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Enrichment: Journal of Multidisciplinary Research and Development

Identification of Dominant Factors of Simple House Building Vulnerability in Earthquake-Prone Areas Using RVS and FTA Methods

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ABSTRACT

Indonesia is in an active seismic area prone to earthquakes, including the city of Surabaya, which is crossed by the Kendeng Fault. Many modest homes in the area were built without considering earthquake resistance standards, thus posing a high risk of damage and casualties. This research aims to evaluate the reliability level of simple house buildings against earthquakes in the Tandes, Asemrowo, and Sukomanunggal Districts, West Surabaya, which are crossed by the Kendeng Fault. The methods used are Rapid Visual Screening (RVS) based on FEMA P-154 guidelines and Fault Tree Analysis (FTA) as a deductive approach to map the causes of structural vulnerability. The results showed that none of the 30 housing units met the safety criteria; 76.7% of buildings require follow-up evaluation, and 23.3% are classified as unsafe. The dominant factors affecting vulnerability include non-standard foundation conditions, the absence of structural fastening elements, the use of wall materials without reinforcement, and the irregularity of building geometry. These findings indicate the need for technical intervention through structural retrofit, public education about earthquake-resistant buildings, and the formulation of regulations for the construction of residential houses in earthquake-prone zones. The combination of RVS and FTA methods has proven effective in providing a comprehensive overview of the structural condition of existing buildings and can be used as the basis for seismic risk mitigation strategies in urban areas.

Keywords: Rapid Visual Screening, Fault Tree Analysis, simple house, earthquake, structural vulnerability, Kendeng Fault

INTRODUCTION

Indonesia is one of the most vulnerable countries to earthquakes in the world. Its location at the confluence zone of three active tectonic plates—the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate—places this region within the Pacific Ring of Fire, one of the world's most active seismic zones. As a result, almost all regions of Indonesia have the potential to experience high-intensity earthquakes that can cause severe damage to infrastructure and threaten human safety. This phenomenon poses a threat not only to coastal areas but also to mainland regions such as Java Island, which is the center of economic activity and population density. Surabaya, the second-largest metropolitan city in Indonesia, is certainly not immune to this risk, especially given the presence of the Kendeng Fault in the East Java region, which is one of the potential sources of earthquakes on the island (Setiawan et al., 2024).

The latest seismic data and geotechnical studies show that the West Surabaya area, which includes Tandes, Asemrowo, and Sukomanunggal Districts, is crossed by an active section of the Kendeng Fault that has the potential to cause moderate to large earthquakes. Research by Syaifuddin et al. (2020) indicates that this area also has liquefaction potential, particularly in zones with alluvial soil and high water saturation, which can exacerbate earthquake impacts on building structures. This high risk has not been fully mitigated by community and local government preparedness in terms of earthquake risk reduction. Many buildings in this area, especially simple residential houses, are constructed without attention to earthquake-resistant structural standards, including design, material selection, and construction techniques.

In this context, the existence of simple houses not designed to be earthquake-resistant is a serious concern. Most of these buildings are constructed independently by community members without technical supervision from construction experts. This situation is compounded by budget constraints, low levels of technical education among the community, and the lack of strict technical regulations from local governments. Mandela and Wanane (2020) emphasized that self-built houses tend to exhibit high structural vulnerability due to the use of non-standard materials, the absence of essential fastening columns, and foundations that are not carefully calculated. In an earthquake scenario, these types of buildings are at great risk of total collapse, potentially leading to fatalities.

To evaluate building vulnerability to earthquakes, the Rapid Visual Screening (RVS) method is an effective, efficient, and globally recognized approach. RVS is a rapid assessment method developed by FEMA to determine the seismic vulnerability of buildings through visual inspection of structural and non-structural elements. This method does not require detailed engineering calculations but provides fairly representative preliminary results to identify whether a building is safe, needs further evaluation, or is at high risk of collapse due to earthquakes (FEMA, 2015). The simplicity and speed of this method make it suitable for large-scale application, especially in densely populated areas like West Surabaya.

The RVS method assigns an initial score based on the building structure type and applies corrections according to actual field conditions, such as building age, number of floors, foundation condition, and the presence or absence of horizontal and vertical fastening elements. The final score determines the safety category of the building structure. Agustin et al. (2020) demonstrated that RVS implementation in various Indonesian regions successfully identified high-risk buildings, enabling timely repair or strengthening before disasters occur.

However, the RVS method has limitations in explaining the causal relationships of factors leading to building collapse. Therefore, the Fault Tree Analysis (FTA) method is used as a complement in this study. FTA is a top-down deductive method that thoroughly analyzes causes of structural damage by starting from the top event and tracing down to root causes. Arman et al. (2022) explain that FTA is highly effective for analyzing complex systems like buildings because it maps logical relationships among failure-causing elements.

Using the FTA approach, causes of collapse—such as foundation failure, walls without reinforcement, and building geometry irregularities—can be classified and visualized in a logic tree diagram. This diagram aids understanding of structural damage patterns systematically and serves as a tool for developing targeted prevention strategies. This analysis is particularly important in high-density urban areas, where a single building collapse can trigger a dangerous domino effect.

Beyond technical factors, social and economic aspects of the community also affect building reliability against earthquakes. Houses built by low-income owners tend to be constructed hastily without adherence to civil engineering standards. Homeowners prioritize cost efficiency over structural safety. Zamzami (2020) showed that the community's low technical understanding causes reliance on local builders' experience rather than expert advice, resulting in houses constructed on unstable ground with shallow foundations and poor-quality materials.

Demographic data from the study area also highlight a correlation between population density and risk level. Setiawan et al. (2024) noted that Tandes and Sukomanunggal Districts are high-density areas in West Surabaya where most residents live in houses of similar typology: single-story, without structural calculations, and adjoining each other without adequate separation. This condition increases the likelihood of cascading damage between buildings if a major earthquake occurs, even when the epicenter is outside the city.

Given these conditions, it is crucial to develop data- and technology-based mitigation strategies that provide comprehensive information about potential structural risks. The combination of RVS and FTA methods represents a relevant and applicable approach to obtain an accurate assessment of simple house buildings' reliability. Besides technical evaluation, the results can inform government policy interventions that adapt to the social and technical characteristics of local communities.

This study focuses on analyzing the reliability of simple houses in West Surabaya, crossed by the Kendeng Fault, using a combination of RVS and FTA methods. The primary objective is to identify dominant factors causing structural vulnerability and evaluate the buildings' ability to withstand earthquake loads. Data were collected through direct observation and structural analysis of 30 housing units across three sub-districts.

The research outcomes are expected to contribute not only to civil engineering science but also to public policy on disaster risk reduction. Local governments, technical institutions, and the public require accurate, data-driven information for making decisions about building, renovating, or strengthening existing structures. In sustainable development contexts, infrastructure resilience to natural disasters is a key indicator. Beyond academic research, this study prioritizes human safety. Thus, structural reinforcement and public awareness of earthquake-resistant construction cannot be delayed. An integrated approach involving technical evaluation, public education, and policy intervention is essential to reducing disaster impacts in vulnerable areas such as West Surabaya.

METHOD

This research uses a quantitative descriptive approach with the main methods of Rapid Visual Screening (RVS) and Fault Tree Analysis (FTA). This approach was chosen because it was able to provide a systematic overview of the condition of simple house buildings in the face of the threat of earthquakes, without having to conduct destructive tests. The RVS method is used to visually assess the structural and non-structural conditions of buildings based on FEMA guidelines P-154 (2015), while FTA is used to map the main causes of potential building collapse through a deductive logic (top-down) approach. The combination of these two methods has been widely used in disaster risk mitigation studies, especially in densely populated areas and active seismic zones (Agustin et al., 2020; Arman et al., 2022).

The research objects are located in three sub-districts in West Surabaya, namely Tandes, Asemrowo, and Sukomanunggal, which are the trajectories of the Kendeng Fault. Each sub-district was sampled as many as 10 simple houses, so that a total of 30 housing units were observed. Data was collected by direct observation in the field using the RVS evaluation form from FEMA which has been adjusted to the classification of medium to high seismicity areas. The information collected included the main structure type, foundation condition, symmetrical/asymmetrical configuration, number of floors, quality of structural connections, and age and use of the building (FEMA, 2015). The assessment was carried out visually and quantitatively, involving corrections to the initial score based on structural modification factors.

The initial score of the structure is determined based on the type of building construction as per FEMA's classification. For example, a single-storey wooden structure (W1) was given an initial score of 3.0, while a non-reinforcement brick wall structure (RM1) received an initial score of 1.0. Correction factors such as vertical irregularity, mass imbalance, soft story, age of the building, and foundation condition are then subtracted from the initial score to produce the final score. This final score became the basis for the classification of buildings into three categories, namely Safe (≥ 3.0), Need for Further Evaluation (2.0–2.9), and Unsafe (< 2.0). The structure of the form and the RVS scoring mechanism are illustrated in the following Table 1 which refers to the third edition of FEMA P-154 (2015) and has been widely used in similar studies in Indonesia (Agustin et al., 2020; Zamzami, 2020).

Table 1. Building Structure Initial Score Based on FEMA P-154 (2015)

Structure Code	Structure Type	Initial Score
W1	Single-storey wood	3.0
W2	Multi flooring wood	2.6
C1	Reinforced concrete – Moment-bearing frame system	2.5
C2	Reinforced concrete – Sliding wall system	2.3
RM1	Masonry walls without reinforcement	1.0
RM2	Masonry walls with reinforcement	1.6

Source: FEMA (2015), with adaptation for the context of simple buildings in Indonesia

After obtaining the final score of the RVS method, the analysis is continued with the Fault Tree Analysis (FTA) method to identify the root cause of structural vulnerability. FTA is carried out by mapping the "top event" in the form of building collapse due to an earthquake, then elaborating it into three levels of causes: (1) failure of the main structure (e.g. missing fastening columns, foundations not up to standard), (2) weakness of non-structural elements (cracked walls, heavy roofs), and (3) environmental factors (proximity between buildings, soft soil, location in active fault zones). FTA uses logical symbols such as AND and OR to show the relationships between events that contribute to collapse (Arman et al., 2022; Nugroho et al., 2021). The error tree diagram is compiled based on the results of observations and field documentation.

The stages of this method as a whole can be described in the Research Flow Diagram in Figure 1, which shows the sequence starting from problem formulation, primary data collection through field observation and filling out the RVS form, structural analysis using the RVS and FTA methods, to the interpretation and recommendation stages. This combination of visual methods and deductive logic allows for the quick and accurate identification of high-risk buildings and the causes of their structural failures. The results of this method are not only used to provide technical recommendations for improvements, but also for the preparation of region-based disaster mitigation strategies (Syaifuddin et al., 2020).

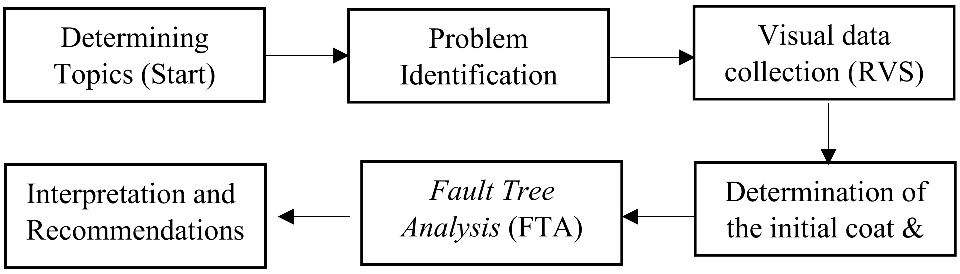

Figure 1. Research Flow Diagram
Source: Analysis results (2024)

RESULTS AND DISCUSSION

The results of this study were obtained through the evaluation of 30 simple house units spread across three sub-districts in the West Surabaya area, namely Tandes, Asemrowo, and Sukomanunggal. The evaluation was conducted using the Rapid Visual Screening (RVS) method based on FEMA P-154 (2015) guidelines. Each house was visually observed and an initial score was recorded based on the type of structure, then given a correction factor based on actual conditions on the ground. Final data in the form of final scores from each house show an overview of the level of vulnerability of buildings to earthquakes in this region.

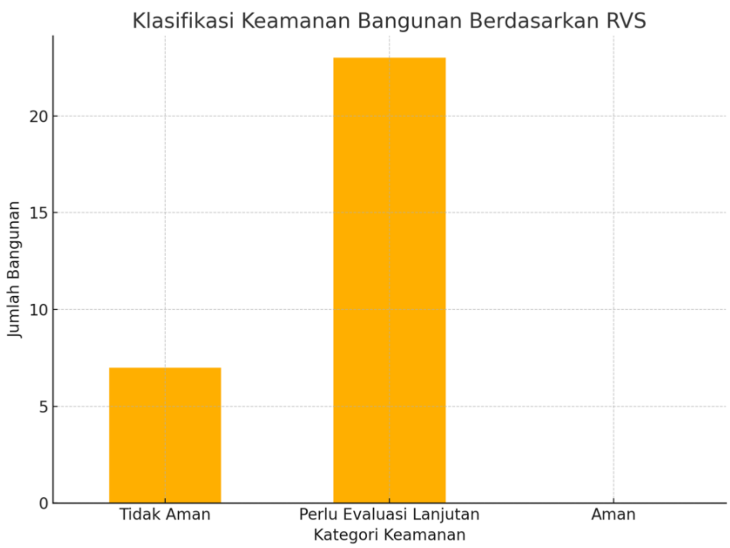

Figure 2. Building Security Classification Bar Diagram
Source: Results of RVS analysis based on field data (2024)

Of the 30 houses reviewed, the results of data processing showed that as many as 7 houses (23.3%) were categorized as unsafe buildings with an RVS score of less than 2.0. Meanwhile, as many as 23 houses (76.7%) were classified into the category of needing further evaluation with scores ranging from 2.0 to 2.9. None of the homes in the study obtained a ≥ score of 3.0 indicating structural safety conditions against earthquakes. This means that all buildings in the study area have a significant risk of damage in the event of an earthquake.

If reviewed per sub-district, Tandes District has 3 houses with a score of < 2.0, Asemrowo District has 3 houses, and Sukomanunggal has 1 house that is included in the unsafe category. The rest, all remaining houses are in the category of needing further evaluation. This suggests that the level of vulnerability was fairly evenly distributed across all three study sites, albeit with slightly varying intensities and building characteristics.

One of the dominant factors that causes a low RVS score is the condition of the building foundation that does not meet standards, especially in buildings that are built independently without technical supervision. In some cases, the foundation is not visible at all, or is built with a depth and width disproportionate to the vertical and lateral loads of the building. This is the main trigger for the risk of structural failure when there is soil movement due to an earthquake.

In addition to the foundation, the absence of vertical and horizontal fastening columns is another cause. Many buildings do not have adequate sloof beam structures, practical columns, or beam rings, so they do not have enough lateral rigidity to withstand the force of an earthquake. When a tremor occurs, buildings like this are very prone to cracks in the walls or even collapse partially due to unrestrained shear forces.

In terms of materials, the majority of buildings use red brick without reinforcement as the main structural wall. This material is very commonly used in the construction of simple residential houses, but it has significant weaknesses to dynamic forces such as earthquakes. The absence of reinforcement on the walls causes the structure to be very fragile and easily collapse, especially when combined with heavy roof elements such as clay tiles.

The age of the building also affects the final value of the RVS. Many of the buildings observed are more than 20 years old, meaning they were built before the enactment of modern earthquake-resistant building standards. The age of an old building is generally accompanied by a decrease in material quality, corrosion of the structural joints (if any), as well as natural deformation that increases the vulnerability of the structure to shocks.

In terms of building configuration, many buildings with asymmetrical geometry are found—for example, L, U, or elongated buildings with uneven load distribution. Configurations like this tend to generate torsional forces during an earthquake, which increases the chance of structural damage, especially if not balanced with the design of a balancing structure such as a shear wall or core system.

In addition to the technical aspects of the structure, the distance between buildings that are too close or even sticky to each other is also a potential problem. In this condition, if one building collapses, there is a potential domino effect that causes other buildings to be affected. This is exacerbated by the irregularity of height between buildings that trigger vertical impacts when there is a ground shift.

The results of filling out the questionnaire also show that the public's perception of the vulnerability of structures is still low, especially in the lower aspect (foundation) compared to the upper part (roof structure). Respondents were more worried about the possibility of collapse from above due to roof collapse, but were less aware of the importance of strengthening the foundation and the connections between the structural elements of the building which are the main determinants of stability when an earthquake occurs.

Fault Tree Analysis (FTA) shows that the main cause of building collapse in this region is the main structural failure, followed by the weakness of non-structural elements, and finally environmental factors. Foundation failure, absence of fastening columns, and the use of weak walls are a combination of factors contributing to low scores in RVS. This reinforces that the handling of key structures is the highest priority in earthquake mitigation strategies in urban areas.

Field observations also found that many homes were built with very short turnaround times and with minimal cost, so many important processes in construction such as structural bonding, load planning, and material strength tests were bypassed. This has an impact on the final quality of the structure which is far from the standard of earthquake-resistant buildings.

From the overall analysis, it can be concluded that the reliability level of simple house buildings in the study area is in critical condition. All samples cannot be categorized as structurally safe, so mitigation measures need to be taken in the form of structural reinforcement (retrofitting), technical education of the community, and updates to regional regulations related to the construction of residential houses in active fault zones.

To clarify the distribution of building safety levels based on the results of the RVS evaluation, the following diagram presents the number of buildings based on the final classification. As can be seen, the majority of buildings are in the category of needing further evaluation, which technically still has the potential to collapse if not addressed immediately.

Discussion

The findings of this study show that all the houses studied in the West Surabaya area did not meet the safe threshold according to the Rapid Visual Screening (RVS) method from FEMA P-154 (2015). These results reflect the critical conditions for the structural readiness level of simple houses in areas identified as being on active fault lines such as the Kendeng Fault. The absence of houses with an RVS score of ≥ 3.0 indicates that no single unit meets the minimum standards of earthquake resistance, a situation that is in line with previous reports on the weak technical standards of residential buildings in Indonesia, especially in the non-public building category (Firdaus et al., 2020). In the context of rapid urbanization in a city like Surabaya, this finding is an important alarm for local governments and disaster authorities.

Furthermore, the analysis of structural elements shows that the dominant factor that causes a low score in RVS is the absence of structural fastening systems such as practical columns, beam rings, and sloofs. These elements are the backbone of the structural reinforcement system of low-rise buildings in order to withstand lateral forces during earthquakes. Buildings without vertical or horizontal fasteners will be particularly vulnerable to wall collapse and horizontal deformation. As revealed by Rinaldi et al. (2021), a free-standing masonry wall structure without a fastening truss system has a risk of collapse up to 70% greater in the event of a seismic event compared to buildings with a fastening system. The absence of this system, as found in the field, is not only the result of technical negligence, but also the limited knowledge and resources of the building owner.

The age factor of the building is another important variable in determining the final score. Buildings that have been established for more than two decades generally do not meet the latest technical requirements such as SNI 1726:2019 concerning Earthquake Resilience Planning Procedures for Building and Non-Building Structures. Apart from the fact that there were no adequate earthquake technical standards during its construction, the age of the building also worsened the condition of the structure through material degradation and the resistance of the joints between elements. Wicaksono et al. (2022) stated that building materials such as mortar and bricks have decreased in strength by up to 30% after 25 years, especially if routine maintenance is not carried out. On the ground, the majority of the buildings reviewed were over 20 years old and showed no signs of having been structurally rehabilitated.

The Fault Tree Analysis (FTA) used in this study also demonstrated the effectiveness of the deductive logic approach in delineating structural failure pathways. By starting from the peak event of an earthquake-induced building collapse, the FTA helps to group the main causes into three broad categories: major structural failures, weakness of non-structural elements, and environmental factors. This method provides clarity of the relationships between events in complex building systems, so that critical points that require technical intervention can be identified. Hidayat et al. (2020) emphasized that the use of FTA in the evaluation of existing buildings strengthens the diagnosis of structural risk because it facilitates a systematic approach, especially in buildings without initial structural design data such as residential houses.

Non-structural elements such as heavy roofs and filler walls are also contributors to vulnerability, although they do not directly cause the collapse of buildings. In this study, it was found that almost all houses use conventional clay tiles with a sitting system without fasteners. The high roof load increases the inertial load during an earthquake, which adds lateral force to the wall. If the wall is not designed as a lateral load-bearing system (e.g. in the absence of vertical reinforcement), then the wall will experience sliding cracks or even collapse. This is strengthened by research by Prasetya et al. (2022) who found that roof load is one of the most influential factors on the base shear force in single-storey buildings with masonry walls.

Environmental factors are also no less important. Some of the houses observed stood very close together, even sticking to each other without gaps. This causes the potential for collisions between buildings when there is a horizontal shift due to an earthquake. This phenomenon is known as the pounding effect, which is the additional damage caused by the impact between two adjacent buildings that have different dynamic responses. Nugraha et al. (2020) in urban earthquake simulations showed that distances between buildings of less than 0.5 meters increased the risk of damage by more than 50%, especially in buildings with different heights or rigidities. In addition, the study area is in alluvial soils with a medium to high liquefaction potential index, based on a study by Syaifuddin et al. (2020), thereby worsening the stability of the foundation structure.

Finally, the results of surveys and interviews show that most building owners do not have a technical understanding of the importance of earthquake-resistant buildings. Aspects of cost, speed of construction, and technical knowledge are the main obstacles in the implementation of security-based construction. This is in line with the findings of Maulidah et al. (2021) who stated that people in dense urban areas prioritize the function and aesthetics of the house over reinforcing structures. In this context, public education is a crucial factor to reduce the structural vulnerability of residential buildings in disaster-prone zones.

The irregularities of the shape and structural system of buildings are a serious issue in the assessment of seismic vulnerability. Many of the houses in the study area had asymmetrical building shapes—either due to unplanned space additions or the original elongated and unbalanced shape in mass distribution. This irregularity causes the center of mass and the center of stiffness of the building to not compress, so that the force of the earthquake will cause a torsional moment that increases the risk of cracking and local collapse. Research by Anwar et al. (2021) corroborates this by stating that asymmetrical buildings in high earthquake zones exhibit a much more extreme dynamic response than symmetrical buildings, even when using similar materials and construction systems.

In terms of policy, there are still large gaps in the regulations governing the construction of residential houses in earthquake-prone areas. Residential houses are not included in the category of public buildings that are required to undergo periodic technical audits or meet special earthquake-resistant provisions, in contrast to educational, health, or other public facilities. Supriyanto et al. (2021) noted that the majority of houses in Indonesia were built without the assistance of construction experts and did not have a validated structural plan. This is an irony in the midst of the government's efforts to encourage community-based disaster resilience, but without being equipped with a strong regulatory infrastructure in the most vulnerable sectors.

When a building is designed without regard to the integrity of the structural system as a whole, the strength of each element becomes useless. This is exacerbated by the lack of mechanical connections between building elements. In this study it was found that most of the joints between the walls and columns (if any) relied solely on mortar mixes without anchors or metal locks. When lateral forces occur due to earthquakes, this type of joint is unable to withstand the relative shifts between the elements, so the building structure loses its completeness completely. Prasetya et al. (2022) refer to weak joints as a "tipping point" in the collapse of the structural system of non-frame buildings.

The community's reluctance to use the services of structural experts also worsened the condition. Economic aspects, distrust, and lack of construction education cause most houses to be built only based on the experience of local builders. In fact, the trial-and-error approach in construction without structural testing is very risky in areas with high seismic activity. Maulidah et al. (2021) emphasize that even though homeowners understand the importance of security, they still do not use professional services because they consider it an "non-mandatory" expense.

The integrative approach between visual assessment (RVS) and deductive logical analysis (FTA) in this study has been proven to provide more comprehensive results. RVS allows for rapid identification of structures that have high vulnerability, while FTA provides a detailed cause-and-effect description of system failure paths. Hidayat et al. (2020) show that the combination of these two methods is very effective in densely populated areas, as it provides data-driven results that can be processed into the basis for technical recommendations and mitigation policies.

The impact of structural vulnerability is not only on physical damage, but can also have implications for the social and psychological aspects of society. After an earthquake event, buildings that look fragile or have suffered cracks will cause prolonged fear of residents, even when no major damage has occurred. This sense of insecurity reduces the quality of life and people's trust in the residential environment. Therefore, in addition to the civil engineering approach, mitigation programs must also involve a psychosocial approach and active communication of disaster risk (Wicaksono et al., 2022).

By looking at the overall data and field findings, it can be concluded that earthquake risk mitigation in dense areas such as West Surabaya is not enough just through counseling or new development. It is necessary to conduct a systematic structural audit of existing buildings using methods such as RVS and FTA, then the results are followed up with a small-scale retrofit program that is in accordance with the economic capacity of the residents. Local governments can work with universities or professional associations to develop a community-based technical assistance model as has been done in Yogyakarta and Padang after the major earthquake.

CONCLUSION

This study successfully identified key factors driving the structural vulnerability of simple houses in earthquake-prone West Surabaya, including missing structural fasteners, unreinforced masonry walls, shallow non-standard foundations, heavy roofing, and irregular building designs, with none of the 30 evaluated houses meeting safety standards. Using the combined Rapid Visual Screening (RVS) and Fault Tree Analysis (FTA) methods, the research establishes a data-driven framework to prioritize retrofitting and policy measures, aiding local governments in updating building regulations and guiding community education on earthquake-resistant construction. For future research, it is suggested to expand the study to include a larger sample size across different regions and integrate socio-economic factors more deeply, as well as investigate the cost-effectiveness and long-term impact of various retrofitting techniques to further enhance seismic risk mitigation strategies in similar urban settings.

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