

Assessment of seismic performance of low-rise reinforced concrete frame structures with masonry infill using fragility curves

Azia Septriyeni Afrizal¹, Jafril Tanjung^{1*}, and Jati Sunaryati¹

¹Civil Engineering Department, Faculty of Engineering, Universitas Andalas, Padang, 25163, Indonesia

Abstract. The seismic performance of reinforced concrete frame structures with masonry infill is a critical area of study due to the complex interactions between the infill and the structural frame during seismic events. This study evaluates the impact of masonry infills on the seismic performance of RC frames by utilizing fragility curves, which are developed through pushover analysis. The presence of masonry infill can significantly enhance the stiffness and strength of reinforced concrete frames; however, it can also lead to unexpected failure modes and reduced ductility. The fragility curves generated provide a probabilistic assessment of damage at different seismic intensity levels, offering valuable insights into the vulnerabilities and resilience of these structures. The findings from this study highlight the importance of considering masonry infill in the design and assessment of RC frames for seismic resistance, and they contribute to the development of more effective seismic design strategies and retrofitting measures for buildings in earthquake-prone regions.

1 Introduction

Indonesia is located near the Pacific Ring of Fire and the Trans Asiatic Earthquake Belt, increasing the likelihood of an earthquake. West Sumatra Province is uniquely positioned in the very center of the Pacific Ring of Fire, a geologically active area renowned for its frequent seismic activity. This province lies at the critical intersection of two major continental plates: the Eurasian Plate and the Indo-Australian Plate, which together contribute to its geological complexity. Additionally, the Semangko Fault runs through the region, further intensifying the seismic potential of the area. Nearby, the Mentawai Fault also intersects with these tectonic plates, establishing a dynamic environment characterized by significant tectonic movements. As a result, all three of these features, West Sumatra Province, the Semangko Fault, and the Mentawai Fault, constitute active seismic regions that are continually influenced by the intricate interactions of the earth's tectonic forces. [1, 2].

Several major earthquakes have occurred in the earthquake-prone regions of West Sumatra Province, among which the earthquake that struck Padang City on September 30, 2009, stands out as particularly significant. This powerful seismic event registered a magnitude of 7.6 on the Richter scale and resulted in extensive damage throughout the city, leading not only to the collapse of numerous reinforced concrete buildings but also to widespread devastation that affected countless residents and disrupted the local infrastructure. The impact of this earthquake served as a stark reminder of the region's

vulnerability to such natural disasters, highlighting the critical importance of implementing effective earthquake preparedness and response strategies to safeguard the community in the future [3].

In Indonesia, the most significant damage caused by earthquakes primarily affects simple structures, particularly because the majority of buildings are low-rise, comprising one or two-story houses. These houses are often constructed without the oversight of building and structural professionals, which leads to inadequate earthquake resistance and results in what are commonly referred to as non-engineered buildings. A prevalent practice in many countries, especially in low-rise reinforced concrete (RC) frames, is the use of masonry infill walls as partition walls. While infill is frequently overlooked in design considerations, extensive research has demonstrated that it can enhance both the lateral stiffness and strength of structural frames. Some studies further suggest that structures exhibiting greater lateral stiffness tend to experience reduced drift demands, thereby making them less susceptible to severe damage during seismic events. This insight underscores the importance of incorporating effective design practices that account for the contribution of infill in earthquake-prone areas, ultimately leading to improved resilience and safety for residents [4-6].

Brick masonry is frequently employed as an infill material in reinforced concrete (RC) structures, particularly in earthquake-prone regions such as West Sumatra, Indonesia. According to findings from a post-earthquake study conducted in the aftermath of a

* Corresponding author: jafriltanjung@eng.unand.ac.id

significant seismic event, as well as experimental outcomes from RC frames subjected to static lateral loading, the performance of these constructions is notably influenced by the presence of infilled brick masonry. While brick masonry infill can enhance the stiffness and lateral strength of the structure, providing critical support during seismic activity, it can simultaneously reduce the overall ductility of the frame. This reduction in ductility can pose significant risks to the residents, as it may lead to a greater likelihood of brittle failure during an earthquake, ultimately compromising the safety and integrity of the building. Therefore, it is crucial to carefully consider the implications of using brick masonry as infill in the design of RC structures, particularly in areas vulnerable to seismic events, to ensure the well-being of occupants [7].

Fired clay bricks are commonly utilized as construction materials for wall assemblies and as infill in reinforced concrete frame structures, particularly in earthquake-prone regions like West Sumatra, Indonesia. Post-earthquake field investigations have revealed that one of the significant causes of fatalities during seismic events is the collapse of brick walls, which can lead to catastrophic consequences for occupants and surrounding structures. It is widely believed that improper bricklaying techniques contribute significantly to these collapses, as inadequate alignment, insufficient bonding, and lack of attention to structural integrity can undermine the overall strength and stability of the walls. Consequently, addressing these construction practices is essential to enhancing the safety and resilience of brick masonry structures in the face of future earthquakes, thereby reducing the risk of injury and loss of life in vulnerable communities [8].

2 Methodology

This section aims to provide a comprehensive overview of the model structures utilized in the research study, the materials selected for construction, and the methodologies implemented to effectively achieve the study's objectives. By detailing these critical components, the intention is to offer readers a clear and thorough understanding of the foundational elements upon which the research is built, thereby enhancing the clarity and context of the findings presented. Through this detailed exploration, we hope to illuminate the rationale behind each choice made during the research process, illustrating how these decisions contribute to the overall integrity and validity of the study.

2.1 Model and material used

The buildings referred to as "ruko" in the city of Padang serve as the primary focus of evaluation in this study, representing typical structures found in the region. These ruko buildings are designed as two-story reinforced concrete structures, characterized by a floor-to-floor height of 4 meters. Additionally, the columns supporting these buildings are sized at 200x200 mm, while the beams

are designed with a dimension of 200x250 mm. This specific architectural configuration not only reflects the common construction practices in Padang but also provides a basis for analyzing their structural performance and resilience under various conditions, particularly in the context of seismic activity. These structures are constructed using concrete of grade K-250, which provides a solid foundation, along with steel that possesses a strength of 400 MPa, ensuring robustness and stability. The building modeling, conducted using the SeismoStruct 2022 software, illustrates the performance of the structures both with and without masonry infill, and these comparative visualizations can be seen in Figs. 1-3.

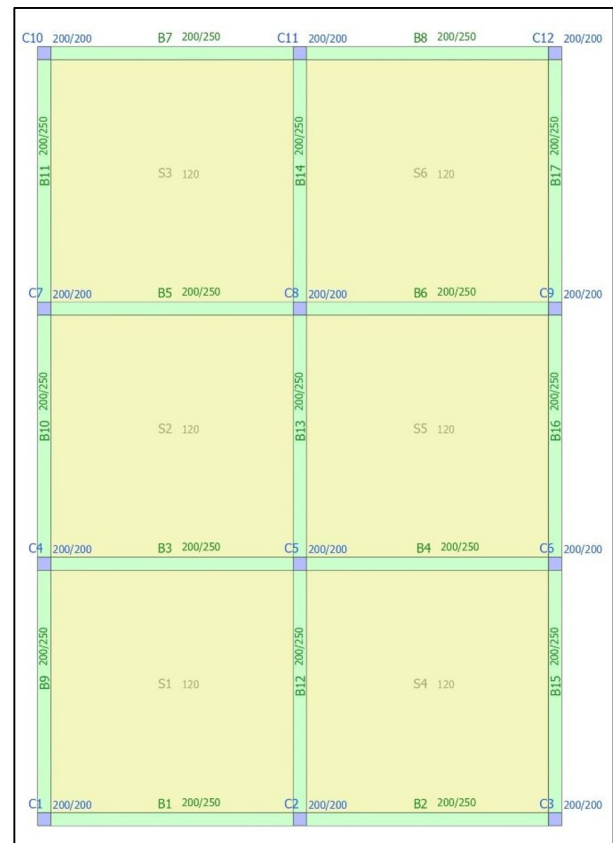


Fig. 1. The layout of the building.

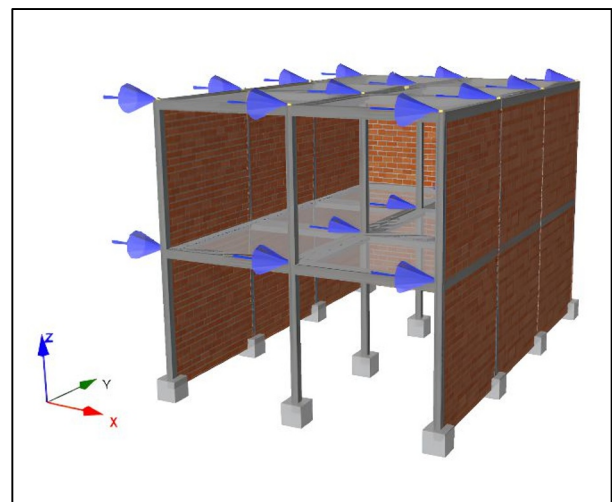


Fig. 2. Masonry building modelling.

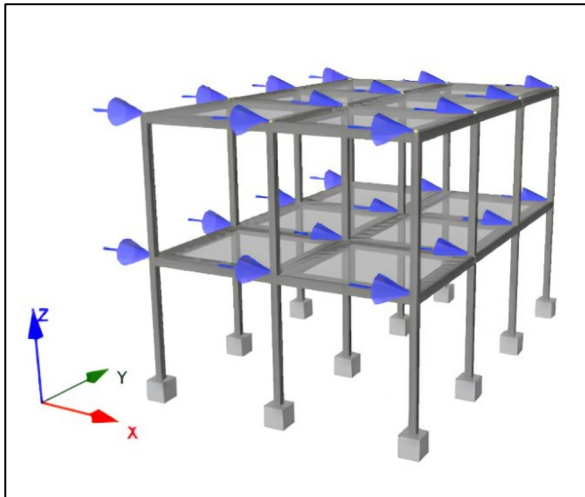


Fig. 3. Without masonry modelling.

2.2 Method

Pushover analysis is an advanced analytical technique in which the structural frame is subjected to a constant height-width partition while simultaneously applying a monotonically increasing lateral force until the desired level of displacement is achieved. This method involves a series of successive elastic assessments that are superimposed to approximate the global force-displacement curve of the structure as a whole. Initially, the gravity loads are applied to the model, which is then represented as either a two-dimensional or three-dimensional configuration. Furthermore, this model incorporates bilinear or trilinear load-deformation diagrams for all components that withstand lateral forces, allowing for a more accurate depiction of the structural behavior under seismic loading conditions. Through this comprehensive approach, engineers can effectively evaluate the performance and resilience of the structure, leading to informed design decisions that enhance its ability to withstand earthquakes [9].

HAZUS (Hazard United States) defines the fragility curve as a crucial analytical tool that illustrates the relationship between the likelihood of experiencing specific levels of damage known as Damage States (DS) in a building and the corresponding intensity of seismic activity, referred to as Intensity Measures (IM). This curve serves as a crucial framework for understanding the intricate relationship between varying levels of earthquake intensity and their potential impact on the structural integrity of buildings. By providing a visual representation of how different seismic forces can affect a structure's performance, the curve enables engineers and planners to more accurately assess risks associated with seismic activity. Consequently, this understanding allows them to implement effective mitigation strategies tailored to enhance the resilience and safety of structures in earthquake-prone areas. In doing so, it fosters informed decision-making that prioritizes both the protection of human life and the preservation of infrastructure in the face of natural disasters [10].

Fragility curves are very useful tools to determine the damage risk of bridge structures due to seismic load. The

probability of exceedance in various damage states of ground motion is displayed by these curves. While there are many different kinds of distribution functions in mathematics, only three are commonly utilized in fragility analysis: uniform, lognormal, and normal distributions. The cumulative distribution function and the normal distribution function are frequently used by engineers. After that, the functions are created to have a lognormal distribution since it is dependable for analyzing the excess of risk and seismic hazard. Stated differently, equation (1) represents the standard equation utilized to generate the fragility curves or conditional exceedance.

$$\text{Fragility} = P [LS | IM = y], \quad (1)$$

Where LS is a limit states or damage states DS, IM is the intensity of ground motion, and y is a reached state due to ground motion intensity IM.

To effectively predict the probability of hazards that may arise both during and after seismic activity, fragility curves have been developed as essential tools in the realm of seismic risk assessment. These curves are widely utilized in engineering practices to mitigate potential damage and minimize energy loss during seismic events, thereby playing a crucial role in informing and supporting building codes and regulations tailored to specific geographic areas. The process of creating fragility curves typically begins with sophisticated methodologies, such as pushover analysis or nonlinear static analysis, which are vital for gaining a comprehensive understanding of how structures respond to varying levels of seismic loading. By employing these analytical techniques, engineers can better assess the vulnerability of different structural systems, ultimately leading to more resilient designs that enhance safety and performance in the face of earthquakes [11].

3 Results and discussion

The results of the fragility curves for the structure, both with and without masonry infill, are comprehensively illustrated in Figs. 4 and 5 for the x-direction, while the corresponding results for the y-direction are presented in Figs. 6 and 7. These figures provide a detailed visual representation of how the presence or absence of masonry infill significantly influences the structural performance and vulnerability during seismic events, enabling a clearer understanding of the varying risk profiles associated with each configuration. By meticulously comparing these curves, we can gain valuable insights into the effectiveness of masonry infill in enhancing the resilience of the structure under lateral loading conditions. This analysis not only highlights the protective benefits offered by masonry infill but also serves to inform future design considerations and risk mitigation strategies, ultimately contributing to the development of safer and more resilient buildings in earthquake-prone areas. Such findings are crucial for engineers and architects as they strive to create structures that can withstand the forces generated by seismic activity, thereby safeguarding both lives and property.

The fragility curve in the x-direction presented in the analysis clearly illustrates that the spectral displacement values for structures incorporating masonry infill are notably smaller when compared to those of structures that do not utilize such infill. This significant difference in displacement values indicates that the presence of masonry infill substantially enhances the overall stiffness and stability of the structures, effectively reducing their vulnerability to lateral forces during seismic events. Consequently, this finding underscores the critical role that masonry infill plays in improving structural performance and resilience, highlighting its importance as a fundamental design consideration in regions that are prone to earthquakes. Furthermore, by emphasizing the benefits of masonry infill, this analysis provides valuable insights for architects and engineers, encouraging them to prioritize this element in their designs to ensure that buildings can withstand the challenges posed by seismic activity, ultimately contributing to the safety and security of communities in high-risk areas.

The curve clearly illustrates that the spectral displacement values for structures incorporating masonry infill are significantly smaller when compared to those of structures that do not include such infill, indicating a marked improvement in performance under seismic loading conditions. Furthermore, it is evident from the detailed analysis that the spectral displacement values observed in the y-direction consistently exhibit lower readings than those measured in the x-direction, suggesting a directional dependency in the structural response to seismic forces. This discrepancy can be attributed to the inherent differences in the dimensions and geometric configurations of the buildings, which directly influence how each structure reacts to lateral loads during seismic events. Such insights not only underscore the critical importance of considering the presence of masonry infill but also highlight the necessity of evaluating the structural dimensions when assessing the overall seismic performance of buildings. Ultimately, these findings inform design practices aimed at enhancing the resilience of structures in earthquake-prone areas, ensuring that they can better withstand the forces of nature and protect the safety of their occupants.

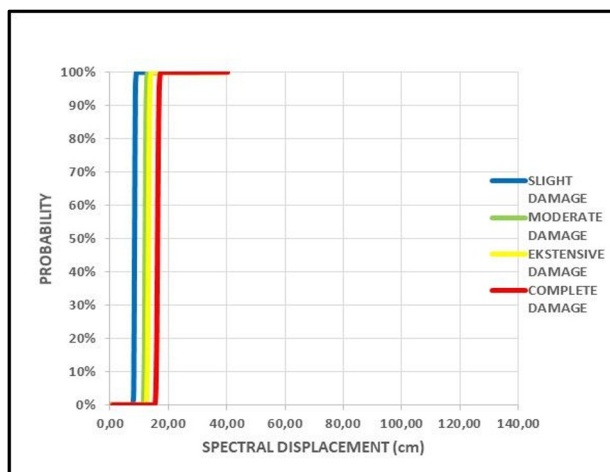


Fig. 4. Fragility curve x-direction with masonry infill.

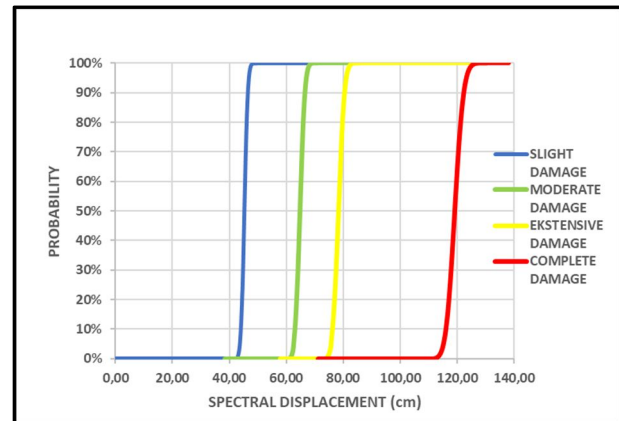


Fig. 5. Fragility curve x-direction without masonry infill.

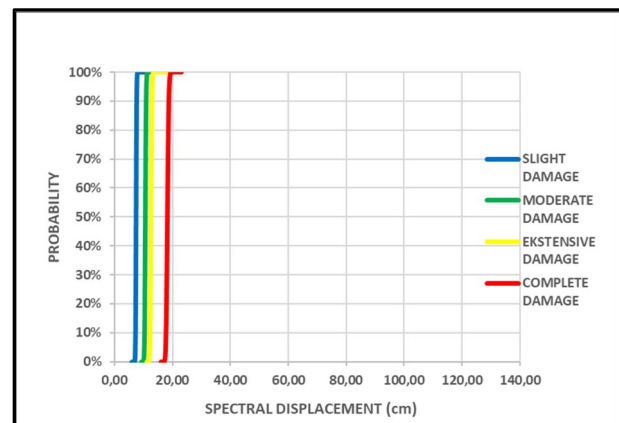


Fig. 6. Fragility curve y-direction with masonry infill.

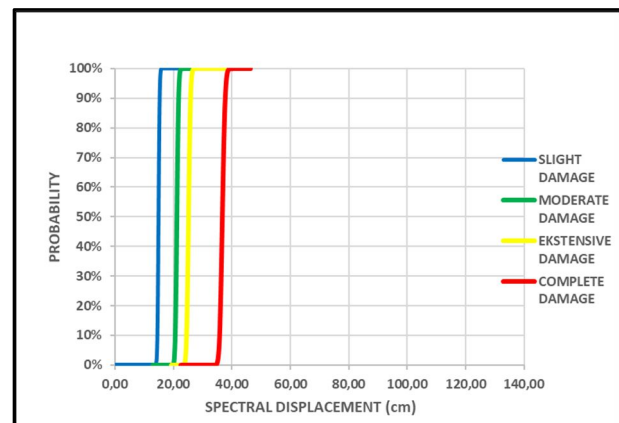


Fig. 7. Fragility curve y-direction without masonry infill.

Based on the results obtained from the comprehensive analysis of the building fragility curves, which compared structures with masonry infill to those without, the probabilities of various damage states can be effectively summarized as follows: these findings provide critical insights into the substantial influence that the presence of masonry infill has on the overall vulnerability of buildings during seismic events. By meticulously quantifying the likelihood of different damage scenarios, this analysis not only highlights the protective benefits conferred by masonry infill in enhancing structural performance but also underscores the urgent need for careful consideration

of such essential structural elements throughout the design and construction processes. This approach is vital for improving the safety and resilience of buildings located in earthquake-prone areas, ensuring that they are better equipped to withstand the forces generated by seismic activity, thereby safeguarding the lives of occupants and the integrity of infrastructure:

3.1 In the x-direction:

In the assessment of damage conditions, the analysis reveals significant disparities in spectral displacement values between structures equipped with and without infill walls. For the slight damage condition, structures lacking infill walls sustain damage at a spectral displacement value of 45.67 cm, whereas those incorporating infill walls exhibit slight damage at a markedly lower displacement of only 8.84 cm. Moving on to moderate damage conditions, the findings indicate that structures without infill walls reach a critical spectral displacement of 63.92 cm, while those with infill walls incur moderate damage at just 12.20 cm. Furthermore, when considering extensive damage, the values are even more pronounced: structures without infill walls experience damage at 77.22 cm, in stark contrast to the 13.26 cm observed for structures with infill walls. Lastly, in the case of complete damage, structures devoid of infill walls withstand a substantial spectral displacement of 118.91 cm, while those with infill walls sustain complete damage at a significantly reduced level of 16.44 cm. These findings emphatically highlight the critical role that infill walls play in enhancing structural resilience across various damage scenarios, underscoring their importance in earthquake-resistant design strategies.

3.2 In the y-direction:

In the analysis of damage conditions, the findings reveal significant differences in spectral displacement values between structures with and without infill walls. For the slight damage condition, structures without infill walls experience damage at a spectral displacement value of 14.82 cm, while those with infill walls demonstrate this damage at a much lower value of 7.51 cm. Similarly, in the case of moderate damage, structures without infill walls reach a critical spectral displacement of 21.17 cm, whereas structures with infill walls sustain moderate damage at only 10.59 cm. Furthermore, for extensive damage conditions, the disparity is even more pronounced, with the threshold for structures lacking infill walls set at 24.84 cm, compared to just 12.52 cm for those that include infill walls. Finally, in scenarios of complete damage, structures without infill walls reach a critical spectral displacement of 36.65 cm, while those with infill walls incur complete damage at a significantly reduced value of 18.33 cm. These results clearly illustrate the protective benefits of masonry infill in enhancing the resilience of buildings against seismic forces.

4 Conclusion

Incorporating masonry infill into reinforced concrete (RC) structures is a prevalent and widely accepted practice in West Sumatra, where it is frequently employed not only to enhance the overall lateral stiffness and strength of buildings but also to significantly improve their ability to withstand the potentially devastating forces generated during seismic events. This integration of masonry infill serves to reinforce the structural framework, allowing buildings to better absorb and dissipate energy from lateral movements, ultimately contributing to their stability and resilience in the face of earthquakes. Moreover, this practice reflects a broader trend in the region, emphasizing the importance of adopting effective construction techniques that prioritize safety and structural integrity, especially in areas that are particularly vulnerable to seismic activity. Through the strategic use of masonry infill, builders and architects aim to create safer living and working environments, ensuring that communities are better protected against the impacts of natural disasters.

However, despite the critical support that this infill provides during seismic events, it can also inadvertently reduce the ductility of the structures, which poses significant risks to the safety and well-being of residents. Post-earthquake studies conducted in these regions have identified improper bricklaying techniques as a key contributing factor to the fatalities resulting from the collapse of brick walls during seismic activity. These alarming findings highlight the urgent need for the implementation of improved construction practices and a greater emphasis on adherence to building standards. It is essential to recognize that ensuring both strength and ductility in structural design is paramount for protecting lives and minimizing damage in the event of future earthquakes. This calls for a comprehensive approach to construction that not only addresses the materials used but also prioritizes skilled labor and rigorous quality control throughout the building process.

The results of the fragility curve analysis reveal compelling evidence that structures equipped with masonry infill exhibit significantly smaller spectral displacement values when compared to those that do not incorporate such infill. This finding strongly suggests that the inclusion of masonry infill within the structural design not only enhances the overall performance of the buildings but also significantly boosts their resilience during seismic events, enabling them to withstand lateral forces more effectively and reliably. Consequently, this indicates that structures that incorporate masonry infill are far more adept at mitigating the impacts of seismic activity than those lacking this crucial component, thereby reducing the potential for damage and enhancing safety. Such insights underscore the paramount importance of considering masonry infill during the design and construction phases of buildings, as it plays a vital role in improving their resistance to the forces generated by earthquakes.

Ultimately, this thoughtful integration of masonry infill into the design and construction of buildings contributes significantly to the safety and well-being of occupants residing in earthquake prone regions, thereby underscoring the urgent need for architects and engineers to prioritize this essential structural element in their design practices. By doing so, they can enhance the overall resilience of structures, ensuring that communities are better safeguarded against the devastating impacts of seismic hazards. This proactive approach not only mitigates the risks associated with potential earthquakes but also fosters a greater sense of security among residents, who can have increased confidence in the integrity of their homes and workplaces. Furthermore, as urban development continues to expand in areas susceptible to seismic activity, the emphasis on incorporating masonry infill becomes even more critical, as it plays a pivotal role in preserving both human life and infrastructure during natural disasters, ultimately contributing to the sustainable growth and stability of these communities in the long term.

References

1. Masrilayanti, R. Kurniawan, A. L. Budi and S. H. Sourkan, IOP Conf., **1041**, 012003, (2021). <https://doi.org/10.1088/1757-899X/1041/1/012003>
2. L. Leilany, Jurnal Rivet, **02**, 01, (2022).
3. T. Al Fajri, R. Imani, and Z. Siregar, Jurnal Teknologi, **10**, 2, (2020)
4. R.S. Leksono, D. Iranata, and H. Kristijanto, Jurnal Teknik ITS, **1**, 1, (2012)
5. R. Suwal and R. Uprety, Journal of Engineering Issues and Solutions, **2**, 1, (2023). <https://doi.org/10.3126/joeis.v2i1.49373>
6. J. Monical and S. Pujol, Structures, **63**, 106345 (2024). <https://doi.org/10.1016/j.istruc.2024.106345>
7. J. Tanjung, F. A. Ismail, Maidiawati, and R. Putra, International Journal of GEOMATE, **18**, 66, (2020) <https://doi.org/10.21660/2020.66.9488>
8. J. Tanjung, F. A. Ismail, Maidiawati, and Y. Hayati, IOP Conf. **933**, 012028 (2020), <https://doi.org/10.1088/1757-899X/933/1/012028>
9. M. Saadi, D. Yahiaoui, N. Lahbari, and B. Tayeb, C.E.J. **7**, 07, (2021) <http://dx.doi.org/10.28991/cej-2021-03091714>
10. D. R. Silitonga, and I. Imran, J. Teknik Sipil, **26**, 1, (2019), <https://doi.org/10.5614/jts.2019.26.1.7>
11. M. Masrilayanti, A. P. Nasution, R. Kurniawan, J. Tanjung, and S. Sarmayenti, sciendo, **17**, 1, (2021), <https://doi.org/10.2478/cee-2021-0022>