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ANALYTICAL STUDY ON THE SEISMIC BEHAVIOR OF NON-STANDARD REINFORCED MASONRY HOUSES RETROFITTED WITH CROSSED FERROCEMENT LAYERS

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ABSTRACT: Indonesia is one of the most earthquake-prone countries in the world, where many reinforced masonry (RM) houses are built without complying with seismic-resistant building standards. These non-standard RM houses are highly vulnerable to severe damage or sudden collapse during strong earthquakes. This study presents a numerical analysis of a retrofitting method for non-standard RM houses using a ferrocement layer with a cross system on the walls. The research involved modeling a 1:4 scaled model of an actual damaged RM house in West Pasaman, Indonesia, using ETABS V.22 software, and applying time-history earthquake loads at acceleration levels of 0.3 g, 0.6 g, 1.0 g, and 1.5 g. The results show that retrofitted non-standard RM houses experience smaller maximum tensile stresses compared to non-retrofitted ones under all earthquake acceleration levels. The reduction in tensile stress indicates that the crossed ferrocement layer effectively improves wall stability and prevents severe damage. This strengthening method can be implemented without demolishing existing structures, making it a cost-effective and practical solution for reducing seismic risks in vulnerable housing.

Keywords: Earthquake, Reinforced Masonry, Retrofitting, Ferrocement Layer, Tensile Stress

1. INTRODUCTION

Indonesia is a country prone to earthquakes due to several geographical and geological factors. Geologically, the structure of the earth's crust in Indonesia lies at the confluence of tectonic plates, which results in the Indonesian region having a high risk of earthquake disasters [1]. Several earthquake incidents occurred in Indonesia, causing many material losses and fatalities, including the West Sumatra earthquake (2009), the Lombok and Palu earthquakes (2018), the West Pasaman earthquake (2022) [2], and the East Java earthquake (2024). During the 25 February 2022 West Pasaman earthquake, at least 2,025 houses were reported damaged, including 1,111 units verified as heavily damaged after BNPB/BPBD verification in West Pasaman Regency. Similarly, the 22 March 2024 East Java (Bawean–Tuban) earthquake sequence caused 4,679 damaged houses across the province (774 heavy, 1,332 moderate, 2,573 light), indicating widespread vulnerability of non-standard RM housing to strong shaking [3]. These figures underscore the need for practical retrofitting strategies for Indonesia's RM dwellings to reduce seismic risk.

Figure 1 shows that RM house buildings are built without paying attention to applicable standards and only based on the practical experience of the community/construction workers without supervision by structural experts, so many have suffered heavy damage and even collapsed due to a major earthquake.

In general, RM houses are built using reinforce/iron on concrete column and beam elements, as shown in Fig. 2. The building of this house is usually strong against earthquake loads, but if the construction of the RM house has structural elements such as beams and columns that are not in accordance with building standards, then it does not have strength against earthquake loads [4-6]. When an earthquake occurs, this house can suffer minor to severe damage, and it can even collapse suddenly.

To avoid the sudden collapse of RM houses that do not meet building standards when an earthquake occurs, research on the numerical analysis of retrofitting of RM houses that do not meet standards and are damaged after an earthquake needs to be carried out. One of the retrofitting methods developed is to use a ferrocement layer with a cross system on the building wall [7-11]. The ferrocement layer is formed by galvanized woven wire in a mortar layer. This method is effective, the cost is relatively cheap, the materials are easy to obtain, and the work can be done by the community or local craftsmen. This research aims to fill the gap by developing research on Retrofitting of RM houses that are not in accordance with standards, which is strengthened using a cross-system ferrocement layer.

This study focuses on a numerical analysis study of the RM houses that are not in accordance with standards by modeling a house model based on the original house in West Pasaman that was damaged after the 2022 West Pasaman earthquake. By conducting this study, it is hoped that all RM houses that do not meet the standards can be strengthened with this method, so that they can reduce the risk of damage and casualties due to earthquakes in the future.

Fig.1 Damage to RM's house due to a major earthquake that occurred in Indonesia; (a) in West Sumatra (2009) ; (b) in Lombok (2018); (c) in West Pasaman (2022); and (d) in East Java (2024)

Fig.2 A simple RM house

2. RESEARCH SIGNIFICANCE

An analytical study was carried out to determine the seismic behavior of the original RM house compared to the RM house retrofitted with a crossed ferrocement layer. This research is very important because the results can be used as a reference for building earthquake-resistant houses in earthquake-prone areas, both in disaster mitigation efforts and in the post-earthquake rehabilitation and reconstruction stage. In addition, the retrofitting method using a ferrocement layer with a cross system is an effective method and is easy to apply by the community independently.

3. ANALYTICAL WORK

3.1 Non-Standard RM House Models

In this numerical study, two house models were modeled, namely the non-standard RM house without retrofitting, and the non-standard RM house with retrofitting using a ferrocement layer with a cross-system. Both models were scaled 1:4 from the original RM house model, which was built not according to earthquake-safe building standards in West Pasaman, which was damaged after the 2022 West Pasaman earthquake. The layout of the model design is in accordance with the shape of the existing house in the community and the needs of the rehabilitation and reconstruction stage in earthquake areas in Indonesia. The research procedure at the model design stage of the non-standard RM model house is as follows:

3.1.1 Model plan drawings

The model plan image of the RM model house was taken to adjust the existing one with a type 36 house with a size of 6 m x 6 m x 4 m. After being scaled 1:4 from the original house size, the size for a simple model house becomes 1.5 m x 1.5 m x 1.0 m (Fig. 3). Models without retrofitting and with retrofitting using crossed ferrocement layer are shown in Figs. 4-5.

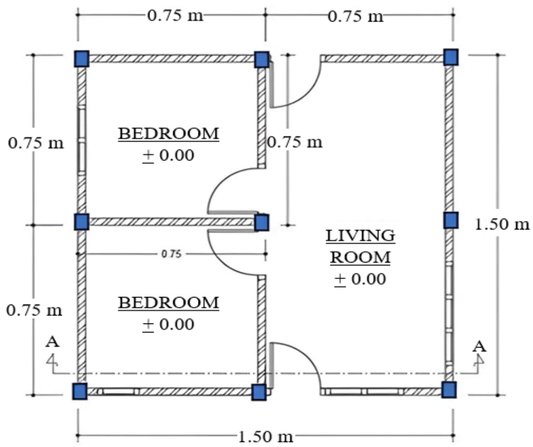

Fig.3 Non-Standard RM Model plan

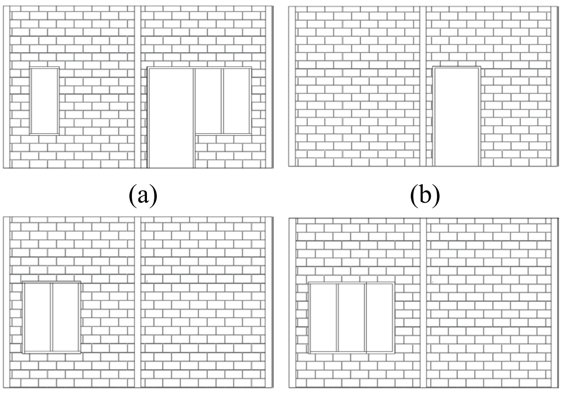

Fig.4 Model house without retrofitting; a) front view, b) back view, c) left side view, and d) right side view

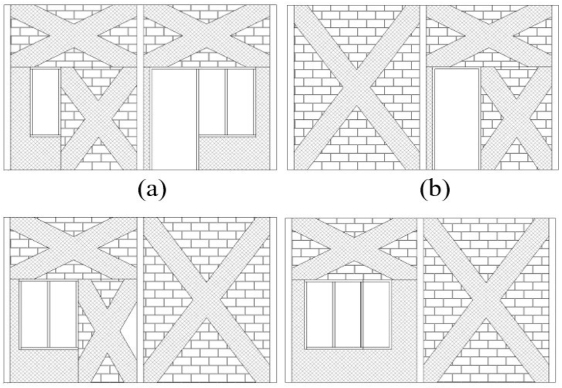

Fig.5 Model house with retrofitting; a) front view, b) back view, c) left side view, and d) right side view.

3.1.2 Detail drawings of Retrofitted Wall

Figure 6 is a detailed drawing of the wall of a model house that is retrofitted with woven wire with a cross system on the wall of the model, given plaster with a thickness of ± 0.5 cm. Plasters and specimen mortar are made with a mixture of cement and sand in a ratio of 1:4.

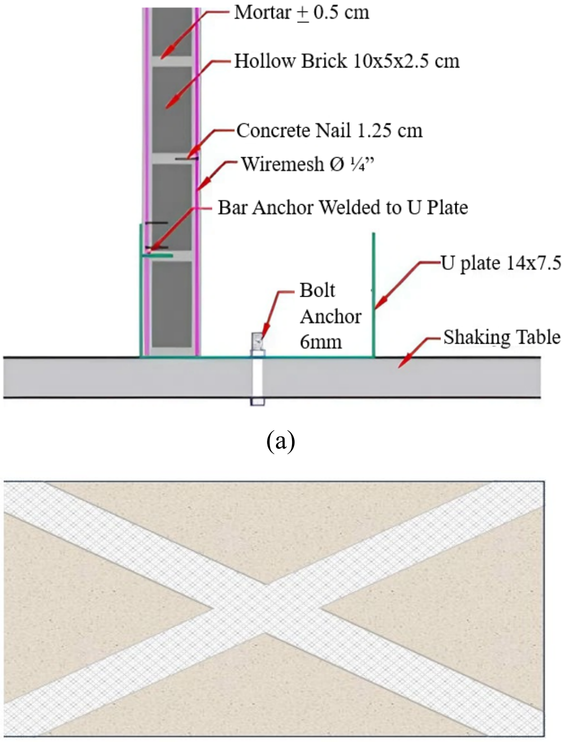

Fig.6 Details of the wall of the house model, and Installation of the ferrocement layer of the cross system on the wall of the house

3.2 Material Properties

This numerical analysis study uses five main materials, namely hollow brick, plaster, concrete, reinforcement bar, and woven wire, which is defined as steel.

The hollow brick has a compressive strength (fc') of 3.3 MPa (Fig.7), a shear modulus of 3096 MPa, an elasticity modulus of 7431.35 MPa, and a specific gravity of 1600 kg/m^3. Plastering has a compressive strength (fc') of 9.9 MPa, shear modulus of 6161.75 MPa, elastic modulus 14788.2 MPa, and specific gravity of 1600 kg/m^3. The woven wire has a yield strength (fy) of 275 MPa, the highest tensile strength (fu) of 620 MPa, a shear modulus of 187500 MPa, and a specific gravity of 8.0 g/cm^3. The reinforced concrete has a comprehensive strength (fc') of 15 MPa, and the reinforcement bar has a yield strength of 280 MPa, and the highest tensile strength (fu) of 420 MPa [12].

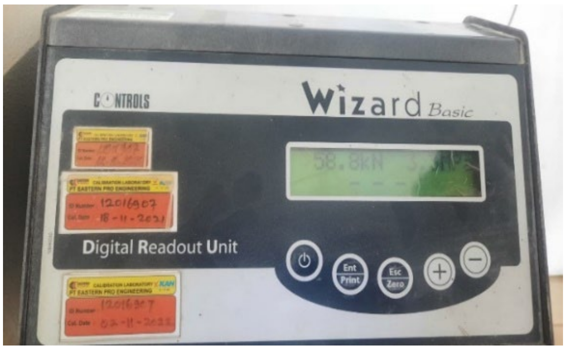

Fig. 7. Compressive strength value of hollow brick

3.3 Modeling

The modeling of the non-standard RM house in this study is shown in Figs.8-9. Figure 8 shows the non-standard RM house model without retrofitting, where the walls are defined as hollow brick walls with section data properties, as shown in Fig.10.

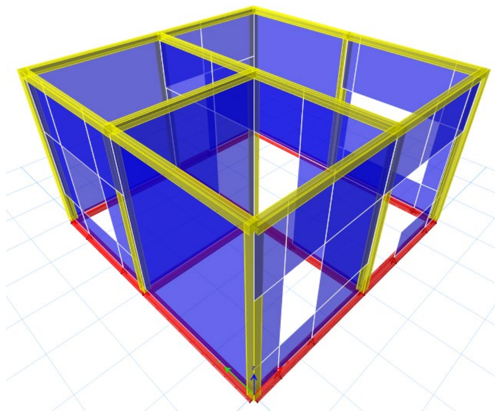

Fig. 8 Modeling of the non-standard RM house without retrofitting

Meanwhile, Fig.9 shows the modeling of the house with its retrofitting, where the red section is the area of the wall with retrofitting, and the blue section is the area of the wall without retrofitting. The section properties of the retrofitted wall are shown in Fig.11, which is defined as a wall consisting of 5 (five) layers. The modeled column is a column that does not meet earthquake safety standards, both in terms of its cross-sectional width and depth, as well as its reinforcement configuration (Fig. 12).

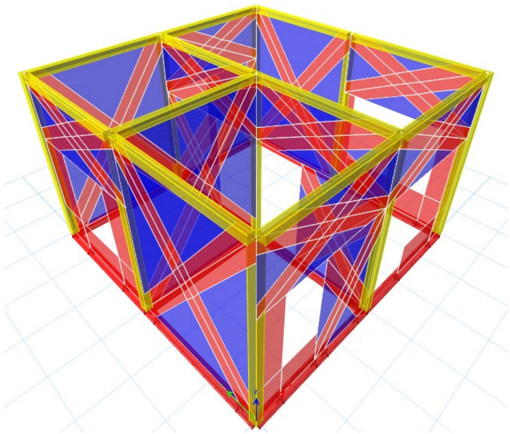

Fig.9 Modeling of the non-standard RM house retrofitted with a ferrocement layer with a crossed system.

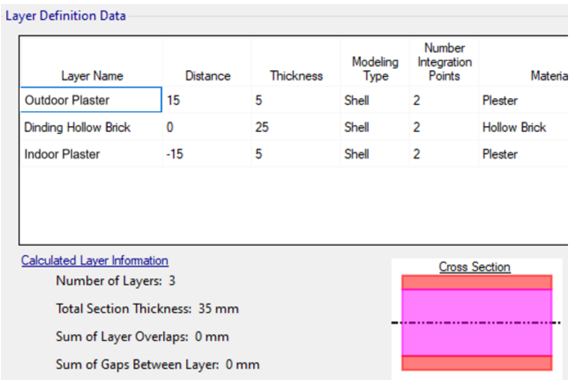

Fig.10 Section properties of walls without ferrocement layer

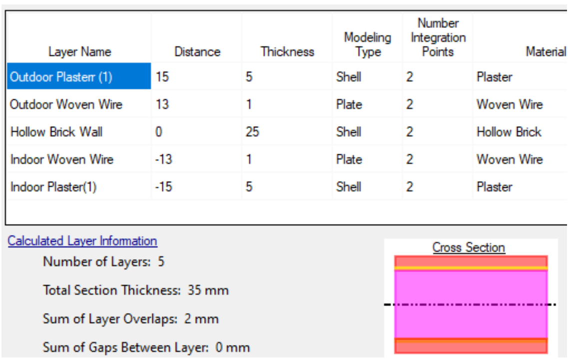

Fig.11 Section properties of walls with ferrocement layer

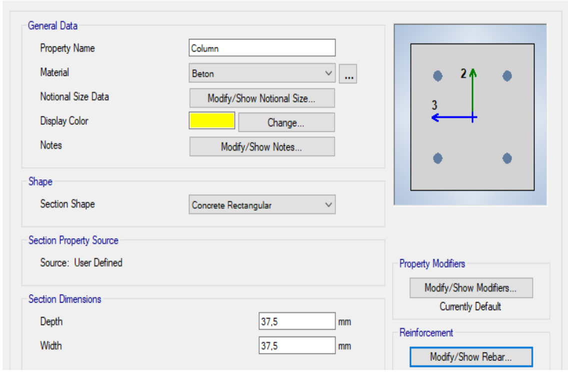

Fig.12 Section Properties of Column

3.4 Loading

The house model weighs 471 kg, as shown in Table 1. A real house without scale weighs 430 kg/m^2 (Table 2). Then the weight of the model house should be based on the following broad scale (equation 1):

$$Ls \times qa = qs \quad (1)$$

where,

Ls: Specimen Area (m^2)
Q: Original Weight House (kg/m^2)
qs : Specimen Weight (kg)

So,

$$2.25\ m^2 \times 430\ kg/m^2 = 968\ kg$$

Therefore, the model house is given an additional load of 500 kg. The additional load is divided into 9 sections, which are inserted in each corner of the model house, as shown in Fig.13.

Table 1. Weight of the model house

Material	kg
Hollow brick weight	157
Mortar weight	246
Weight of the roof frame and the roof	68
Total weight of Specimen	471

Table 2. Weight of the original house

Material	kg
Hollow brick weight	10606
Mortar weight	4172
Weight of the roof frame and the roof	718
Total weight of Specimen	15496
qa: Dead load weight of the original house	430 kg/m^2

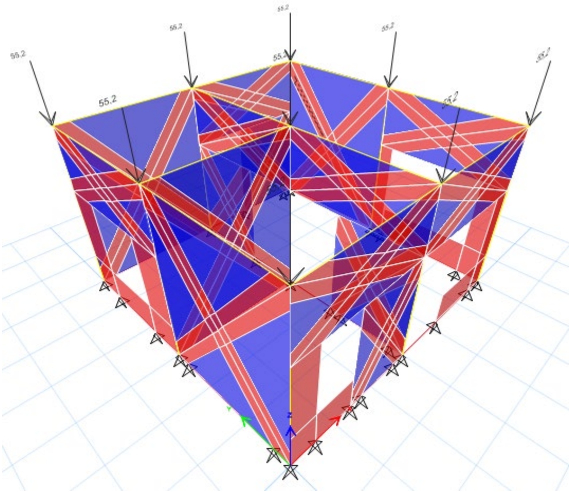

Fig.13 Additional dead loads on model houses

3.5 Numerical Analysis with Time History Analysis

Numerical analysis was carried out in the study using the time history of the earthquake load. There are four variations of the given earthquake acceleration load, namely 0.3 g, 0.6 g, 1.0 g, and 1.5 g, with a duration of 10 seconds for each acceleration variation.

4. RESULTS AND DISCUSSION

4.1 Behavior of House Models at 0.3 g Earthquake Acceleration

Based on the analysis results from ETABS V.22 software with a 0.3 g earthquake acceleration, the tensile stress on the walls of both the unretrofitted and retrofitted houses is primarily shown in yellow and green in Figs.14-15, respectively.

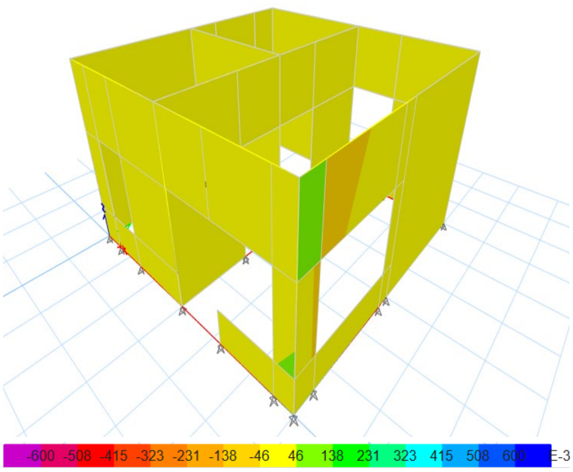

Fig.14 Wall tension pattern on non-standard RM wall due to 0.3 g earthquake acceleration

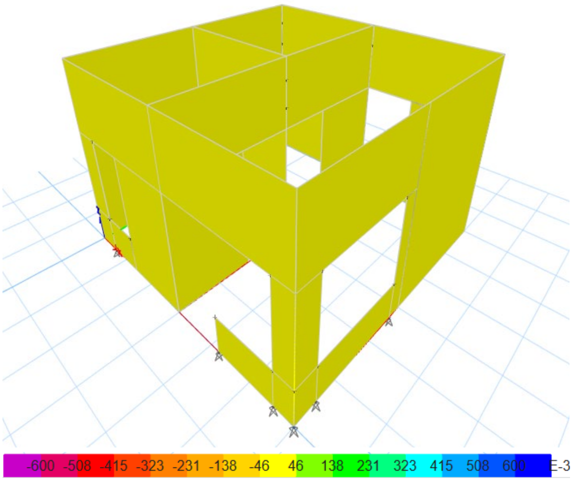

Fig.15 Wall tension pattern on retrofitted non-standard RM wall due to 0.3 g earthquake acceleration

For the unretrofitted house, the maximum tensile stress reaches 0.07 MPa, which is below the tensile strength of the hollow brick (0.264 MPa). The tensile strength of the hollow brick is calculated as 8% of its compressive strength, which is 3.3 MPa, resulting in 0.264 MPa. Although the stress is below the tensile capacity, any tensile stress on unreinforced walls is considered a high-risk category that could lead to cracks and collapse.

In contrast, the house retrofitted with a crossed ferrocement layer shows a significantly lower maximum tensile stress of 0.03 MPa. Even if the tensile stress were to exceed the hollow brick's tensile capacity, the wall would remain safe due to the high tensile resistance provided by the woven wire reinforcement in the ferrocement layer. The woven wire serves to maintain wall stability and prevent damage.

4.2 Behavior of House Models at 0.6 g Earthquake Acceleration

The analysis results for the 0.6 g earthquake acceleration, shown in Fig. 16 (unretrofitted) and Fig. 17 (retrofitted), indicate that the highest tensile stress occurs in areas with large openings, such as the living room.

In the unretrofitted house, the maximum tensile stress reaches 0.12 MPa. While this value is still below the tensile strength of the brick walls (0.264 MPa), it represents a significant increase from the 0.3 g acceleration. The stress distribution is more widespread and intense, particularly around windows and doors, which are typically points of weakness. This increased stress level suggests a higher risk of cracking and damage, which could compromise the structural integrity of the wall during a prolonged seismic event.

Conversely, the retrofitted house shows a much smaller maximum tensile stress of only 0.09 MPa. This demonstrates the effectiveness of the ferrocement layer with a cross system in absorbing and distributing seismic forces. Even though the stress value is still present, the wall's ability to withstand these forces is significantly enhanced by the woven wire. The wire, with its high tensile strength, acts as a secondary reinforcement system, preventing the wall from failing catastrophically even if the stress were to exceed its own tensile capacity. The overall behavior of the retrofitted model remains stable and secure, indicating its good performance under moderate earthquake loads.

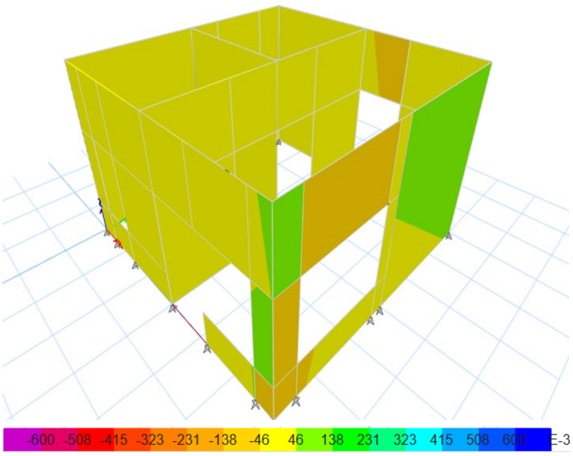

Fig.16 Wall tension pattern on non-standard RM wall due to 0.6 g earthquake acceleration

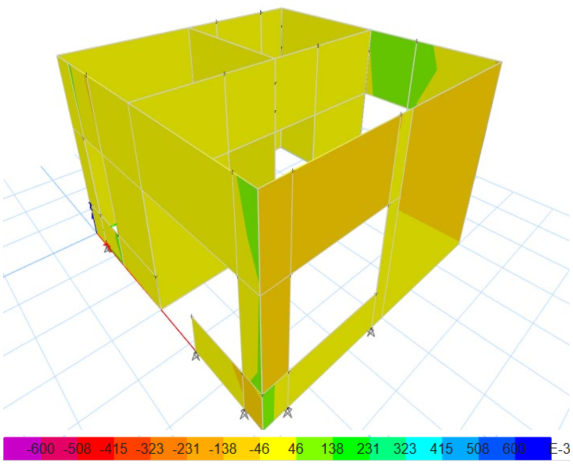

Fig.17 Wall tension pattern on retrofitted non-standard RM wall due to 0.6 g earthquake acceleration

4.3 Model House Behavior at 1.0 g Earthquake Acceleration

The analysis results for the 1.0 g earthquake acceleration show a more significant difference between the two models. In the unretrofitted house, as seen in Fig. 18, higher tensile stresses begin to appear, marked by blue areas. These areas indicate stress values between 0.231 MPa and 0.323 MPa. Overall, the maximum tensile stress value in this model is 0.26 MPa. This indicates that the hollow brick walls are approaching a critical point where severe damage, such as major cracking or collapse, could occur.

In contrast, in the retrofitted house (Fig.19), the tensile stresses are still dominated by yellow and green areas. This indicates that the stresses are much lower and more evenly distributed. The maximum tensile stress value in this model is only 0.18 MPa. This striking difference proves that the ferrocement layer with the cross system effectively dampens and distributes earthquake energy, preventing dangerous stress concentrations. These results show that in addition to increasing the strength of the walls, houses retrofitted with a crossed ferrocement layer can also reduce the pressure that occurs on the walls.

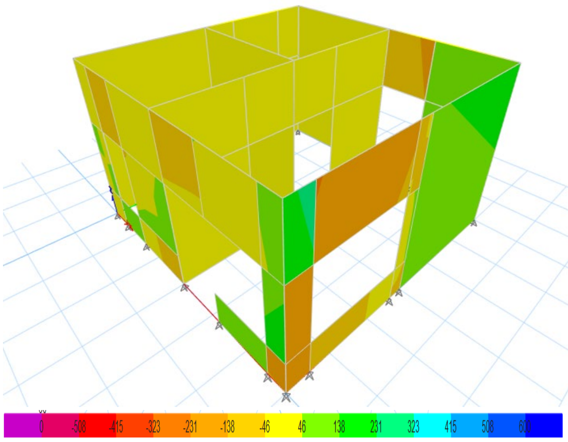

Fig.18 Wall tension pattern on non-standard RM wall due to 1.0 g earthquake acceleration

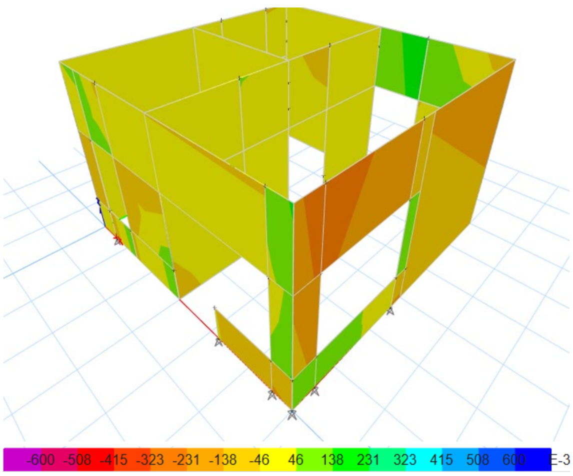

Fig.19 Wall tension pattern on retrofitted non-standard RM wall due to 1.0 g earthquake acceleration

4.4 Model House Behavior at 1.5 g Earthquake Acceleration

The analysis results for the 1.5 g earthquake acceleration, shown in Fig.20 (unretrofitted) and Fig.21 (retrofitted), demonstrate a striking difference in the behavior of the two models. At this high acceleration level, the unretrofitted house experiences a significant maximum pressure of 0.21 MPa. This value is dangerously close to the critical resistance limit of the brick walls, increasing the risk of severe damage.

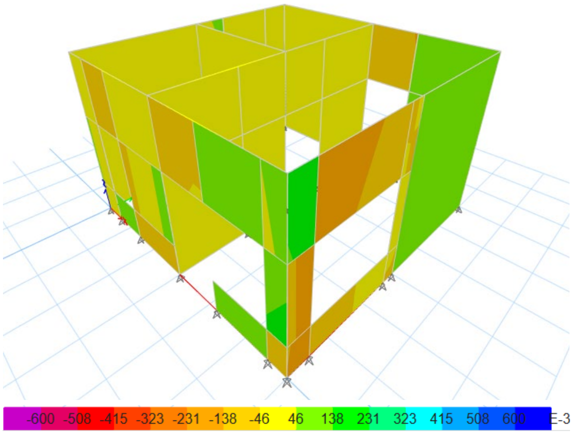

Fig.20 Wall tension pattern on non-standard RM wall due to 1.5 g earthquake acceleration

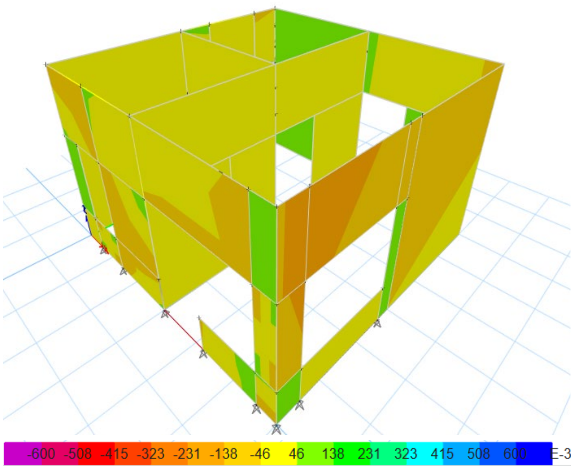

Fig.21 Wall tension pattern on retrofitted non-standard RM wall due to 1.5 g earthquake acceleration

In contrast, the house retrofitted with a ferrocement layer shows a much superior performance. The maximum pressure on its walls reaches only 0.11 MPa. These results prove that this retrofitting method not only increases the wall's strength but also effectively reduces the pressure caused by seismic loads. With a significantly lower stress value, the walls of the retrofitted house remain stable and secure, preventing severe damage or collapse even under very high earthquake acceleration.

It should be noted that the numerical analysis using ETABS is subject to several limitations. The model is based on a 1:4 scaled model, which may introduce scale effects that do not fully capture the behavior of full-scale masonry houses. In addition, the wall composition was simplified into representative material layers, while in reality, the construction quality, workmanship, and irregularities in mortar joints may vary significantly. These assumptions, although necessary for computational feasibility, can introduce uncertainties in predicting the actual seismic response of non-standard RM houses.

5. CONCLUSION

Based on the results of the analysis, it can be concluded that RM houses built without meeting seismic-resistant standards are highly vulnerable to severe damage or collapse during strong earthquakes. The hollow brick walls in these houses do not have adequate resistance to seismic loads. To address this vulnerability, one of the most effective retrofitting methods is the use of a ferrocement layer with a cross system on the walls. This method is not only effective but also practical, as the materials are easy to obtain and the application can be done by local communities or construction labor without demolishing the existing structures.

The numerical analysis demonstrates that retrofitted houses experience smaller maximum tensile stress values at every level of earthquake acceleration, with the largest reduction in tensile stress occurring in the 1.5 g earthquake acceleration of 47% (from 0.21 MPa to 0.11 MPa). This proves that the retrofitting system is highly effective in maintaining the stability of the walls and preventing damage such as cracks or collapse. The analysis results show that the tensile stress on the retrofitted house never exceeds the tensile capacity of the hollow brick. The presence of the woven wire, which has a high tensile resistance, ensures that the walls remain safe and stable.

Overall, this retrofitting method is a cost-effective and practical solution for seismic risk reduction in vulnerable housing, both as part of disaster mitigation efforts and in the post-earthquake reconstruction phase.

Despite the promising results, the findings of this study should be interpreted with caution due to the inherent limitations of the numerical modeling. Scale effects, simplification of wall composition, and the exclusion of construction irregularities may influence the accuracy of the simulated response. Future work is recommended to validate the numerical results with experimental shaking table tests on larger-scale specimens and to incorporate more detailed modeling of material.

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