HAVE THE EARTHQUAKE RESILIENT INDONESIAN TRADITIONAL HOUSES BEEN STUDIED ENOUGH?

APAKAH RUMAH-RUMAH TRADISIONAL INDONESIA YANG TAHAN GEMPA SUDAH CUKUP DIPELAJARI?

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Abstract

Indonesia possesses hundreds of traditional house typologies due to its vast cultural diversity of more than 500 ethnic groups. Many of these structures, especially in earthquake-prone regions, have demonstrated remarkable seismic resilience. Despite these ingenious structural adaptations, modern earthquake-resistant building technologies in Indonesia rarely draw inspiration from traditional architecture. This raises a fundamental question: Is there a lack of compatibility between traditional structural knowledge and contemporary building practices, or is the limited technological development primarily due to insufficient research on this topic? To address this issue, this study aims to identify the 'missing link' between traditional earthquake-resistant principles and modern buildings in Indonesia. This study conducts a systematic literature review of peer-reviewed publications to assess the current state of research on the seismic-resistant features of Indonesian traditional houses. Two complementary analyses are employed. The first is a bibliometric analysis of publications indexed in Scopus between 1981 and 2025, examining parameters such as publication trends, citation counts, and journal impact factors. The second is a narrative review focusing on structural aspects, including spatial layout, structural system (substructure and superstructure), and traditional timber joinery systems, to map prevailing discourses and identify knowledge gaps. The bibliometric analysis reveals a total of 38 Indonesian publications compared to 71 Japanese publications, indicating a significant disparity in both quantity and methodological depth. Most Indonesian studies rely on qualitative descriptive methods, while quantitative approaches such as experimental or numerical analysis remain scarce. The narrative review identifies two major gaps: (1) a material–construction gap, where traditional timber-based structures face challenges in modern application, and (2) a methodological gap, where research remains phenomenon-driven rather than systematically quantified. These findings suggest that the limited technological advancement is less a matter of incompatibility between traditional and modern structures, and more a reflection of insufficient, underdeveloped research methodologies in the Indonesian context.

Keywords: Traditional architecture; Earthquake resistance; Building structure.

INTRODUCTION

As an archipelagic country, Indonesia possesses a high degree of diversity, encompassing biodiversity, the variety of visual landscape characters (Gunawan et al., 2019), geographical conditions, cultural traditions, and social backgrounds (Sari et al., 2024). All these diverse elements interact with one another to shape the tropical character of Indonesia's traditional landscapes (Gunawan et al., 2019), one of which is reflected in the rich legacy of its traditional vernacular architecture (Winiarti et al., 2022; Sari et al., 2024). This traditional architecture not only embodies local wisdom but is also highly responsive to sustainability issues (Lindarto & Harisdani, 2024). Its sustainable characteristics are evident in design principles, construction techniques, and material selection preferences that are closely aligned with the natural environment (Sari et al., 2024). The typology of construction developed in a particular region is generally influenced by various factors, including geological and geographical characteristics, climatic conditions, socio-economic levels of the population, availability of materials, skills of construction labor, and the history of natural disasters that have occurred in the area (Lang et al., 2018).

Indonesia is inherently an earthquake-prone region. This condition is influenced by its geographical location at the convergence of three major active tectonic plates of the world (Saptaningtyas et al., 2023). This unique geographical setting has formed fault lines and one of the most active volcanic arcs in the world (Aryadi et al., 2024). Based on model analyses of 8,000 earthquake events that occurred in Indonesia within a single year, the Meteorology, Climatology, and Geophysics Agency (BMKG) reported that 350 of these were significant earthquakes felt by the population, with 15 of them causing severe damage (Razzaq et al., 2025). In the case of Indonesian traditional houses, construction techniques that have evolved over hundreds of years have demonstrated a remarkable ability to adapt to natural disasters and changing times (Saptaningtyas et al., 2023).

Various articles, reports, and field observations on structural elements rooted in local wisdom have demonstrated their effectiveness in protecting buildings against natural disasters, including earthquakes (Sari et al., 2020). Indonesian traditional houses, which often use timber as their primary construction material, were not originally designed with modern structural engineering considerations. Nevertheless, they have proven to withstand seismic shocks without causing serious damage to their structural components (Karina et al., 2018). One example can be seen during the 2014 earthquake in Pidie Jaya. Several modern concrete mosques collapsed, while traditional timber mosques remained standing with only minor damage that was easy to repair (Sari et al., 2020). In Aceh, earthquakes with magnitudes ranging from 6.5 to 9.0 were able to crack and topple conventional reinforced concrete buildings. Interestingly, there were no reports of the collapse of houses using mortise and tenon joints, which are commonly found in traditional timber constructions (Nursaniah et al., 2022). The weakness of modern construction was not only evident in Aceh. The 2018 earthquake in Palu also revealed the vulnerability of reinforced concrete buildings, with most failures occurring at beam–column joints and in infill masonry walls (Nursaniah et al., 2022). In contrast, most traditional houses in Sulawesi remained intact (Sari et al., 2024). A similar situation occurred in Bali during the 1976 earthquake. Modern constructions suffered significant damage, while Meru structures, which are found in major Balinese temples, remained strong and stable (Dwijendra, 2020). Joglo houses in Yogyakarta, traditional buildings that have existed since the sixteenth century, were also found to have survived the earthquakes in 2001, 2004, 2006, and 2023 without structural damage (Pranata et al., 2025).

On the other hand, Japan has a geographical context that is quite similar to Indonesia because it is located along the Asian Ring of Fire. It is one of the countries with the highest levels of seismic activity in the world. In addition to earthquakes and tsunamis, this archipelagic nation is also vulnerable to typhoons and volcanic eruptions. These conditions have made Japan one of the most disaster-prepared countries, supported by strict building regulations designed to prevent infrastructure collapse during earthquakes (Schreurs, 2021). As a pioneer in disaster management, Japan’s strategies, particularly in responding to earthquakes, have significantly shaped practices and inspired policies at the global level (Zaré M & Ghaychi Afrouz S, 2012).

Japan has a long history of developing various earthquake-resistant construction techniques. This is reflected in traditional Japanese houses, which were designed using a flexible assembly system. This system allows the building structure to move in a controlled manner during seismic events, thereby dissipating vibrational energy. Traditional architectural knowledge has been adapted and refined in the modern context to create earthquake-resistant buildings. For example, the construction of the Tokyo Sky Tree (634 m) adopted the Shimbashira-Seishin technique, or central column vibration control, which had already proven effective in five-story pagoda structures. In the case of the Tokyo Sky Tree, this traditional technology was further developed by combining it with passive and active control systems. The result is a hybrid seismic resistance technology that makes the tower one of the safest structures in the world in its height class (Bock et al., 2011). In this study, Japan serves as a comparative background to highlight the potential for modernizing traditional seismic wisdom in Indonesia. While Japan has successfully evolved these techniques into advanced systems, a similar integration remains absent in Indonesia. This disparity raises a critical question: If Japan can evolve traditional techniques into advanced seismic systems, why has Indonesia not achieved the same? Consequently, investigating the compatibility of Indonesian traditional structures with modern practices is essential to bridge this technological gap.

While several systematic reviews have explored traditional building structures, specialized discussions focusing on Indonesian traditional buildings remain scarce. This research gap presents an opportunity to investigate the compatibility between traditional earthquake-resistant technologies and contemporary construction. The primary objective is to identify the 'missing link' between traditional earthquake-resistant principles and modern buildings in Indonesia, focusing on substructures, superstructures, connection systems, and spatial layouts. Therefore, this study provides a comprehensive literature review of local seismic-resilient wisdom in Indonesian traditional architecture.

SEARCHING STRATEGIES

This study employs a systematic review method with a structured approach to identify, select, and analyze literature on earthquake-resistant structural technologies in traditional buildings in Japan and Indonesia. This method was chosen for its advantages in reducing potential selection bias and providing results that are consistent and replicable (Rahman et al., 2024). The systematic literature review follows a rigorously established protocol, including search strategies, inclusion and exclusion criteria, and data extraction procedures, thereby minimizing the risk of bias arising from author preferences and opinions (Chinn, 2021). Nevertheless, the researcher acknowledges that certain biases may still influence the outcomes of this review, stemming from publication tendencies, selection criteria, and external factors such as author proactivity, positionality, rhetorical strength, or data-driven articles that may lead to overestimation of findings. The Scopus database was selected as the primary source for this review due to its comprehensive coverage of publications related to traditional architectural construction. The search strategy in this study was formulated as follows.

Name of database	: Scopus
Period of data	: from 1981 to 2025

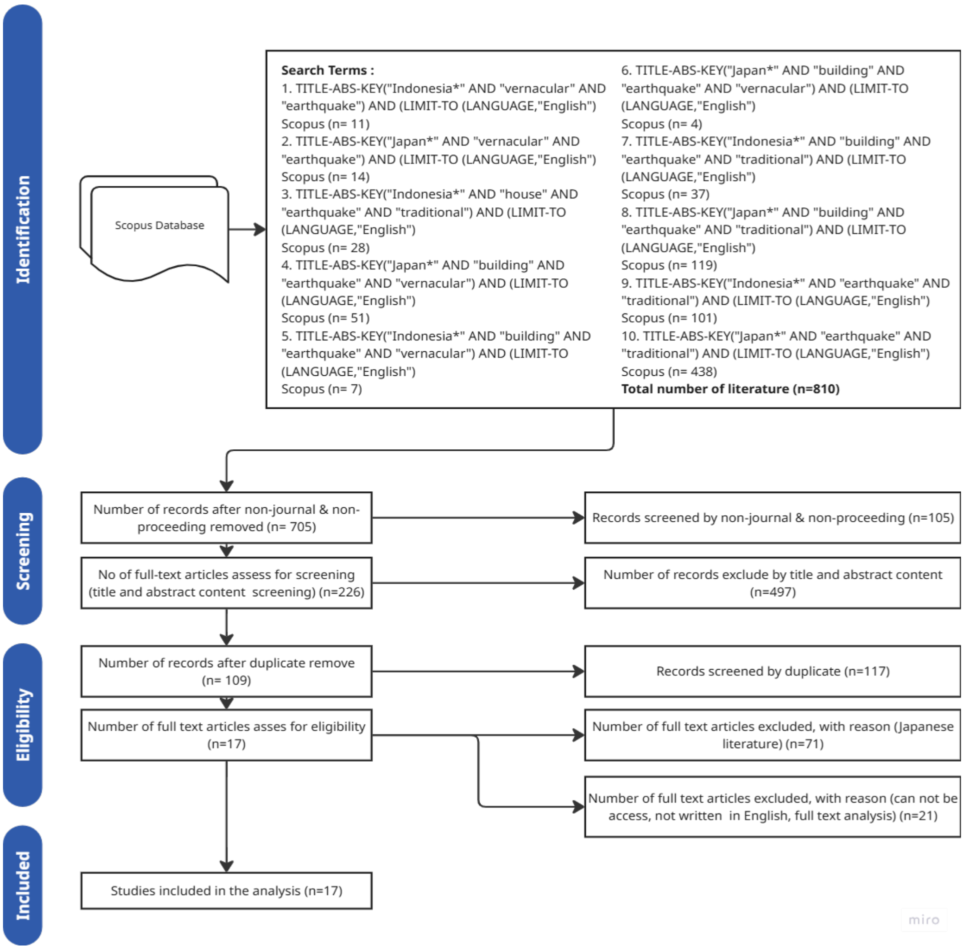

Figure 1. The Process of Selecting Studies in The Review

The search strategy was designed to capture a broad range of literature while remaining relevant to the objectives of this systematic literature review. The keywords and phrases used in the search terms were as listed in Figure 1. The terms, including 'traditional', 'vernacular', and 'local wisdom', were utilized primarily as search strings to maximize literature retrieval rather than as the central focus of semantic debate. By employing these terms interchangeably in the search strategy, the review ensures a comprehensive capture of relevant studies across different terminological preferences in the existing literature. To ensure a systematic and transparent methodological process, the literature search was conducted on July 16, 2025. Repeating the search after this date may yield additional documents published subsequently. The selection process involved two main stages, namely screening and eligibility assessment. In the initial stage, after obtaining the literature using the search terms, document types other than journal articles and conference papers were excluded. In the next stage, titles and abstracts were reviewed to remove studies that were not relevant to the topic of structural aspects in traditional buildings. Because the search terms often returned duplicate records, repeated journal entries were also excluded. The remaining articles were then reviewed in full to assess their eligibility based on predefined criteria. These two steps ensured that only literature relevant to the objectives of the review was included for further in-depth analysis.

After the literature selection process, the synthesis phase involved systematically analyzing and summarizing the findings from the selected studies to extract meaningful insights and recognizable patterns. Based on the systematic review methodology, a total of 38 Indonesian articles and 71 Japanese articles published between 1981 and 2025 were included in the bibliographic analysis. For the in-depth content analysis, only Indonesian literature was examined after duplicate articles had been removed in the previous stage. Out of the 38 papers, one article was excluded because it was not written in English, twelve articles were excluded due to lack of full-text access, and eight articles were excluded because their content was not sufficiently relevant to the structural context of traditional houses. As a result, seventeen Indonesian articles were included for detailed content analysis. This paper is systematically structured into four primary stages to map the seismic resilience of traditional architecture. It begins with a Bibliometric Analysis (Section 3) to examine Japanese and Indonesian publication trends, followed by General Insights (Section 4) into research methodologies and the role of local genius in disaster response.

The core discussion is presented in Structural & Architectural Insight (Section 5), which provides a comprehensive technical breakdown of building layouts, substructures, superstructure systems (column-beam and roof construction), and joinery systems transitioning toward modern interlocking techniques. These analyses are synthesized in a Summary of Findings to inform the Conclusion (Section 6), which addresses existing research gaps and future directions for earthquake-resistant technology.

BIBLIOMETRIC ANALYSIS

Figure 3 illustrates the fluctuating pattern of literature publications from 1981 to 2025 on the selected research topic. The line chart below shows the number of publications produced each year in Indonesia and Japan. A consistent upward trend in publication output is not evident in the graph. However, Japan shows an earlier start and a greater volume of research on traditional building structures compared to Indonesia. Based on the publication trends, Japan reached its peak in the number of publications on traditional construction topics in 2015. In the following years, there was a steady decline in research interest, and in the past two years no publications on similar topics were found.

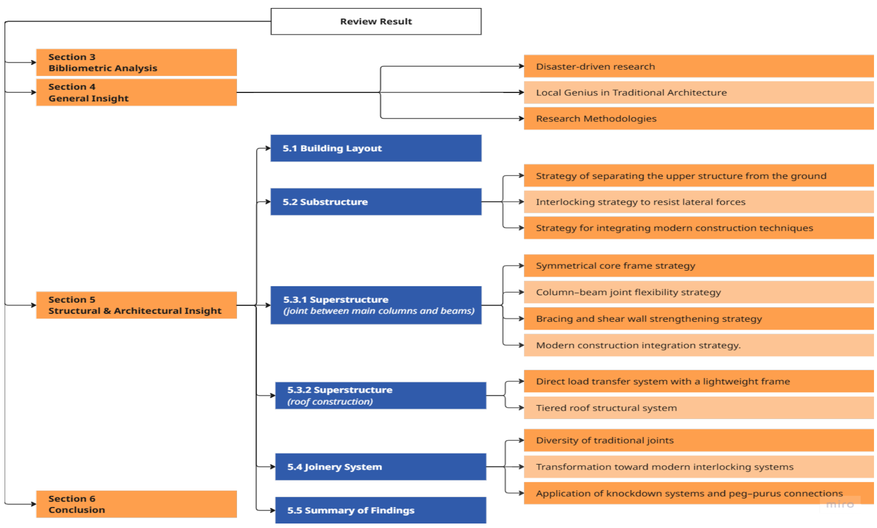

Figure 2. Topic Studied in The Review

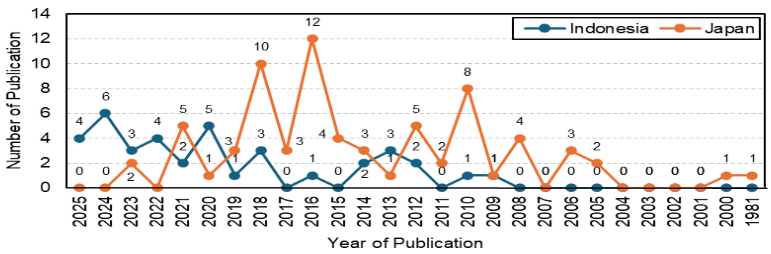

Figure 3. Number of Publication per Year in Indonesia and Japan

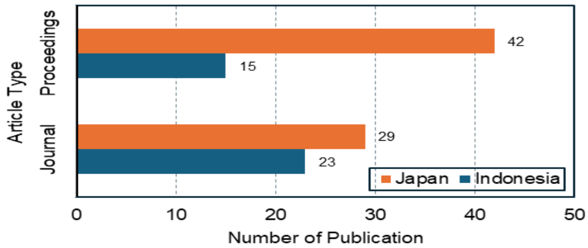

Figure 4. Article Type of Indonesia's and Japan's Literature

In contrast to Japan, Indonesia has only recently begun to show an upward trend in research interest on traditional building construction. Figure 3 also indicates that in Indonesia this research field has experienced varying levels of interest over time, with a general tendency toward growth. In this Systematic Literature Review (SLR), the types of publications used consist of journal articles and conference papers or proceedings. These two types of studies were selected because they are published in peer-reviewed journals and conference proceedings, which are prioritized due to their methodological rigor and ease of access (Higgins et al., 2021). In addition, these types of literature are widely considered the primary and most reliable sources for systematic literature reviews (Garousi et al., 2019). Figure 3 presents a comparison of the number of publications on traditional building construction between journal articles and conference papers in Japan and Indonesia. The data show that the proportion of journals to proceeding publications is higher in Indonesia than in Japan. Although the total number of journal articles in Indonesia and Japan is relatively similar, Japan has a greater number of publications that are still in the form of conference proceedings.

Based on the range of citation counts for each publication, no significant differences were found between the Indonesian and Japanese studies. In both cases, the literature is still dominated by publications with fewer than three citations. The analysis of journal credibility reveals that while all retrieved publications are Scopus-indexed, a significant portion of them are featured in journals without an official Web of Science (WoS) indexing. However, Japanese research shows a stronger positioning in the global scientific community, as 20.8% of the articles retrieved in this review are published in WoS-indexed journals, compared to only 9.5% for Indonesia. This indicates that while both countries rely heavily on Scopus-indexed platforms, Japanese studies tend to attain higher visibility and recognition within the more selective WoS-indexed journals.

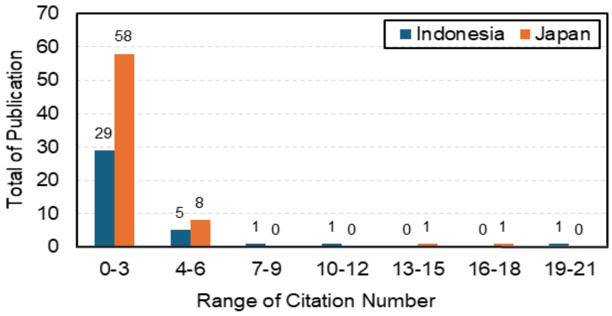

Figure 5. Range of Citation Number of Indonesia's and Japan's Literature

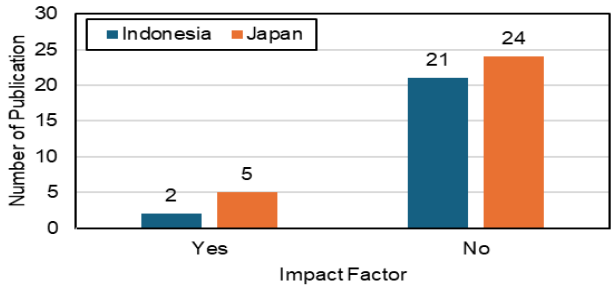

Figure 6. Journal with Impact Factor of Indonesia's and Japan's Journal Publisher

GENERAL INSIGHT

From the 17 screened literatures, the rationale for selecting traditional architectural objects was based on observed natural disaster events and their impacts on buildings, including both structural resilience and supporting aspects. Other studies, however, framed their research background around the inherent values embedded in traditional architecture. The unique local wisdom specific to each location served as the starting point for these investigations.

Research on traditional building structures in Indonesia has been conducted across 17 locations; however, Kalimantan and Papua are noted as major islands where no studies on earthquake-resistant structures have been found among the five largest islands in Indonesia. The provinces of Aceh, North Sumatra, South Sumatra, South Sulawesi, West Java, Yogyakarta, Bali, East Nusa Tenggara (NTT), and West Nusa Tenggara (NTB) have frequently served as the context for research on earthquake-resistant traditional buildings. Major earthquakes that have occurred in these provinces are repeatedly discussed across different studies, including the Aceh earthquakes in 2004 and 2016, the Palu earthquake in 2018, and the Yogyakarta earthquake in 2006. These destructive seismic events have prompted research on traditional building structures, which have proven to be more resilient to earthquake shocks compared to modern buildings.

The unique elements of local wisdom from each region in Indonesia are involved in nearly all 17 reviewed studies. Local wisdom is knowledge formed from real-life experiences of communities, modified and passed down across generations through traditions (Sari et al., 2020). This local wisdom encompasses ideas or practices rooted in the core values of a community, repeatedly applied, believed to serve as a guide for life, and transmitted over time (Sari et al., 2020). Thus, local wisdom can be understood as human efforts to respond to various objects, events, or phenomena in a particular environment using rational thought. In Indonesia, traditional knowledge has been proven capable of creating safer living environments by significantly reducing disaster risks. A comprehensive approach to environmental and socio-cultural aspects has traditionally been applied in settlement planning and housing, supporting community life for centuries (Dayaratne, 2018). Vernacular building technology demonstrates adaptive capacity to environmental changes and sustainability due to its contextual responsiveness to local climate, materials, and culture. Therefore, engaging in a dialogue with past traditions is necessary in contemporary architectural design to ensure its continuity (Nursaniah et al., 2022).

According to Sari, L.H. et al. (2020), there are four main principles of local wisdom that can be applied in contemporary architecture. First, local wisdom should be integrated with an understanding of the surrounding natural and cultural context. Second, local wisdom is dynamic and capable of adapting to global developments. Third, its application must provide tangible benefits, such as increasing income, reducing costs, supporting production efficiency, and improving the quality of community life. Fourth, local wisdom is generally simple yet comprehensive, often transmitted orally, aligned with local conditions, culture, and environment, while remaining flexible to accommodate community needs, resource availability, and changing times.

The selection of materials in traditional buildings can be identified as an element of local wisdom, repeatedly discussed in several studies. The use of ulin wood (ironwood) in the traditional houses of Nusa Tenggara Timur, Sa'o Ria, reflects local wisdom that considers the availability and abundance of materials in the surrounding environment (Razzaq et al., 2025). Still in NTT, locally sourced palm wood (*Borassus flabellifer*), which is widely available, is also used as the primary structural material in Ammu Hawu traditional houses (Karina et al., 2018). In the Sasak traditional buildings of Lombok, NTB, tinus wood is commonly used as a structural column element (Saptaningtyas et al., 2023). A similar practice occurs in the Gayo highlands, Aceh, where the abundant Surenwood (*Toona sureni*) is utilized as material for various building types in Blangkejeren (Sari et al., 2024).

In addition to the locality aspect of materials, their strength and durability have also been a focus of study in Indonesian literature. In the traditional houses of South Nias, Omo Hada and Omo Sebua, the use of local woods such as Afoa, Berua, Manawado, Siholi, and others has attracted research interest from Japanese scholars. It is noted that Afoa wood has a compressive strength comparable to that of Japanese wood, while Berua and Manawado are two to three times stronger than the woods commonly used in Japan (Razzaq et al., 2025). The use of ulin wood (ironwood) as a supporting material for columns in the traditional Sa'O Ria buildings is considered to enable a flexible yet robust structural design. Ulin wood effectively secures column connections by safely transferring forces without causing local failure and helps reduce major stresses from earthquakes. Moreover, its elastic properties allow it to absorb seismic energy without resulting in sudden failure. This wood is also resistant to extreme environmental conditions, such as high humidity and infestations by pests or wood-boring insects (Razzaq et al., 2025).

The use of lightweight materials such as wood and bamboo is also highlighted in the traditional Sundanese buildings, Imah Panggung. The central part of the wood is known for its ability to resist compression, while the outer part can resist tension, making wood an excellent building material. A similar advantage is observed in bamboo, which is abundant and has potential for use in various building elements, including interior, exterior, and structural components (Maknun et al., 2016). In the traditional Bugis-Makassar houses, locally sourced woods such as teak, ironwood, meranti, and bitti are considered more flexible than hardwoods, enabling them to better absorb seismic vibrations compared to pine and cypress used in traditional Chinese buildings (Aryadi et al., 2024).

Among the 17 studies on the earthquake resistance of traditional building structures in Indonesia, eight employed a qualitative approach, four used a quantitative approach, and five applied mixed methods. The literature in Indonesia is dominated by qualitative approaches with the objective of using descriptive-exploratory methods, employing data collection techniques such as observation, interviews, and literature review. In contrast, the fewer quantitative studies primarily utilized experimental methods, simulations, computational studies, and behavioral analysis. Qualitative approaches are essential for understanding the cultural context and local construction practices; however, in Indonesian literature, few studies are accompanied by measurable quantitative analyses, such as experimental testing, shaking table tests, or numerical modeling.

This situation contrasts with Japanese literature, which has extensively studied the seismic behavior of traditional buildings using systematic experimental and analytical approaches supported by strong empirical databases. Quantified research offers advantages in the construction field, as it produces numerical data that can be standardized, compared, and replicated. Moreover, this approach facilitates the rapid transfer of technology from the laboratory to the field, as tested designs or techniques can be modified and mass-produced with measurable reliability.

The difference in research paradigms between Indonesia and Japan is suspected to be a contributing factor to the technological innovation gap in earthquake-resistant construction. Indonesia still relies heavily on local wisdom that is insufficiently quantified, whereas Japan has transformed traditional knowledge into the engineering foundation of modern building structures.

STRUCTURAL & ARCHITECTURAL INSIGHT

The studies on traditional building structures across 17 locations in Indonesia reveal considerable diversity. In addition to research focusing on the overall structural system of traditional buildings, some studies highlight specific components, such as joint systems. Several investigations explore the potential integration of traditional and modern construction materials. Studies on evacuation space programs have also been conducted in traditional building case studies. Beyond examining structural strength or earthquake resistance, some studies include analyses of passive design performance, such as ventilation, lighting, and acoustics, within the same literature alongside structural evaluations. This diversity in research focus reflects the character of Indonesian studies, which generally aim to uncover multiple aspects of traditional knowledge simultaneously within a specific traditional building. In studies analyzing the entire building structure, discussions are typically divided into three areas: foundation, columns and beams, and roof construction, with some also detailing the joint systems between these components.

Building Layout

Although studies on earthquake resistance in traditional buildings often focus on structural systems, building layout plays an equally important role in determining stability and the movement patterns of occupants during disasters. In the context of Indonesian traditional architecture, spatial configuration is influenced not only by cultural values and daily functionality but also reflects adaptation to specific environmental conditions, namely earthquakes. According to Razzaq (2025), who studied the traditional Sa’O Ria houses in

NTT, in addition to column configuration, building layout is crucial for earthquake safety. Seismic shaking affects the entire structure, so simpler layouts are better able to maintain overall building stability. Conversely, more complex layouts tend to produce uneven structural responses, as horizontal torsion effects are stronger in areas farther from the center of gravity, increasing seismic vulnerability (Razzaq et al., 2025).

Another study on the spatial organization of ten traditional houses among the Bugis-Makassar and Toraja ethnic groups in South Sulawesi found that cultural differences influenced variations in the relationships between frequently accessed spaces and internal circulation. Corridors (tamping) and kitchens were identified as the most frequently accessed areas connecting all spaces, making them the most suitable evacuation zones in Bugis traditional houses. In contrast, in Toraja traditional houses, areas near the main entrance, such as the veranda and stairs, were identified as the best evacuation areas (Sari et al., 2024).

Substructure

The foundation system plays a crucial role in maintaining structural stability against earthquake forces. Key characteristics of foundation systems identified in the literature include flexibility, separation from the ground structure, and the use of non-rigid joint systems that allow the structure to adapt to lateral forces. In general, foundation systems in these studies can be categorized into three main groups based on their earthquake resistance strategies: (1) strategies for separating the superstructure from the ground, (2) interlocking strategies to resist lateral forces, and (3) strategies integrating modern construction techniques.

In the first strategy, the foundation (umpak) is allowed to have no rigid connection with the ground, with columns standing flexibly atop the foundation elements. This principle is applied in the stilt foundations (umpak) of the Indrapuri Mosque and Tengku Dipucok Krueng Mosque in Pidie Jaya, Aceh, enabling the buildings to remain flexible and follow ground movements during earthquakes (Sari et al., 2020). A similar system is implemented in the traditional Sundanese houses, Imah Panggung, using stone umpak in cylindrical (buleud), trapezoidal (lisung), or cubical (balok) shapes, placed directly on the ground or partially embedded. Based on technical analyses of earthquake-resistant building requirements, this foundation system has been shown to meet the prescribed standards (Maknun et al., 2016).

In the second strategy, which adopts an interlocking joint system between the foundation and columns, a locking mechanism is enabled. This strategy is observed in the foundation structures of traditional Joglo houses in Yogyakarta and Bale Tani houses in Lombok. Performance analysis of 20 Joglo houses revealed that the tenon at the end of the column plays a crucial role in maintaining the column’s position atop the foundation. This system allows the structure to withstand lateral forces during earthquakes; however, damage to the tenon may cause the column to shift, potentially leading to total structural failure (Prihatmaji et al., 2013). In Bale Tani, a traditional house in Lombok, the pedestal system employs a knockdown mechanism with a clamp system that secures the column to the foundation. This system allows the building to move flexibly with seismic vibrations and return to its original position once the shaking subsides (Saptaningtyas et al., 2023).

In the third strategy, the integration of modern construction techniques into the foundation elements of traditional building systems was applied in the Sa’o Ria houses in Nusa Tenggara Timur. The use of bore pile foundations in these traditional buildings has been shown to significantly enhance structural resistance, while ensuring compliance with safety standards and reducing potential risks during earthquakes (Razzaq et al., 2025).

Superstructure (Column to Beam System)

The central structural system, consisting of columns, beams, and walls in traditional Nusantara buildings, exhibits diverse strategies for earthquake resistance. These strategies can be classified into four main approaches: (1) symmetrical core frame strategy, (2) column-beam joint flexibility strategy, (3) bracing and shear wall reinforcement strategy, and (4) modern construction integration strategy.

The load distribution strategy through a symmetrical core frame utilizes a configuration of main columns and beams arranged symmetrically to create overall frame rigidity. One example of this traditional building structural system is the Saka Guru, found in traditional mosques in the Gayo highlands, Aceh, and the Soko Guru in Joglo houses in Yogyakarta. Saka Guru or Soko Guru is a structural system commonly observed in traditional mosques across Indonesia (Sari, L.H. et al., 2024). The Soko Guru system consists of four main columns interconnected by binding beams known as Blandar (Pranata et al., 2025). This structural system is considered capable of resisting seismic vibrations due to its load distribution mechanism between the four main columns and the outer columns. The symmetrical arrangement of the four main pillars with the outer pillars provides overall structural rigidity. These main pillars reduce moments on the beams supporting roof loads, thereby enhancing earthquake resistance (Sari et al., 2024).

The structural joint flexibility strategy emphasizes the ability of structural connections to move in a controlled manner during vibrations, thereby reducing the risk of collapse due to excessive rigidity. In the traditional Indrapuri and Tengku Dipucok Krueng mosques in Aceh, wooden peg joints not only connect columns and beams but also reinforce the structure to support roof loads. These joints enable the system to move flexibly in response to seismic movements (Sari et al., 2020).

The reinforcement strategy using bracing and shear walls is employed as an additional element to strengthen the main frame against lateral forces. A study conducted by a group of Japanese researchers on traditional wooden houses in South Nias found that large columns and bracing support living spaces, with structural component connections made entirely without nails.

Transverse beams connecting multiple columns were considered effective in providing resistance against horizontal forces (Sadaka et al., 2013). Another study simulating the collapse of ten Ammu Hawu traditional building models, with variations in the positions of vertical shear walls and bracing elements, found that the main columns on the ground floor are the primary elements supporting the overall structure against seismic shaking. The addition of a bracing system was shown to be most effective in enhancing the strength between structural elements compared to vertical shear walls, thereby improving building stability and earthquake resistance (Karina et al., 2018). Furthermore, in the traditional Bale Tani houses in Lombok, tenon and mortise techniques are used in the connections between wooden beams and columns, reinforced with bracing to increase column and beam stiffness (Karina et al., 2018).

In the same study, the strategy of material modernization was applied not only to the foundation but also by integrating vernacular structural systems with modern technology. Research on the traditional Sa’o Ria houses in Nusa Tenggara Timur (NTT) showed that the use of steel columns significantly enhanced structural resistance while ensuring compliance with safety standards and reducing potential risks during earthquakes (Razzaq et al., 2025).

Superstructure (Roof Construction)

The roof structural system in traditional buildings influences the distribution of vertical and lateral loads to the supporting elements below. The roof shape, materials used, and the connection system between elements determine the roof mass and the transmission of lateral forces during building vibrations. In the literature, two main approaches to roof structural systems are observed. First, lightweight frame systems with flexible joints provide a more uniform response to seismic forces, whereas heavy or multi-tiered roofs require structures capable of distributing loads and maintaining overall stability. Based on load distribution mechanisms and roof structural configurations, roofs can be categorized as follows: (1) direct load transfer with lightweight frames, and (2) multi-tiered roof structural systems.

The direct load transfer system with a lightweight frame is characterized using simple, light, and flexible roof elements. The roof load is transferred directly through the roof frame to the ring beams and columns without passing through a layered support system, resulting in a structure with low mass and joints that allow deformation between elements to absorb seismic forces and prevent sudden structural failure. This strategy is commonly found in traditional vernacular houses, such as the Bale Tani traditional buildings in Lombok. In these buildings, the ring beams are connected using a pen–purus system with a knockdown joint mechanism. The ring beams typically function as ties between columns and transfer roof loads through the rafters. Only a single main truss and bamboo rafters support the thatch roof covering without additional battens (Karina et al., 2018). Similarly, the roof structure of Imah Panggung, a traditional Sundanese house, features a lightweight and simple construction, with a roof frame made of bamboo and wood and a covering of hateup kiray and ijuk (Maknun et al., 2016).

In Bugis-Makassar traditional houses, the roof load transfer mechanism is also direct, with gable roofs being one of the characteristic features. Thick wooden walls and tiled roofs provide additional strength against lateral forces induced by earthquakes. However, if the roof materials are replaced with lighter alternatives such as zinc sheets or palm fiber, the level of protection against lateral forces decreases (Aryadi et al., 2024), highlighting the critical role of material choice in this system. Similar examples can be observed in limasan, kampung, and panggangpe roof types in Java, which rely on simple rafters and battens with traditional wooden joints to directly transfer loads to columns and beams (Ismunandar, 1997). The combination of knockdown joints and lightweight structures makes these traditional buildings more responsive to seismic vibrations.

In contrast to the direct and lightweight structural systems, multi-tiered roof structures rely on the vertical and horizontal distribution of loads through layered roofs, connecting beams, and wooden joints to achieve stability among elements. This system is typically found in religious buildings or noble residences, which feature monumental roof forms with greater mass and more complex structural configurations. In the traditional Meru religious buildings in Bali, the roof is arranged in multiple tiers, with each layer resting on the one below, and the petaka (ridge beam) acting as a tie for the rafters at the top. Roof loads are transmitted downward through the titimamah beams, then transferred to the saka posts as the primary vertical load-bearing elements. Horizontal loads are distributed via the sineb-lambang beams, while the canggahwang (support beams) connect beams to posts to reinforce the structure and enhance its aesthetic value. The wooden joints use mortise and tenon connections with pegs or wedges, along with a clasp and tie system, without nails. The dimensions of all elements follow the Hasta Kosala-Kosali rules, with the lower frame consisting of four corner posts reinforced by side and row posts in large Meru structures, resulting in a robust and stable structural system capable of withstanding various loads, including seismic forces (Dwijendra, 2020).

A simpler multi-tiered roof system can also be observed in the Indrapuri Mosque and Tengku Dipucok Krueng Mosque in Aceh. The traditional design of these mosques features a standard configuration with a three-story roof, where the roof structure is twice the height of the walls and integrated with openings for natural ventilation. In the case studies of these two mosques, the Indrapuri Mosque distributes the roof load evenly across 36 wooden columns. In contrast, the Tengku Dipucok Krueng Mosque has a single main central column supporting the highest tier of the roof. The second-tier roof load is supported by 12 wooden columns, while 20 additional columns carry the load of the lowest-tier roof (Sari et al., 2020).

Based on roof shapes, traditional Javanese houses are classified into four main types: joglo, limasan, kampung, and panggangpe (Ismunandar, 1997). Among these four types, the joglo roof is the most complex and sophisticated in terms of construction systems and wooden joint techniques, whereas the panggangpe roof is the simplest (Tjahjono, 1989). The joglo roof employs a planar system using wide horizontal rafters and wooden battens. There are two main patterns for rafter arrangement (Santosa & Prihatmaji, 2010). The first is the fishbone pattern, in which rafters are installed radially and converge at a single central point. The second is the parallel pattern, in which rafters are arranged in parallel configuration, as the name suggests.

The upper beams support the heavy roof load and are connected through a complex bracket system. The lower beams are installed slightly below the roof height and are interlinked via three-component joints involving columns and beams. The main roof rests on four primary columns that support a bracket system in the form of inner and outer wooden pyramids. The outermost rectangular beams of the outer pyramid (the highest beams) support the rafters of the side roof structures. The rafters are laid horizontally and connected to the highest beams of the outer pyramid using dovetail joints reinforced with wooden pegs.

Joinery System

Wooden joint systems in traditional architecture play a crucial role in maintaining structural performance under dynamic loads, particularly earthquakes. These joints function both as connectors and as structural elements that allow controlled deformation without compromising stability. In general, literature studies on joint systems can be categorized into two main themes: (1) the diversity of traditional joints, and (2) the transformation into modern interlocking systems.

In studies of earthquake-resistant building structures, the critical points are typically located at the joints, specifically the connections between columns and beams. Therefore, in earthquake-resistant buildings, these joints are designed to mitigate seismic vibrations transmitted from the foundation (Saptaningtyas et al., 2023). The diversity of traditional structural joints has been studied in the traditional Ghumah Baghi architecture in South Sumatra. This study identified eight types of joints with a total of 36 variations used across the lower structure, middle structure, and roof structure. Some of the identified joint types include halved joints, lap joints, and two-way neck joints, with the roof structure being the most complex, containing the highest number of construction elements and joint systems compared to other structural parts. The joint types are dominated by roll joints, which are known for their high adaptability to earthquake vibrations and ease of assembly and disassembly. The study also found that technological developments have influenced traditional joint systems, as traditional elements such as pegs, wooden components, and rattan ropes are increasingly being replaced by metal materials, including nails and hinges, as reinforcement for joints (Ibnu et al., 2023).

The application of knockdown systems and the use of pegs and purus are always found and serve as characteristic features of traditional joint systems in Nusantara buildings. For example, in the Bale Tani traditional houses in Lombok, the use of pegs and purus in a knockdown joint system has been identified (Saptaningtyas et al., 2023). Peg-based joints can also be found in the column-beam connections of traditional mosques in Aceh (Sari et al., 2020). In the traditional Sundanese house, Imah Panggung, bonding, purus joints, and pegs are used in the floor frame, walls, and foundations (Maknun et al., 2016). The use of pegs and purus allows the building to move flexibly in response to seismic vibrations.

The transformation of traditional joint principles into contemporary technology is also evident in a study on the adaptation of mortise-and-tenon joints in 18 contemporary houses in Aceh.

This study found that the interlocking concept in brick construction, known as the H-profile, shares the same essential principle as mortise-and-tenon joints. The H-profile enables an interlocking system that resists forces acting parallel to the wall, ensuring that each wall segment locks together and maintains stability against bidirectional seismic forces. In addition to being earthquake-resistant, this interlocking brick system is also environmentally friendly, cost-effective, and allows for rapid construction (Nursaniah et al., 2022). These findings demonstrate the continuity of traditional structural principles in the form of more modern materials and construction techniques.

Summary of Findings

Based on the literature review conducted on earthquake-resistant structures in traditional Indonesian buildings, the studies focus on several main themes. These primary themes include load distribution systems; types and techniques of wooden joints; spatial organization and layout; and the principles of adapting traditional structures for contemporary buildings.

The most frequently encountered studies focus on the load distribution systems in the substructure and superstructure elements of traditional buildings. The commonly used research method is descriptive qualitative, employing data collection techniques such as interviews, observations, and literature review. Research on the types and techniques of traditional wooden joints has also been conducted across all literature objects; however, studies focusing on the in-depth exploration of a single traditional house have only been conducted on Ghumah Baghi. The third theme, examining the organization and spatial layout of traditional buildings to explore the relationship between circulation patterns and evacuation access across different cultural contexts, was carried out on traditional houses in Sulawesi. Finally, research on adapting traditional structural principles to contemporary buildings has so far been conducted only on traditional Acehnese houses. The potential for applying traditional structural systems to modern architecture remains unexplored, despite its significant potential for contemporary earthquake-resistant architectural design.

CONCLUSION

Architectural designs of the past exhibit distinctive patterns that consistently follow a continuity, establishing a logical connection between the past and the present. However, this continuity has begun to shift with modern developments and is often not optimally utilized in contemporary contexts. The first missing link between the seismic resilience principles of traditional and modern buildings lies in the aspects of materials and construction. Among the four architectural aspects studied, room layout, substructure and superstructure elements, and joint systems in traditional buildings, the use of wood has become less relevant to modern societal conditions. Several studies have examined efforts to adapt traditional house structures into modern residential buildings. However, in terms of materiality and construction, limitations in wood availability, high material costs, the large scale of traditional houses, land constraints, and the complexity of construction methods present challenges for applying wooden structures today (Sari et al., 2024). Some researchers also argue that traditional design principles are considered low-quality and difficult to implement in modern buildings (Fernandes et al., 2013).

The second missing link lies in the methodological aspect of knowledge development. Eleven out of seventeen analyzed studies highlight the seismic advantages of traditional buildings based on post-disaster observations or phenomenon-driven research. This approach positions phenomena as the primary source of knowledge, with theory serving as a tool to facilitate understanding of the phenomena, rather than the other way around (Lumineau et al., 2025). Consequently, this approach provides limited guidance on how to integrate practical knowledge to address challenges arising from the observed phenomena (Raabe et al., 2021). As a result, these studies do not sufficiently produce design principles that can be widely tested and implemented.

This is also evident from the low number of quantified studies among the reviewed articles. Only four out of seventeen studies employed quantitative methods, such as experimental studies, simulations, computational analyses, and behavioral studies. To overcome the limitations of phenomenon-driven research, integration with a structured methodological approach can be pursued to strengthen the practical application and generalization of the knowledge produced (Raabe et al., 2021). Research on earthquake-resistant structures in traditional Indonesian buildings, seven out of its seventeen studies has focused on the description and exploration of local knowledge. Therefore, further development on the technical-practical aspects is necessary to accelerate the adaptation of this local knowledge in the contemporary construction industry.

These two gaps indicate that the main challenge in bridging the seismic resilience principles of traditional and modern buildings lies not only in the technical aspects of materials and construction but also in the research methodology, which has yet to transform traditional knowledge into design principles that can be widely tested and applied. Therefore, further research combining phenomenological approaches with experimental and quantitative methods is needed. Future research must prioritize a transition from descriptive observations toward systematic experimental testing and numerical modeling within the fields of structural engineering and material science, particularly to evaluate the performance of hybrid systems that integrate traditional seismic principles with contemporary materials. Such a quantified approach is essential to transform qualitative local wisdom into applicable engineering data, ensuring that traditional structural logic can be reliably adapted into the contemporary construction industry.

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