International Journal of Science and Healthcare Research
Vol. 9; Issue: 3; July-September 2024
Website: ijshr.com
ISSN: 2455-7587

Research Article

Parametric Study of Structural Seismic Response: Correlation Between Lateral Load, Displacement, and Stiffness

Samsul Abdul Rahman Sidik Hasibuan

[1]Department of Civil Engineering, Universitas Medan Area, Medan, Indonesia.

Corresponding Author: Samsul Abdul Rahman Sidik Hasibuan

DOI: https://doi.org/10.52403/ijshr.20240304

ABSTRACT

Indonesia, located near the convergence of major tectonic plates, often experiences significant earthquakes that impact buildings. Many houses damaged by earthquakes are simple structures with red brick masonry. This study analyzes the seismic performance of masonry houses using ETABS software, assuming the houses are in seismic zone 4 and built on soft soil. The analysis focuses on the correlation between lateral loads, displacement, and structural stiffness. The results indicate that the maximum lateral load occurs in the X direction, while the maximum displacement occurs in the Y direction, indicating higher flexibility in the Y direction. Higher structural stiffness reduces displacement but also increases inertia forces. The nonlinear correlation between lateral loads and displacement, as well as the decrease in effective structural stiffness with increasing lateral loads, underscores the importance of balancing stiffness and flexibility in structural design. This study provides valuable insights for earthquake-resistant building design, particularly for masonry houses in earthquake-prone areas of Indonesia. The analysis emphasizes the importance of reinforcing critical areas and ensuring a more uniform distribution of lateral loads to enhance structural resilience to earthquakes.

Keywords: ETABS, House, Life Safety, Performance, Seismic

INTRODUCTION

Residences are one of the primary human needs inseparable from daily life. Therefore, the capability and resilience of houses need to be thoroughly examined to ensure the smooth functioning and comfort of society. Indonesia, as a country located in the Ring of Fire region, possesses a unique yet high-risk geographical position. Its location at the convergence of several major tectonic plates, including the Eurasian, Indo-Australian, and Pacific plates, results in high seismic activity and frequent earthquakes [1]. This condition significantly impacts infrastructure and buildings across Indonesia. Parametric studies of seismic response in structures, focusing on the correlation between lateral loads, displacement, and stiffness, represent a crucial step towards enhancing seismic resilience in Indonesian buildings. Analyzing the correlation between these parameters can provide valuable insights for designing earthquake-resistant structures [2]. A better understanding of the relationship between lateral loads, displacement, and stiffness can aid in optimizing structural designs and improving overall building safety. Based on field study reports, the collapse of buildings due to major earthquakes in Indonesia predominantly involves structures that were not adequately designed [3]. These buildings often rely on simple structures like red brick masonry walls or confined brick masonry without proper structural calculations. This phenomenon is widespread across earthquake-affected areas in Indonesia, resulting in building collapses and significant loss of life [4]. Addressing this issue seriously is crucial due to its profound impact on public safety. The majority of earthquake-damaged buildings are houses, whereas tall buildings generally withstand earthquakes better due to their carefully considered structural capabilities [5, 6]. This difference underscores the importance of accurate analysis and design in enhancing structural seismic resilience, especially for simple houses often built without adequate structural calculations. SNI 15-2094:2000 [7] provides definitions and specifications for red bricks, a widely used building material in Indonesia. Red bricks are defined as rectangular prism-shaped building materials, solid or with holes, with a maximum hole volume of 15%. They are used for constructing building walls and are made from clay, with or without additives, fired at specific temperatures. Given their extensive use in Indonesia, understanding their seismic behavior is crucial within the context of this parametric study. Although red bricks are generally used as non-structural elements for partition walls in buildings or high-rise constructions, practical usage often sees them employed as structural components in simple house constructions. In these cases, brick walls function as load-bearing elements supporting the structures above them. While common, this practice can pose significant risks if not accompanied by proper structural calculations and designs, particularly concerning earthquake resilience [8, 9]. Given the critical role of red bricks in Indonesian construction, improving their product quality is essential. Enhancement efforts can focus on two main approaches: firstly, improving the inherent material quality of the bricks themselves, and secondly, exploring the addition of other materials to enhance their structural performance [10, 11]. In the context of parametric studies, a thorough understanding of the characteristics of materials used in construction is crucial. Brick, as a primary construction material in Indonesia, comes in various standardized sizes outlined in SNI 15-2094:2000. These size variations (as depicted in Table 1) can influence the structural behavior of buildings, including their response to seismic loads. Therefore, careful analysis of how variations in brick sizes affect the seismic response of structures should be part of this parametric study. Mechanical characteristics of bricks (as shown in Table 2), such as elasticity modulus, shear modulus, and bulk modulus, play a crucial role in determining the structural seismic response. These characteristics influence how structures respond to lateral loads, the extent of displacement, and the overall stiffness behavior during earthquakes. For linear analysis conditions, the stiffness of brick wall structures is expected to be directly proportional to the geometric shape of the wall in its intact, crack-free state. However, real-world scenarios during earthquakes often exhibit nonlinear structural behavior. Therefore, this parametric study also needs to consider aspects of nonlinearity in its seismic response analysis. In some earthquake scenarios, brick walls contribute to lateral load-bearing. Cracks occurring in brick walls indicate load transfer from the portal to the brick walls. This phenomenon underscores the importance of understanding the interaction between the main structural frame and the brick infill walls in seismic response analysis [12]. Furthermore, some buildings experience soft-story collapse mechanisms. This collapse occurs due to different configurations of infill brick walls between the ground floor and upper floors. Failures observed in simple brick masonry houses can be seen in Figure 1 [13]. This phenomenon highlights the need to consider overall structural configurations in seismic response analysis, not just focusing on the strength of individual structural components. This parametric study aims to analyze the correlation between lateral loads, displacement, and stiffness in the context of structural seismic response. Lateral loads generated by earthquakes can vary in terms of magnitude, frequency, and duration. Understanding how these variations affect structural displacement and how structural stiffness modulates this response is crucial for developing effective seismic risk mitigation strategies. Displacement, as a key indicator of structural response to seismic loads, requires comprehensive analysis [14]. This includes not only maximum displacement but also displacement patterns throughout the building height, interstory drift, and residual displacement after earthquakes. A comprehensive analysis of these displacement parameters can provide valuable insights into structural performance during and after seismic events [15]. Structural stiffness, determined by geometric and material properties, plays a crucial role in seismic response [16]. Structures that are too rigid may experience greater inertia forces during earthquakes, while overly flexible structures may undergo excessive displacement. Therefore, finding the optimal balance between stiffness and flexibility is a primary goal of this parametric study [17]. In the context of buildings with brick walls, in-plane and out-of-plane wall behavior under lateral loads also requires thorough analysis. Brick walls, especially unreinforced ones, tend to be vulnerable to out-of-plane failures during earthquakes. Therefore, this parametric study will also include an analysis of how variations in brick wall designs and configurations affect the overall seismic response of structures. To achieve the research objectives, simple brick masonry houses will be modeled and analyzed using ETABS software [18, 19, 20]. The models will assume they are located in seismic Zone 4 with a peak ground acceleration of 0.20 (g) and constructed on soft soil. These parameters are selected based on typical conditions found in various earthquake-prone regions of Indonesia. The findings of this parametric study are expected to significantly contribute to our understanding of structural seismic response, particularly those utilizing brick walls as a primary component. These findings can be used to develop better design guidelines, improve construction standards, and ultimately enhance the safety and resilience of buildings against earthquakes in Indonesia and other active seismic regions. In conclusion, parametric studies of structural seismic response, focusing on the correlation between lateral loads, displacement, and stiffness, represent a crucial step towards enhancing seismic resilience in Indonesian buildings. By comprehending the complex interactions between these parameters, we can develop more effective and innovative design strategies to address future seismic challenges. The results of this research are expected to make a significant contribution to safer and more sustainable construction practices in Indonesia and provide a foundation for further research in earthquake engineering.

Table 1. Variation in Brick Sizes

Module	Thickness (mm)	Width (mm)	Length (mm)
M-5a	65±2	90±3	190±4
M-5b	65±2	110±4	190±4
M-6a	52±3	110±4	230±4
M-6b	55±3	110±6	230±5
M-6c	70±3	110±6	230±5
M-6d	80±3	110±6	230±5

Table 2. Solid Materials

Materials	Elastic Modulus, E (N/m^2)	Shear Modulus, G (N/m^2)	Bulk Modulus, B (N/m^2)
Iron, gypsum	100×10^9	40×10^9	90×10^9
Steel	200×10^9	80×10^9	140×10^9
Brass	100×10^9	35×10^9	80×10^9
Aluminum	70×10^9	25×10^9	70×10^9
Concrete	20×10^9		
Brick	14×10^9		
Marble	50×10^9		70×10^9
Granite	45×10^9		45×10^9
Wood (pine)			
(parallel to grain)	10×10^9		
(perpendicular to grain)	1×10^9		
Nylon	5×10^9		
Bone (limb)	15×10^9		

Figure 1. Failure in masonry brick houses

METHODS

Parametric study on seismic response of masonry structure focusing on correlation between lateral load, displacement, and stiffness utilizes finite element analysis method with equivalent static seismic load approach. The analysis is conducted using ETABS software, enabling detailed modeling and comprehensive structural analysis. The analysis procedure comprises several main stages:

Structural Modeling

The masonry brick house structure is modeled in ETABS considering geometry, material properties, and appropriate boundary conditions. The brick size variations used in the modeling are M-5a, with dimensions defined based on SNI 15-2094:2000, as shown in Table 1. The modeling results of the brick house in ETABS software are presented in Figure 2.

Definition of Seismic Loads

Seismic loads are defined using the equivalent static method available in ETABS. Key parameters included are:

1. Seismic zone factor: The structure is assumed to be in Seismic Zone 4.
2. Soil type: Assumed the building is erected on soft soil.
3. Response reduction factor: Determined based on the structure type and expected ductility level.

Once these parameters are defined and the analysis is run, the lateral loads are automatically defined by the software.

Parametric Analysis

Parametric analysis is performed by varying several key parameters to evaluate their influence on the seismic response of the structure. Parameters varied include:

1. Structural stiffness: Modified through variations in wall thickness and structural configuration.
2. Lateral loads: Varied through changes in seismic input parameters.

3. Opening configurations: Variations in size and position of openings in walls.

Evaluation of Structural Response

Structural response is evaluated focusing on three main parameters:

1. Lateral loads: Distribution and magnitude of shear forces on structural elements.
2. Displacement: Maximum displacement, inter-story drift, and deformation patterns of the structure.
3. Stiffness: Effective stiffness of the structure and changes in stiffness due to cyclic loading.

Correlation Analysis

Results from parameter variations are analyzed to identify correlations between lateral load, displacement, and stiffness. This analysis includes:

1. Statistical regression to identify quantitative relationships among parameters.
2. Sensitivity analysis to determine the most influential parameters on seismic response.
3. Evaluation of nonlinearities in the relationships between parameters.

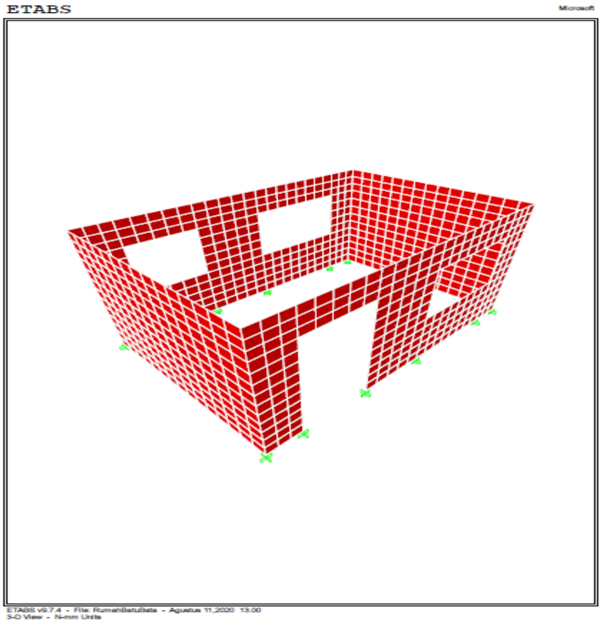

Figure 2. Modeling of masonry brick house

RESULT

Parametric study on seismic response of masonry structure focusing on correlation between lateral load, displacement, and stiffness yielded several key findings. Analysis results using ETABS software provided a comprehensive overview of the behavior of masonry brick houses under seismic loads.

Deformation and Stress Due to Seismic Loads

Results from running ETABS software for deformation and stress due to seismic loads in X and Y directions are depicted in Figure 3. This analysis provides crucial information on stress distribution and deformation patterns of the structure under lateral loads.

Structural Failure Analysis

Based on stress and deformation patterns in masonry brick houses as shown in Figure 3, critical areas prone to failure can be identified. These areas are marked in red on the model, indicating stress concentrations exceeding material capacity or significant deformation.

Correlation between Lateral Load, Displacement, and Stiffness: Parametric analysis revealed several important correlations between lateral load, displacement, and structural stiffness:

1. Relationship between Lateral Load and Displacement
   Analysis results indicated a nonlinear relationship between increasing lateral load and structural displacement. At low lateral load levels, displacement tends to increase proportionally. As lateral load increases, the rate of displacement increase becomes more significant, indicating nonlinear structural response.
2. Influence of Stiffness on Displacement
   Structures with higher stiffness generally exhibit smaller displacements for the same lateral load. However, increased stiffness can also lead to higher inertia forces during earthquakes.
3. Effect of Lateral Load on Stiffness
   Effective structural stiffness tends to decrease with increasing lateral load, especially beyond the elastic limit of the material. This stiffness reduction correlates with increased displacement rate.

Failure Pattern Analysis

Based on the results displayed in Figure 3, several primary failure patterns can be identified:

1. Stress Concentrations
   Areas marked in red indicate high stress concentrations, which could potentially initiate structural failure.
2. Deformation Patterns
   Structural deformations appear more significant in certain directions, indicating variations in stiffness in different directions.
3. Failure in Structural Elements
   Some structural elements, especially those marked in red, show higher potential for failure compared to other areas.

Implications for Structural Design

The findings of this analysis have significant implications for the structural design of masonry brick houses in earthquake-prone areas:

1. Optimization of Stiffness
   Designs need to balance stiffness to reduce displacement without creating overly rigid structures susceptible to large inertia forces.
2. Distribution of Lateral Loads
   There is a need for strategies to evenly distribute lateral loads throughout the structure to avoid stress concentrations.
3. Enhancement of Ductility
   Improving structural ductility can assist in distributing seismic energy and reducing brittle failure risks.
4. Reinforcement of Critical Areas
   Areas identified with high stress (marked in red) require specific reinforcement.

This parametric study provides valuable insights into the behavior of masonry brick houses under seismic loads. The identified correlations between lateral load, displacement, and stiffness can serve as a basis for developing more earthquake-resistant designs, especially for simple houses in earthquake-prone regions in Indonesia. These results also underscore the importance of detailed seismic analysis in the design process, even for seemingly straightforward structures like masonry brick houses.

DISCUSSION

Lateral Loads

X-direction seismic loading resulted in higher maximum lateral loads (2087.82 kN) compared to the Y-direction (1453.24 kN). This indicates that the structure is more vulnerable to seismic forces in the X-direction.

Displacement

Despite higher lateral loads in the X-direction, maximum displacement occurs in the Y-direction (0.14 m) compared to the X-direction (0.04 m). This suggests that the structure exhibits higher flexibility in the Y-direction.

Drift

Consistent with displacement, maximum drift is also higher in the Y-direction (0.075 m) compared to the X-direction (0.025 m).

This reinforces the indication of greater flexibility in the Y-direction.

Shear Force

Maximum shear force values are higher in the X-direction (377.11 kN) compared to the Y-direction (270.53 kN), consistent with the higher lateral load in the X-direction.

Stiffness

The structure demonstrates significantly higher stiffness in the X-direction (481,699.75 kN/m) compared to the Y-direction (166,492.27 kN/m). This explains why displacement and drift are smaller in the X-direction despite receiving higher lateral loads.

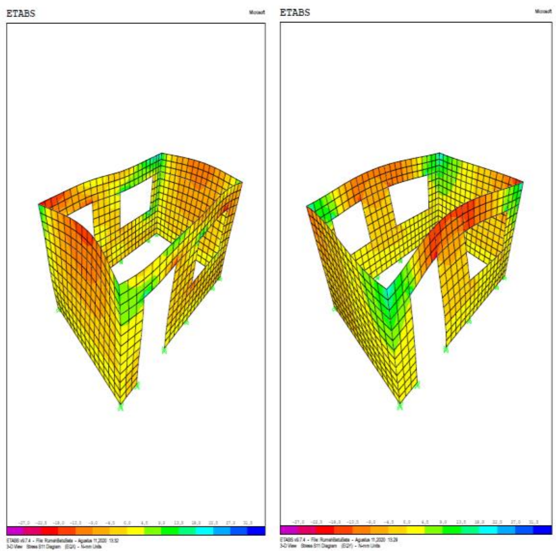

Figure 3. Stress and deformation due to X and Y-directional earthquakes

CONCLUSION

Based on the results and discussions from the parametric study on seismic response of masonry structure focusing on the correlation between lateral load, displacement, and stiffness in brick masonry houses, several important conclusions can be drawn. There exists a nonlinear relationship between increasing lateral load and structural displacement. At low levels of lateral load, displacement tends to increase proportionally. However, as lateral load increases, the rate of displacement increase becomes more significant, indicating a nonlinear response of the brick masonry house structure.

Structures with higher stiffness generally exhibit smaller displacements for the same lateral load. However, increased stiffness can also lead to increased inertia forces during earthquakes, which need to be considered in structural design. Effective structural stiffness tends to decrease with increasing lateral load, especially after surpassing the elastic limit of the material. This decrease in stiffness correlates with an increase in displacement rate, emphasizing the importance of maintaining a balance between stiffness and flexibility in structural design.

The maximum lateral load occurs in the X direction at 2087.82 kN, compared to 1453.24 kN in the Y direction. This indicates that the structure is more vulnerable to seismic forces in the X direction, attributed to the higher stiffness value in the X direction of 481,699.75 kN/m compared to 166,492.27 kN/m in the Y direction. The maximum displacement occurs in the Y direction at 0.14 m, which is larger than the 0.04 m in the X direction, indicating higher flexibility of the structure in the Y direction. Similarly, the maximum drift is also larger in the Y direction at 0.075 m compared to 0.025 m in the X direction, reinforcing the indication of higher flexibility in the Y direction.

The maximum shear force value is higher in the X direction at 377.11 kN compared to 270.53 kN in the Y direction, consistent with the higher lateral load in the X direction. Structural design needs to balance stiffness to reduce displacement without creating overly rigid structures vulnerable to large inertia forces. Strategies such as distributing lateral loads more evenly throughout the structure and enhancing structural ductility can help reduce the risk of brittle failure. Specific reinforcement of areas identified with high stress is also necessary to improve structural resilience against seismic loads.

Overall, this parametric study provides valuable insights into the behavior of brick masonry houses under seismic loads. The correlations identified between lateral load, displacement, and stiffness can serve as a basis for developing more earthquake-resistant designs, especially for simple houses in earthquake-prone areas in Indonesia. These results underscore the importance of detailed seismic analysis in the design process, even for seemingly simple structures like brick masonry houses.

REFERENCES

1. Artemieva, I. M., Hans Thybo, and Alexey Shulgin. "Geophysical constraints on geodynamic processes at convergent margins: A global perspective." *Gondwana Research* 33 (2016): 4-23.
2. Yenidogan, Cem. "Earthquake-resilient design of seismically isolated buildings: A review of technology." *Vibration* 4.3 (2021): 602-647.
3. Pribadi, Krishna S., et al. "Post-disaster housing reconstruction in Indonesia: Review and lessons from Aceh, Yogyakarta, West Java and West Sumatera earthquakes." *Disaster recovery: Used or misused development opportunity* (2014): 197-223.
4. Mavrouli, Maria, et al. "The impact of earthquakes on public health: A narrative review of infectious diseases in the post-disaster period aiming to disaster risk reduction." *Microorganisms* 11.2 (2023): 419.
5. Jain, Sudhir K. "Earthquake safety in India: achievements, challenges and opportunities." *Bulletin of Earthquake Engineering* 14 (2016): 1337-1436.
6. Zengin, Başak. "A Review of the Earthquake Caused Damage on Reinforced Concrete and Masonry Buildings in Turkey." *Technological Advancements in Construction: Selected Papers* (2021): 447-455.
7. Standar Nasional Indonesia. 2000. SNI 15-2094-2000 Bata Merah Pejal Untuk Pasangan Dinding. Jakarta
8. Menna, Costantino, et al. "Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings." *Sustainable Cities and Society* 77 (2022): 103556.
9. Capacci, Luca, Fabio Biondini, and Dan M. Frangopol. "Resilience of aging structures and infrastructure systems with emphasis on seismic resilience of bridges and road networks." *Resilient Cities and Structures* 1.2 (2022): 23-41.
10. Zhuang, Zicheng, et al. "A comprehensive review of sustainable materials and toolpath optimization in 3D concrete printing." *npj Materials Sustainability* 2.1 (2024): 12.
11. Afgan, Sher, and Chen Bing. "Scientometric review of international research trends on thermal energy storage cement based composites via integration of phase change materials from 1993 to 2020." *Construction and Building Materials* 278 (2021): 122344.
12. Pokharel, Sijan, et al. "Seismic Performance of Masonry-Infilled RC Frames and Its Implications in Design Approach: A Review." *Practice Periodical on Structural Design and Construction* 29.2 (2024): 03124001.
13. Bhattacharya, Subhamoy, Sanket Nayak, and Sekhar Chandra Dutta. "A critical review of retrofitting methods for unreinforced masonry structures." *International Journal of Disaster Risk Reduction* 7 (2014): 51-67.
14. Cunha, A., et al. "A critical review of current approaches on the determination of seismic force demands on nonstructural components." (2014).
15. Zameeruddin, Mohd, and Keshav K. Sangle. "Review on Recent developments in the performance-based seismic design of reinforced concrete structures." *Structures*. Vol. 6. Elsevier, 2016.
16. Bapir, Baban, et al. "Soil-structure interaction: A state-of-the-art review of modeling techniques and studies on seismic response of building structures." *Frontiers in Built Environment* 9 (2023): 1120351.
17. Schenk, Mark, and Simon D. Guest. "On zero stiffness." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 228.10 (2014): 1701-1714.
18. Verma, Rajnandan, and Raghvendra Singh. "Comparative Analysis of Pre-Engineered Steel Building and Conventional Steel Building Using Etab-A

Review." *International Research Journal of Modernization in Engineering Technology and Science* 2.02 (2020).

19. Deshmukh, Shiv Kumar, and Nitesh Kushwaha. "Study On Residential Building of Constant Area and Different Shape Using ETABS: A Review." (2020).
20. Borah, Bonisha, Hemant B. Kaushik, and Vaibhav Singhal. "Analysis and design of confined masonry structures: review and future research directions." *Buildings* 13.5 (2023): 1282.

How to cite this article: Samsul Abdul Rahman Sidik Hasibuan. Parametric study of structural seismic response: correlation between lateral load, displacement, and stiffness. *International Journal of Science & Healthcare Research.* 2024; 9(3): 18-26. DOI: *https://doi.org/10.52403/ijshr.20240304*

******