DCEA Disaster in Civil Engineering and Architecture

Popular Scientist

Research Article

Seismic Performance Analysis of Buildings Strengthened with X-Bracing Systems under Dynamic Earthquake Loads

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Articles History: **Received:** 3 October 2025; **Revised:** 29 October 2025; **Accepted:** 9 November 2025; **Published:** 12 November 2025

Abstract

Indonesia, as an archipelagic country located within the Pacific Ring of Fire, has a high level of vulnerability to earthquakes. However, many buildings in earthquake-prone regions have not yet been optimally reinforced against dynamic seismic loads, thereby posing risks to both safety and structural performance. This study analyzes the structural performance of the Cempaka Lima General Hospital building in Banda Aceh, Aceh, Indonesia, using Simeulue earthquake data as the dynamic load. Simeulue Island experienced several major earthquakes, including the significant events in 2004 and 2012, which highlight the region's high seismic vulnerability. The objective is to evaluate improvements in stiffness, stability, and seismic performance of the building after the application of X-bracing, and to compare these with its condition prior to reinforcement. The novelty of this research lies in the implementation of an X-bracing system in a hospital building located in a high seismic hazard zone, utilizing local earthquake data to yield more realistic results. The findings indicate that the axial force in the unbraced structure reached 20,714.6 kN, whereas after the addition of bracing it decreased to 20,616.33 kN. The largest base shear with bracing occurred on the first floor, at 6512.97 kN (X-direction) and 6497.5 kN (Y-direction). The maximum displacement without bracing was recorded on the fourth floor at 0.564 mm (X-direction), while in the braced structure the displacement was significantly reduced. The story drift values were also below the limit specified by the Indonesian National Standard, which is 2% of the story height, thus fulfilling seismic performance requirements. These results demonstrate that the use of X-bracing can significantly enhance structural stability and maintain the service performance of hospital buildings in earthquake-prone areas.

Keywords: Base Shear, Bracing X, Displacement, Story Drift, Time History

Introduction

Indonesia is an archipelagic country situated within the Ring of Fire, one of the most tectonically active regions in the world. This geographical condition makes Indonesia highly vulnerable to geological hazards such as earthquakes, tsunamis, and volcanic eruptions [1,2]. Data from the Meteorology, Climatology, and Geophysics Agency (BMKG) record hundreds of earthquakes with significant magnitudes occurring each year, both tectonic and volcanic in nature. Major earthquake events such as the 2004 Aceh earthquake and tsunami, the 2009 Padang earthquake, the 2018 Lombok earthquake, and the 2018 Palu earthquake have demonstrated catastrophic impacts in the form of infrastructure damage, loss of life, and substantial economic losses [3,4].

From a structural engineering perspective, earthquakes generate ground vibrations accompanied by dynamic lateral forces that can induce large deformations in buildings. If a building is not designed according to seismic resistance standards, such excessive deformations may lead to structural failure or even total collapse [5,6]. Therefore, building regulations in Indonesia require the application of seismic design standards [7].

Hospitals, as vital infrastructure, demand stricter structural performance requirements than ordinary buildings [8]. Many previous studies have shown that hospital damage caused by earthquakes often hampers medical response, making it crucial to enhance hospital structural resilience [9–11]. In Indonesia, the urgency to strengthen hospital buildings is increasing, particularly in Aceh, one of the regions with the highest seismic activity [12].

Bracing is an additional structural element in the form of diagonal members installed in the building frame to improve lateral stiffness and reduce deformation caused by earthquake or wind loads [13,14]. Bracing systems function by converting a moment-resisting frame into a lateral load-resisting system, so that seismic forces are not only resisted by flexural moments in columns and beams but are also transferred to the diagonal elements through axial tension-compression mechanisms [15].

There are various bracing configurations, including concentric bracing, eccentric bracing, V-bracing, inverted V (chevron), and X-bracing. Among them, X-bracing is one of the most efficient because it significantly reduces inter-story drift and enhances the lateral load capacity of the structure with a relatively uniform distribution of axial forces [16-18]. Nevertheless, it should be noted that the use of bracing must also consider architectural aspects so as not to disrupt the building’s functional space [19].

In Indonesia, research on the effectiveness of X-bracing in hospital buildings remains very limited, particularly analyses based on local earthquake data. Yet hospitals are essential infrastructure that must remain functional after earthquakes, making structural performance evaluation crucial [20]. Most previous studies have emphasized equivalent static or response spectrum analysis, which, while useful for preliminary design, cannot fully describe the dynamic behavior of structures. These two methods cannot represent the influence of earthquake duration, complex frequency content, or modal interactions [21,22]. Conversely, time history analysis provides a more realistic representation since it uses actual earthquake records, thereby allowing for the evaluation of key parameters such as base shear, inter-story drift, and deformation distribution. The use of local earthquake data, such as the Simeulue earthquake, further increases the relevance of the results because it reflects the actual seismic conditions in Aceh

https://doi.org/10.70028/dcea.v2i2.64

[23]. Thus, the application of X-bracing analyzed using time history methods based on local earthquake data becomes an innovative approach, contributing significantly to hospital building strengthening strategies in earthquake-prone regions.

Based on this background, the research is focused on the Cempaka Lima General Hospital building located in Banda Aceh, Aceh, Indonesia. The selection of this building as the research object is not only due to its vital function but also because of its location in a region with high seismic activity, making it crucial to ensure that the building has adequate seismic performance. Hospitals fall under the category of essential buildings that require higher seismic resistance standards compared to ordinary buildings [24]. This is because healthcare facilities must continue operating after an earthquake to support emergency response. Therefore, evaluating the structural performance of the Cempaka Lima General Hospital is a strategic step to assess the extent to which this building withstands dynamic loads from local earthquakes, while also assessing the effectiveness of the applied structural strengthening system.

In this study, the analytical method employed is time history analysis, a dynamic approach capable of simulating structural responses to actual earthquake records [25]. The Simeulue earthquake record was used as the dynamic load input because it is considered representative of the seismic conditions in Aceh, located near the Indian Ocean megathrust subduction zone [26]. The primary objective of this research is to analyze the stiffness and stability of the Cempaka Lima General Hospital structure after reinforcement with an X-bracing system. The analysis includes evaluations of key parameters such as axial forces, maximum moments, base shear, inter-story drift, and overall structural deformation.

This study introduces the application of an X-bracing system to a hospital building in Aceh, evaluated using dynamic loading data from the Simeulue earthquake. The findings highlight that X-bracing effectively improves the building’s seismic performance while ensuring that inter-story drift remains within the permissible limits defined by ACI and SNI standards.

Materials and Methods

This section describes in detail and systematically the processes and stages related to data collection, data processing, and data analysis in order to obtain the research results. The research steps are outlined in several section.

Data collection

The data required to model the building structure consist of both primary and secondary data. Primary data were obtained directly from field surveys conducted at the Cempaka Lima General Hospital building, including information on the quality of concrete materials used and structural measurements. In addition, secondary data were also utilized. These included architectural drawings and structural details derived from as-built drawings (technical drawings that describe the building structure after construction was completed), seismic hazard maps, and site.

https://doi.org/10.70028/dcea.v2i2.64

The research site is the Cempaka Lima General Hospital in Aceh, located at Jalan Politeknik Aceh No. 23, Beurawe, Kuta Alam District, Banda Aceh City, Indonesia. The building data analyzed in this study are as follows:

- Coordinates: N 5º 33’8.90” E 95º 20’5.44”
- Soil condition: Soft Soil (Class E)
- Building function: Public Health Services
- Structural system: Reinforced Concrete
- Number of stories: 4 floors
- Concrete strength: fc’ = 25 MPa (K-300), Elastic Modulus of Concrete (E = 4700√fc’ = 22,540 MPa)
- Reinforcement steel: Diameter < 14 mm: fy = 240 MPa (plain bar), Diameter ≥ 14 mm: fy = 320 MPa (deformed bar)
- Structural system: Special Moment Resisting-Frame (SMRF).

Structural Modeling

Structural analysis was carried out based on the existing dimensions and conditions in order to obtain the internal forces resulting from various load combinations. The tool used was a computer equipped with structural analysis software, namely ETABS. During this phase, the plans (design drawings and planning documents) were analyzed, and the actual implementation was also examined. Based on the results of this structural analysis, the strength of the column and beam elements, as the primary load-bearing members, was evaluated.

The Cempaka Lima General Hospital building in Aceh was constructed using reinforced concrete structures. The material properties used are as follows:

- Concrete strength: fc’ = 25 MPa (K-300)
- Elastic modulus of concrete: 4700√fc’ = 22,540 MPa
- Steel quality: fy = 420 MPa, fu = 545 MPa (BjTS 420B), fy = 280 MPa, fu = 405 MPa (BjTP 280)
- Unit weight of steel: 7850 kg/m^3

In this structural design, an X-type concentrically braced frame (CBF) configuration is adopted. The system is engineered using gusset plates that are capable of dissipating seismic energy when subjected to dynamic excitation or lateral loads. Despite its effectiveness in enhancing lateral stiffness and strength, this configuration exhibits a limitation in ductility, as it possesses a reduced capacity to sustain significant plastic deformation prior to structural failure. Meanwhile, the applied loads include dead loads, live loads, wind loads, seismic loads, and other relevant loads corresponding to the function and location of the structure.

https://doi.org/10.70028/dcea.v2i2.64

The structural element dimensions used in the data processing method were derived from field survey results. The floor slab modeled was a reinforced concrete slab with a thickness of 12 cm. The floor slab was modeled as a rigid diaphragm. In ETABS, slab modeling was performed using the Slab Section feature. After entering the material and structural data, the modeling was conducted according to the previously defined grid. The modeling results are shown in Figures 1 and 2.

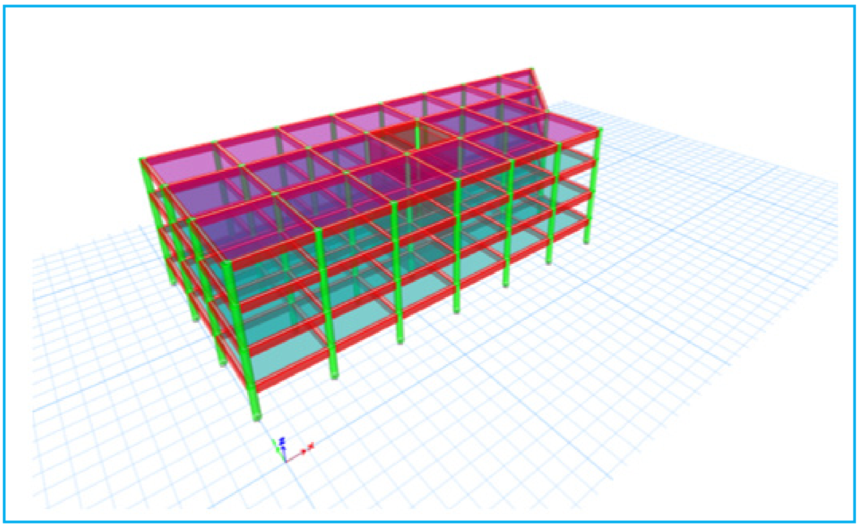

Figure 1. 3D modeling result of the Cempaka Lima General Hospital building using ETABS without bracing

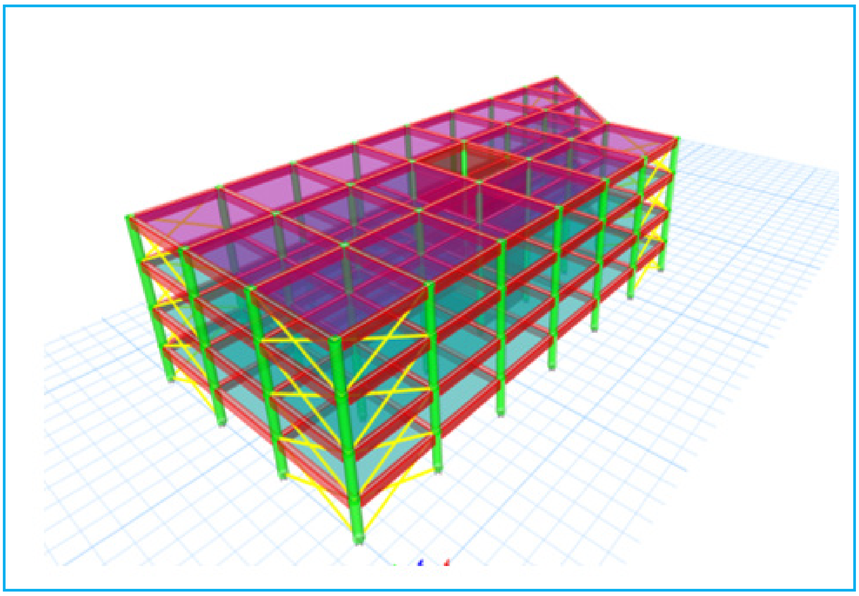

Figure 2. 3D modeling result of the Cempaka Lima General Hospital building using ETABS with bracing

Time History Analysis

The earthquake load used in the time history analysis was in the form of ground acceleration records, and in this study the Simeulue earthquake record was employed. The structural modeling for the building can be seen in Figure 3.

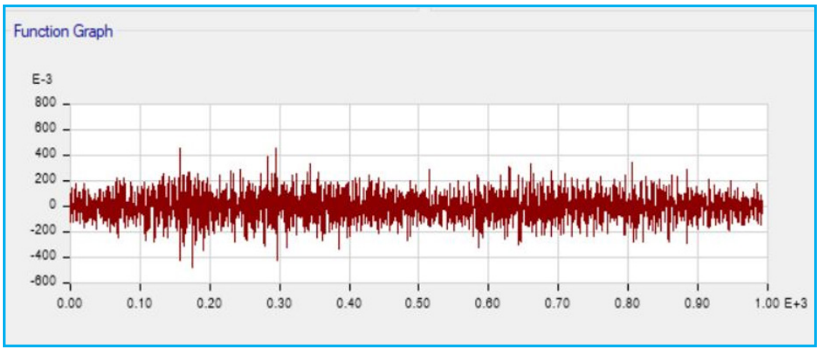

Figure 3. Seismograph graph of the Simeulue Earthquake

Results And Discussion

The research results are presented in the form of graphs, which can be used to discuss issues related to the study plan.

Axial Force

In the axial force diagram without bracing, the value at Story 1, Column D80, was 20,714.64 kN. For the axial force with bracing, the value at Story 1, Column D80, was 20,616.33 kN.

The values of base shear obtained represent the forces in the X- and Y-directions for each structural response under the time history method. These values are the output results from the ETABS (student version) analysis and are presented in Figures 4 and 5.

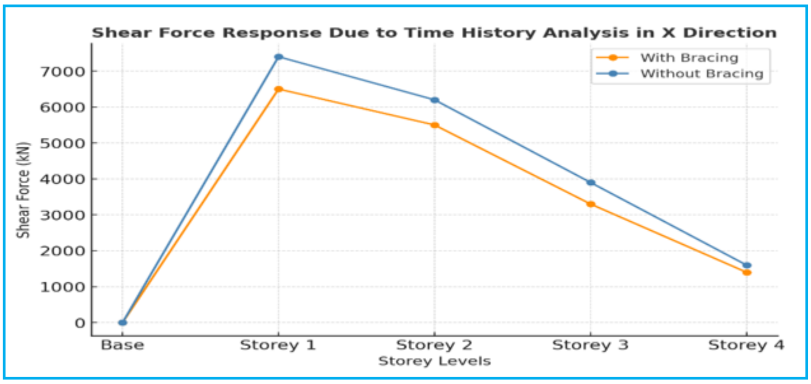

Figure 4. Base shear graph from time history analysis in the X-direction of the Simeulue Earthquake

From Figures 4 and 5, the base shear values for load combinations with and without bracing under the time history (TH) method can be observed for both the X- and Y-directions. In Figure 4, the base shear values obtained from ETABS (student version) for elevations under the X-direction time history analysis show that, with bracing, the maximum base shear at the first floor reached 6512.97 kN, whereas without bracing the base shear in the X-direction was 6468.21 kN. This indicates that the addition of bracing increases structural stiffness, allowing the lateral forces acting on the structure to be transferred more efficiently through the bracing elements. This improvement is consistent with the findings of Zhang

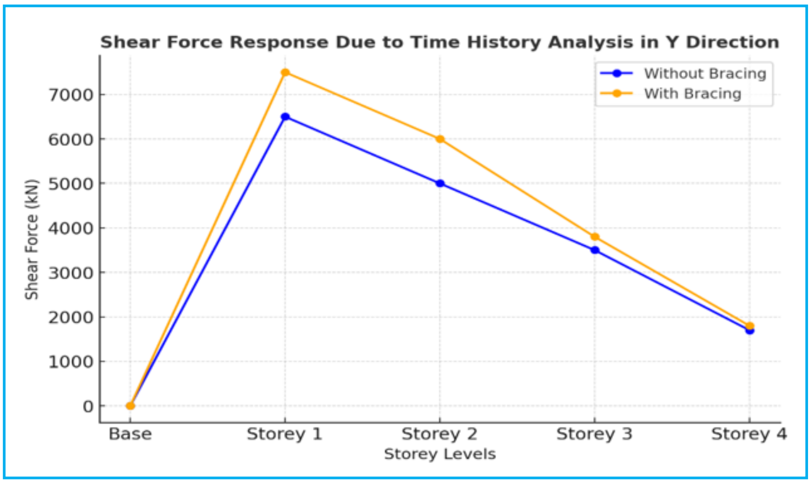

Figure 5. Base shear graph from time history analysis in the Y-direction of the Simeulue Earthquake

et al. (2023), who reported that concentric braced frame (CBF) systems enhance the distribution of lateral loads and significantly reduce inter-story drift [27].

Meanwhile, in Figure 5, the maximum base shear resulting from the Y-direction time history analysis for both models showed that, without bracing, the base shear at the first floor was 6497.5 kN. After applying bracing, the base shear in the Y-direction decreased to 6480.17 kN. This phenomenon suggests that the presence of bracing does not always increase base shear, but helps to distribute lateral loads more evenly across all structural elements [28].

Maximum Lateral Displacement at the Fourth Floor

The displacement at each story refers to the movement that occurs at the top joint of a column directly adjacent to the column of the story above it. The loads considered in the displacement calculation were based on the applied load combination formulas. The displacement values presented below (Figures 6 and 7) are shown in the form of displacement graphs according to the load combinations.

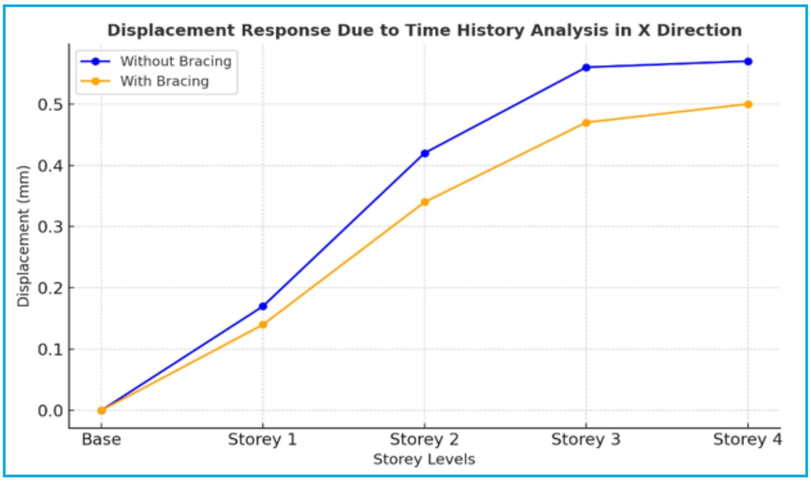

Figure 6. Displacement graph from time history analysis in the X-direction of the Simeulue Earthquake

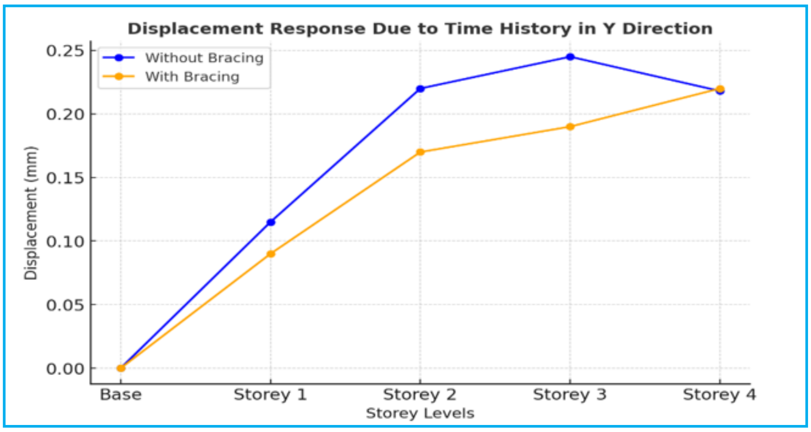

Figure 7. Displacement graph from time history analysis in the Y-direction of the Simeulue Earthquake

In Figures 6 and 7, the displacement values for each envelope of load combinations can be observed for both the X- and Y-directions. In Figure 6, the maximum displacement resulting from the X-direction time history analysis of the two models was obtained in the unbraced structure, with a maximum value of 0.564 mm occurring at the fourth floor. After the application of bracing, the displacement in the X-direction decreased to 0.505 mm. Meanwhile, in Figure 7, the maximum displacement from the Y-direction time history analysis of the two models was recorded in the unbraced structure, with a maximum value of 0.244 mm at the third floor. With the use of bracing, the Y-direction displacement decreased to 0.191 mm. These findings demonstrate that the bracing system functions to increase lateral stiffness, thereby restraining excessive deformation in the structure [28].

Mechanically, this reduction in displacement occurs because the bracing acts as an additional element that resists lateral forces, so that the load is not only transferred to the columns and beams but is also distributed through the bracing members. This is consistent with previous studies [29]. Other studies further confirm that the addition of bracing modifies the fundamental period of the structure, resulting in a more controlled dynamic response to earthquake input [30].

Results of Inter-Story Drift Analysis (Story Drift)

Story drift values were obtained from the ETABS (student version) output tables and subsequently calculated in accordance with the prescribed procedure. Based on SNI 1726-2019, the inter-story drift limit must be less than 0.02 or 2% of the story height below the floor level being evaluated. The maximum inter-story drift values in both the X- and Y-directions obtained from the modeling can be seen in Figures 8 and 9.

From Figures 8 and 9, the story drift values with and without bracing in the X- and Y-directions can be observed. In Figure 8, the maximum story drift from the X-direction time history analysis of both models was obtained in the unbraced structure, with a value of 0.000061 m at the second floor. With the application of bracing, the story drift in the X-direction decreased to 0.000051 m. In Figure 9,

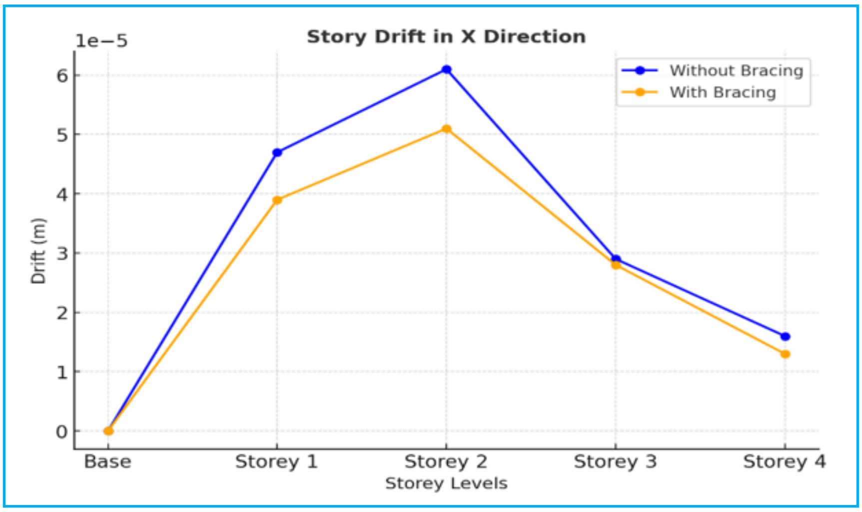

Figure 8. Story drift graph from time history analysis in the X-direction of the Simeulue Earthquake

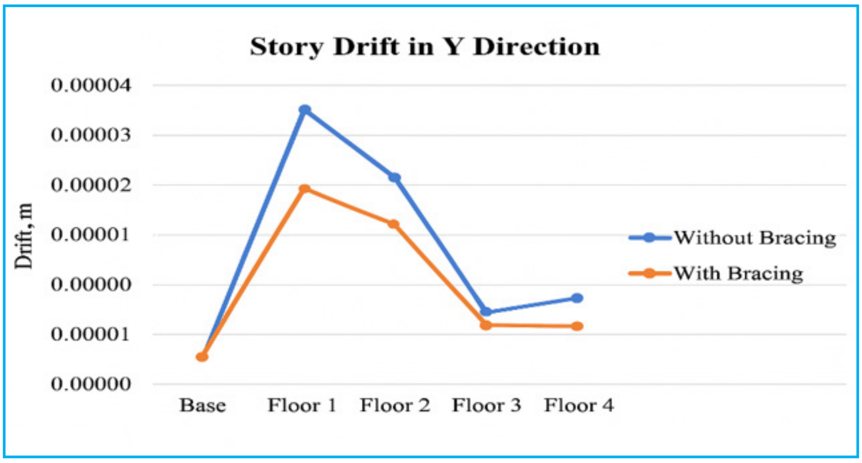

Figure 9. Story drift graph from time history analysis in the Y-direction of the Simeulue Earthquake

the maximum story drift from the Y-direction time history analysis was obtained in the unbraced structure at the first floor, with a value of 0.000033 m. With bracing, the story drift in the Y-direction decreased to 0.000024 m. Both of these values are within the allowable drift limit, which must be less than 0.02 or 2% of the story height; in this case, 2% × 4 m = 0.08 m.

The findings in Figures 8 and 9 indicate that the use of a bracing system makes a significant contribution to enhancing lateral stiffness while reducing relative inter-story deformation, thereby improving the building’s safety against potential structural and non-structural damage. The reduction in story drift resulting from the application of bracing is consistent with previous studies showing that the X-bracing configuration provides the most effective performance in limiting inter-story drift compared to chevron or single diagonal configurations [31]. Other studies have further emphasized that bracing not only reduces drift but also helps mitigate torsional irregularities in multi-story buildings, which are often one of the main causes of structural failure during earthquakes [32].

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Structural Safety Verification

From the structural modeling analysis of the Cempaka Lima General Hospital building, both with and without the implementation of X-bracing, it was observed that each configuration satisfies the minimum safety requirements stipulated in the applicable design standards. However, a significant difference in structural response was identified between the two models. When X-bracing is incorporated into the structural system, the overall lateral displacement and inter-story drift are substantially reduced, indicating an improvement in lateral stiffness and seismic resistance. In contrast, the unbraced model exhibits higher displacement values, reflecting lower stiffness and greater susceptibility to lateral deformation during seismic excitation.

Furthermore, the verification of structural safety, as illustrated in Figures 10 and 11, confirms that the addition of X-bracing not only enhances the building's stability but also optimizes its performance under dynamic loading conditions. These findings suggest that the integration of X-bracing contributes to improved energy dissipation capacity and ensures that the structure remains within the permissible deformation limits prescribed by ACI and SNI codes, thereby increasing the reliability and resilience of the hospital under earthquake loading scenarios.

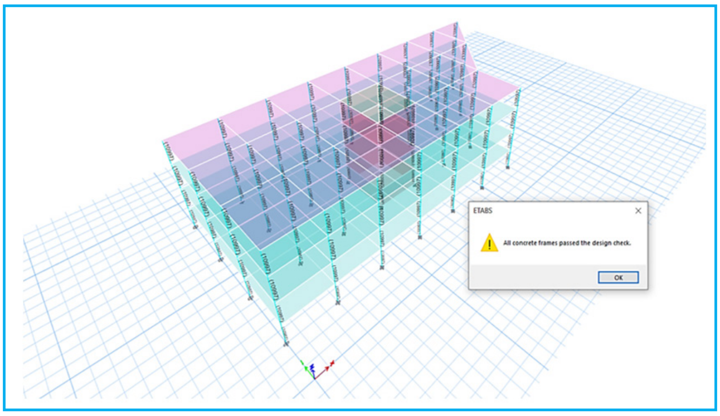

Figure 10. Structural safety verification of the Cempaka Lima General Hospital without bracing

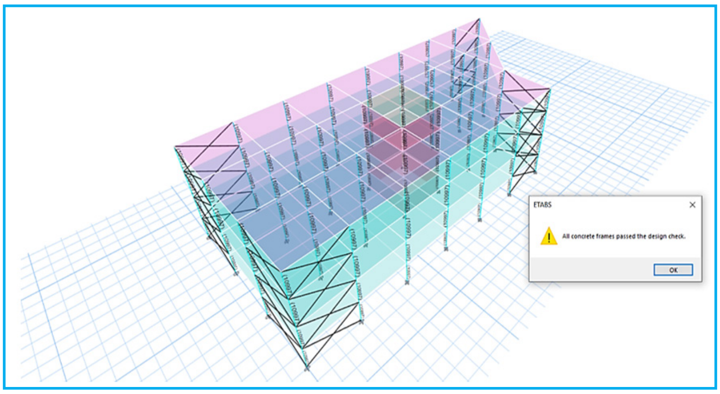

Figure 11. Structural safety verification of the Cempaka Lima General Hospital with bracing

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Conclusions

Based on the results of the time history analysis using the Simeulue earthquake record on the Cempaka Lima General Hospital building, several key findings were obtained as follows:

- The application of X-bracing made a significant contribution to improving structural stability, as evidenced by the reduction in axial force from 20,714.64 kN to 20,616.33 kN.
- The largest base shear occurred on the first floor, in both the X- and Y-directions, with a significant reduction when the bracing system was applied.
- The maximum displacement without bracing was recorded as 0.564 mm at the fourth floor (X-direction) and 0.244 mm at the third floor (Y-direction), both of which were reduced after the installation of bracing.
- The story drift values at all floors remained below the permissible limit of 2% as specified in SNI 1726-2019, with maximum values of 0.000061 m (X-direction) and 0.000033 m (Y-direction) in the unbraced structure.

The novelty and innovation of this research lie in the application of time history analysis using local Simeulue earthquake data for essential hospital buildings, which has rarely been examined in previous studies. The integration of the X-bracing system proved effective in reducing lateral deformations and enhancing stiffness without exceeding the drift limits specified by standards. The practical benefit of this research is that it provides a technical reference for the planning and retrofitting of essential buildings, particularly hospitals in earthquake-prone zones, thereby improving occupant safety, minimizing structural damage, and ensuring the continuity of vital hospital functions after a disaster.

Acknowledgement

The authors would like to express their gratitude to Iskandar Muda University and the Aceh Earthquake Disaster Mitigation Study Center for providing facilities and data support for this research. Appreciation is also extended to the Technical Team of the Cempaka Lima General Hospital in Banda Aceh for supplying technical information related to the building's structure. Furthermore, sincere thanks are conveyed to fellow researchers and structural laboratory students who contributed to the data analysis process and validation of the research findings.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this article.

Author Contributions

Nur Lathifah: methodology, calculation, writing- original draft preparation. **Imransyah Idroes:** data curation, visualization. **Munirul Hady:** conceptualization, visualization, investigation. **Bunyamin Bunyamin:** visualization, supervision, writing – review & editing. **Heru Pramanda:** formal analysis, investigation.

Data Availability Statement

The data used to support the findings of this study are included within the article.

References

[1] N. A. Pambudi, "Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy," Renew. Sustain. Energy Rev., vol. 81, pp. 2893–2901, 2018.

[2] M. Masum and M. A. Akbar, "The Pacific ring of fire is working as a home country of geothermal resources in the world," in IOP Conference Series: Earth and Environmental Science, 2019, vol. 249, no. 1, p. 12020.

[3] J.-C. Gaillard et al., "Ethnic groups' response to the 26 December 2004 earthquake and tsunami in Aceh, Indonesia," Nat. Hazards, vol. 47, no. 1, pp. 17–38, 2008.

[4] Bunyamin, "Comparison of deflection of hollow block concrete blocks with normal reinforced concrete beam," in AIP Conference Proceedings, 2019, vol. 2059, no. 1, p. 20039.

[5] B. Bunyamin, M. Silviana, and L. Lindawati, "Influence of precast concrete joints on the ductility of beam elements," in Journal of Physics: Conference Series, 2021, vol. 1882, no. 1, p. 12032.

[6] M. Hasan, T. Saidi, M. Afifuddin, and B. Setiawan, "The assessment and strengthening proposal of building structure after the Pidie Jaya earthquake in December 2016," J. King Saud Univ. Sci., vol. 35, no. 1, pp. 12–23, 2023.

[7] A. 7-22 L. C. Subcommittee, "Structural Reliability Guidance in Asce 7-22: Principles and Methods," 2025.

[8] Y. Hooda and P. K. Goyal, "Seismic assessment of a hospital building: a case study," in IOP Conference Series: Earth and Environmental Science, 2021, vol. 796, no. 1, p. 12006.

[9] C. Zhai, P. Yu, and W. Wen, "A physical-organizational method for the functionality assessment of a hospital subjected to earthquakes," J. Earthq. Eng., vol. 26, no. 14, pp. 7119–7139, 2022.

[10] O. Z. Ibrahim, "Resilience of hospital structures under seismic loads: A case study informed by the 2023 Mara{\c{s}} earthquake," in Structures, 2025, vol. 74, p. 108642.

[11] P. Yu, C. Zhai, J. Liu, S. Pei, Z. Song, and L. Xie, "Resilience assessment methods for hospitals subjected to earthquakes: State of the art," Earthq. Eng. Resil., vol. 1, no. 1, pp. 40–59, 2022.

[12] N. Rahman, H. Heridadi, L. Lasmono, M. Imansyah, and F. Bahar, "Lesson learn earthquake disaster in Pidie Jaya Aceh in 2016 to realize a disaster-resistant community," in E3S Web of Conferences, 2021, vol. 331, p. 4004.

[13] Y. Zhou, H. Shao, Y. Cao, and E. M. Lui, "Application of buckling-restrained braces to earthquake-resistant design of buildings: A review," Eng. Struct., vol. 246, p. 112991, 2021.

[14] D.-P. N. Kontoni and A. A. Farghaly, "Enhancing the earthquake resistance of RC and steel high-rise buildings by bracings, shear walls and TMDs considering SSI," Asian J. Civ. Eng., vol. 24, no. 7, pp. 2595–2608, 2023.

[15] Y. Razzouk, M. Ahatri, K. Baba, and A. Majid, "Optimizing seismic bracing systems for reinforced concrete buildings based on height and seismic zone," Civ. Eng. Archit., vol. 11, no. 6, pp. 3430–3450, 2023.

[16] A. Gutierrez-Lopez, O. E. Alvarado-Valle, D. Tolentino, and J. R. Gaxiola-Camacho, "Structural reliability of steel buildings with X-bracing systems considering the performance-based seismic design philosophy," Appl. Res., vol. 3, no. 3, p. e202300040, 2024.

[17] I. Hidayat, M. Suangga, R. Suwondo, and M. Sami, "Seismic performance analysis of retrofitting building structure with type X bracing," in IOP Conference Series: Earth and Environmental Science, 2021, vol. 794, no. 1, p. 12011.

[18] A. Yassin and K. Sadeghi, "Structure behaviour under seismic loads using x-bracing, inverted v-bracing systems and without bracing," Int. J. Innov. Sci. Res. Technol. Connect., vol. 8, no. 1, 2023.

[19] A. Alnajjar, "Seismic Bracing for Earthquake-Resistant Design: Architectural Functioning and Enhancing Building Safety and Aesthetics Suggestions, Case of Istanbul," Digit. Int. J. Archit. Art Herit., vol. 2, no. 2, pp. 24–42, 2023.

[20] A. Sal Moslehian, T. Kocaturk, F. Andrews, and R. Tucker, "The nature of innovation in hospital building design: A mixed grounded theory study," Constr. Innov., vol. 23, no. 4, pp. 792–814, 2023.

[21] P. Zakian and A. Kaveh, "Seismic design optimization of engineering structures: a comprehensive review," Acta Mech., vol. 234, no. 4, pp. 1305–1330, 2023.

[22] M. Faiz and R. Kumar, "Comparative effectiveness of equivalent static analysis \& response spectrum analysis in extreme seismic zones," in IOP Conference Series: Earth and Environmental Science, 2023, vol. 1110, no. 1, p. 12013.

[23] H. J. Wattimanela, N. T. Puspito, and H. Batkunde, "Simeulue Earthquake Activity Analysis Using the MLE Method.," Indones. J. Geogr., vol. 57, no. 1, 2025.

[24] A. Singh and S. Palissery, "Preferred Seismic Performance Attainment in Important Buildings," Eng. Fail. Anal., vol. 158, p. 107952, 2024.

[25] R. Pang, B. Xu, Y. Zhou, and L. Song, "Seismic time-history response and system reliability analysis of slopes considering uncertainty of multi-parameters and earthquake excitations," Comput. Geotech., vol. 136, p. 104245, 2021.

[26] T. Anggono et al., "Shallow subsurface velocity model at Simeulue Island, Indonesia inferred from ambient vibration records," in IOP Conference Series: Earth and Environmental Science, 2021, vol. 789, no. 1, p. 12061.

[27] C. Zhang and C. Loss, "Evaluation of seismic fragilities of special concentrically braced frame hybrid buildings equipped with prefabricated cross-laminated timber-steel composite floor diaphragms," Bull. Earthq. Eng., vol. 21, no. 14, pp. 6423–6452, 2023.

https://doi.org/10.70028/dcea.v2i2.64

[28] A. Z. Abdulhameed, M. A. Ahmed, and A. A. Karim, “The Impact of Bracing System Distribution and Location on Seismic Performance Enhancement of Multi-Story Steel Buildings.,” Math. Model. Eng. Probl., vol. 10, no. 5, 2023.

[29] M. R. Maheri and A. Fathi, “The Effects of X-Brace Configuration on the Seismic Performance of Retrofitted RC Frames,” Iran. J. Sci. Technol. Trans. Civ. Eng., vol. 46, no. 6, pp. 3995–4018, 2022.

[30] N. Z. Ahmed, M. Osama, and W. Attia, “Prediction of the fundamental period of vibration of braced frame systems in irregular steel buildings,” Cogent Eng., vol. 9, no. 1, p. 2122183, 2022.

[31] D. S. Sophianopoulos and M. I. Ntina, “Investigation of the Seismic Performance of a Multi-Story, Multi-Bay Special Truss Moment Steel Frame with X-Diagonal Shape Memory Alloy Bars,” Appl. Sci., vol. 14, no. 22, p. 10283, 2024.

[32] O. Akyürek, “Analysis of different cross-frame placements to enhance torsional irregular buildings against structural failure under earthquake bidirectional loadings: A case study,” Bitlis Eren Üniversitesi Fen Bilim. Derg., vol. 10, no. 2, pp. 480–491, 2021.