observations," *Earthquake Spectra*, vol. 39, no. 3, pp. 1658–1682, Aug. 2023, doi: 10.1177/87552930231173454.
- [19] O. Nady, S. Y. Mahfouz, and S. E.-D. F. Taher, "Quantification of Vertical Irregularities for Earthquake Resistant Reinforced Concrete Buildings," *Buildings*, vol. 12, no. 8, p. 1160, Aug. 2022, doi: 10.3390/buildings12081160.
- [20] B. S. Nasional, *SNI 1726:2019 Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Nongedung*. Jakarta, 2019.