International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 1
ISSN: 2088-5334

Essential Transformation of Mortise-and-Tenon Joints for Earthquake-Resistant Contemporary Housing (a Case Study in the Aceh Province, Indonesia)

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***Abstract*— Mortise-and-tenon joints reinforced with split wedges and dowels are traditional joint systems that have been the mainstay of vernacular houses for Acehnese people to endure earthquakes for centuries. This joint is no longer used now because the construction of houses uses conventional rigid frame techniques. The essential transformation of this connection in the product is urgently needed in Aceh because many conventionally landed houses experienced cracks and collapsed during several recent earthquakes. This paper aims to analyze the essential parts of mortise-and-tenon joints based on the transformation of vernacular houses in Aceh. In-depth interviews were conducted using open-ended questions with the homeowners of 18 vernacular houses in the Aceh province, who were selected using the purposive sampling method to determine the characteristics of house construction based on geographical areas. Simultaneously, direct observations were made at home (including measurements, redrawing, and photo-taking). The data collection also uses literature study techniques to examine further the principles of mortise-and-tenon joints' performance against earthquakes and obtain the latest technological information regarding joints whose performance is identical to mortise-and-tenon joints when facing earthquake forces. This paper suggests that a good alternative to conventionally constructed joint systems is an Aceh concept that uses an interlocking brick design, namely in the composition of an H-profile with a distinctive color to support the uniqueness of the interlocking shape. This interlocking design has the essential mortise-and-tenon joints of Aceh vernacular houses that are earthquake-friendly, ecological, cost-effective, and quick to build.**

***Keywords*— Essential transformation; mortise-and-tenon; contemporary housing; earthquake; Aceh province.**

Manuscript received 9 Feb. 2021; revised 21 May 2021; accepted 29 Jun. 2021. Date of publication 28 Feb. 2022.

I. INTRODUCTION

In Aceh, Indonesia, people must always be aware of earthquakes because tectonic plates cross the Aceh region. The house must be one's main concern because mistakes in the design will endanger the safety of the building and its occupants. People living in earthquake-prone areas should have solutions implemented in their homes to respond to the existing hazards [1]. Anticipation of disasters must be done by adopting the principle of earthquake resistance to avoid collapsing houses that could harm the community [2]. Geological conditions, geography, climate, occupants' socio-economic status, building materials, the available construction skills, and the types of natural disasters that are often an area has experienced in the past can also affect the typology of construction [3].

A traditional construction technique that has long been a structural solution in seismic areas is mortise-and-tenon joints, a wooden joint commonly used in various parts of the world, including in Aceh. Its use from generation to generation shows that this connection system has been tested in the geological and geographical conditions of the Aceh region, which is in a moderate to the strong earthquake zone, according to research [4], with a maximum ground peak acceleration of 0.73 g. Several earthquakes have resulted in the collapse of reinforced concrete structures in Aceh. The last strong earthquake in 2016 was very heartbreaking and made us realize that the analysis of vernacular house technology is important and very urgent. Such damage is not only found in

Aceh. Damage to reinforced concrete houses occurring at beam-column joints and the collapse of masonry infill walls was also detected in the Palu earthquake in 2018 [5]. Fig. 1 shows the position of the Aceh province on the Indonesian earthquake-zone map, which, of course, must be taken into consideration for serious house design in Aceh, now and in the future.

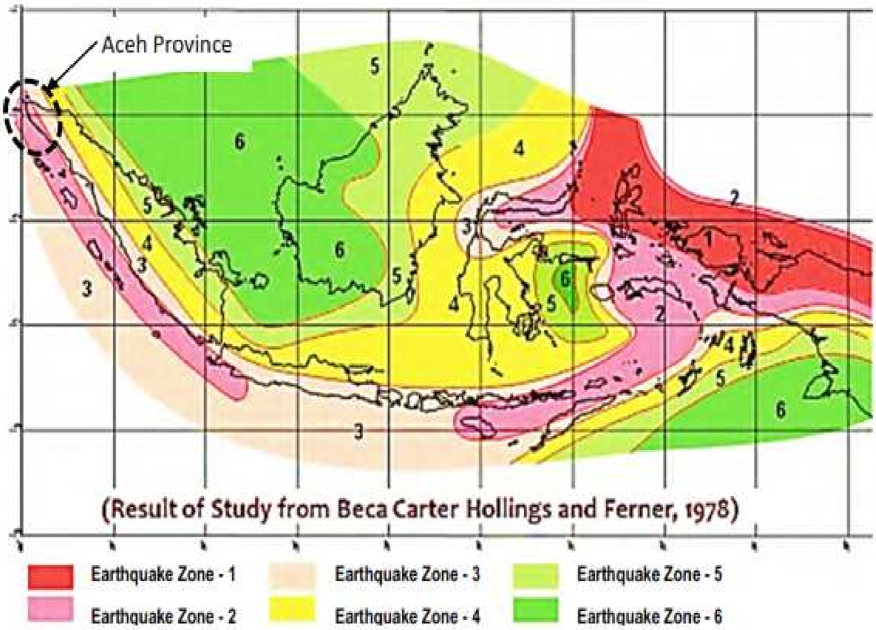


Fig. 1 The earthquake map of Indonesia [6]

Analysis of Aceh's vernacular house construction system technology is now important and urgent to produce contemporary earthquake-resistant housing construction that is sustainable. This study will produce a fundamental transformation from mortise-and-tenon joints to contemporary housing with the latest technology. The interlocking system method in mortise-and-tenon joints works to unite the various lateral forces on the building frame so that it is earthquake-resistant.

The seismic behavior of wooden structures is highly dependent on the performance of their joints, and mortise-and-tenon joints were the main joint form used in ancient wooden structures to respond to earthquakes. According to Mahayuddin et al [7] and Xie et al [8], Mortise-and-tenon joints have been used throughout the world for centuries due to their durability, beauty, and ease of use for entire buildings. Mortise-and-tenon joints provide a strong interlocking between joint members with high friction or damping resistance so that it absorbs most of the earthquake energy [9]. The depth of the notch has a strong influence on the strength of the joint [10]. After several earthquakes, gaps may appear between joint members, but this can be corrected by inserting wooden pegs [11]. This damage has a detrimental effect on the lateral behavior of the wooden frame as its stiffness and energy-dissipation capacity are weak, so it needs strengthening or tight repair [12]–[14].

Earthquake-resistant economical housing is needed in seismically-active areas in developing countries because there is often a significant loss of life and collapse of houses due to earthquakes [15]. Mortar-free terrain structures under earthquake loads could be a solution. Shifting building typologies also need to be considered in the context of affordability, sustainability, and future disaster risk reduction [16], [17]. Literature studies suggest that earthen construction materials are generally cheaper, cleaner, and more thermally comfortable [18]. This is relatively the same as in Aceh, Indonesia.

The use of mortise-and-tenon joints in the creative design of cultural products is to find solutions to design, modeling, material, and other problems and apply a design philosophy as a result of cultural rearrangement. More consideration should be given to changes in material and structural applications. The mortise-and-tenon structure can be better used to solve existing problems [19].

II. Materials and Method

Field data was collected using the purposive sampling method, with the criteria found in stilted houses being identified based on geography. The selection was made through observation and study of the area characteristics. Location 1 is the *Aceh Besar* District, upstream of the *Krueng Aceh* River. The house's floor height varies around the river between 1–2.5 meters because it is prone to flooding, while it is 0.5–0.8 meters in the highlands. Location 2 is the *Bireun* Regency, on the east coast of Aceh, with lowlands that have undergone a sedimentation process so that the land extends to the Malacca Strait. Many of the swamps are connected to large rivers, but during the dry season, they often experience drought. The floor height of the house is 1.5–2.5 meters, indicating a flood-prone environment. Location 3 is the *Nagan Raya* District, on the west coast of Aceh, with hilly characteristics and several sloping plains. High rainfall and sea storms cause the coastal land to be covered with sand so that river water cannot flow into the sea and instead form swamps, estuaries, and lakes. Fig. 2 shows the distribution of vernacular houses in Aceh Province which were sampled.

Based on the results of the field studies, several typologies of stilted houses and their joint systems were found. The fieldwork also consisted of a series of in-depth interviews with the homeowners of 18 houses spread over the three research locations. Open-ended questions were used to obtain detailed information about the history of their home, how the house protected its residents from earthquakes, how residents maintained their homes, and how they handled changes and adjustments. Measurements, redrawing, photo taking were also carried out, and direct home observations to study and evaluate the structural joint system, building materials, and technology. The results of the interviews were documented through written notes and voice recordings which were then summarized and synchronized with the observations.

Data from literature reviews were also needed to examine the performance principles of traditional Aceh mortise-and-tenon housing joints and conventional rigid-frame housing systems in the face of earthquakes in more depth. Literature studies were also used to conduct in-depth studies of the latest technological developments and joint materials that are identical to the performance of mortise-and-tenon joints in the face of earthquake forces. The study's results discussed the possibility of applying this mortise-and-tenon joint system to housing development in Aceh, the essential transformation process from mortise-and-tenon systems to current developments, the materials used, and the form of a new joint system.

The analysis results were mapped and interpreted according to the degree of transformation. The core of the mortise-and-tenon joint was analyzed and discussed according to this category. The concept of architectural aesthetics was added to the analysis to enrich the findings. Other essential elements observed were the typology of the pile and base joints, the house poles' shape, and the soil's stability. The observations highlighted how connection and pile typologies were modified and how these changes affected the culture of housekeeping. Discussions and evaluations were carried out with the homeowners during the interview.

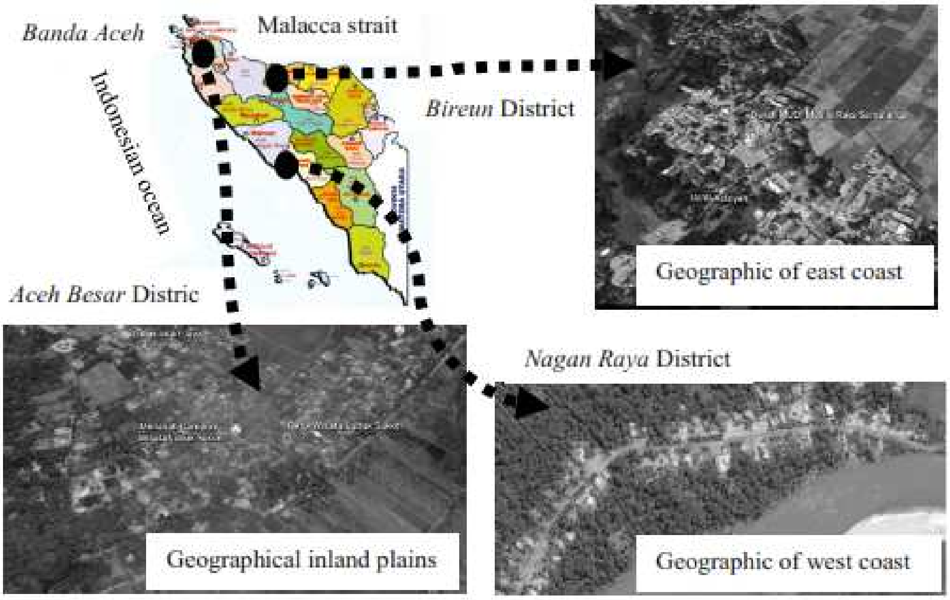


Fig. 2 Distribution of samples of vernacular houses in Aceh Province

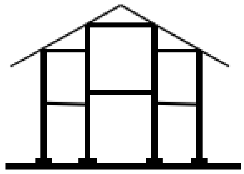
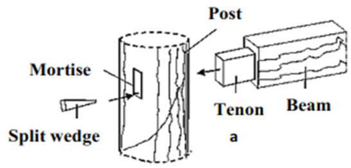
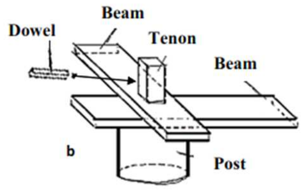
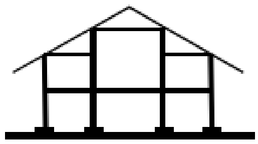
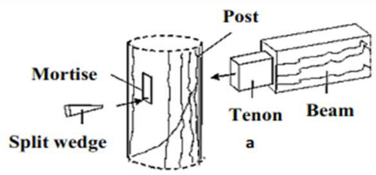
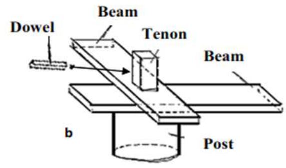
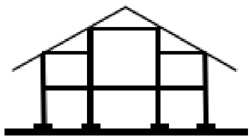
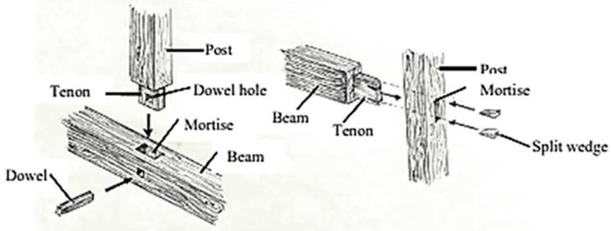
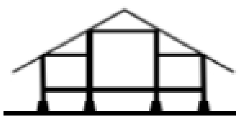
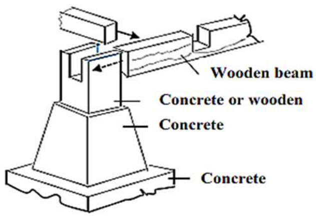
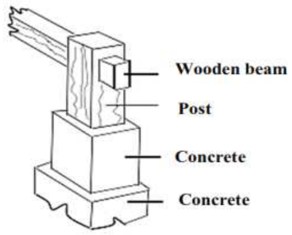
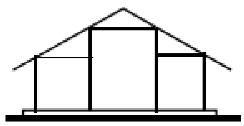
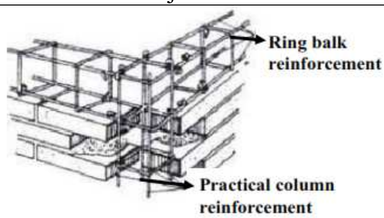
III. Results and Discussion

A. Transformation of Materials and Technology

The area of tropical forest in Aceh during the development of vernacular architecture was quite extensive and has been preserved. Based on that, the mortise-and-tenon connection technology was developed for the design of earthquake-resistant houses. The posts of the house are placed on flat cobblestones that are slightly buried in the ground. This construction behaves like a roller if a lateral force reduces the earthquake's energy. Tenons are formed at the ends of the members of a structure called rails and are cut to the size of a square or rectangular hole into posts or blocks. There is usually a shoulder seat when the joint fully enters the mortise hole. The joints are clamped to lock with a split wedge/dowel. This joint system causes stiffness in various directions (horizontal, vertical, diagonal) to withstand multidimensional forces. The mortise-and-tenon joint provides a sturdy finish, which also gives it an attractive appearance.

In Aceh, an illegal logging law that prohibits people from clearing forests carelessly has been implemented. The scarcity of wood affects prices and is therefore not economically viable to be used in public housing construction. But Aceh also produces various kinds of mining materials commonly used for conventional construction. Cement was available because there was a cement factory. The mobility is currently quite high so that building materials such as iron, glass, steel, and so on are fulfilled. The entry of manufactured materials gave new hope to the community in building housing because new alternative materials can be applied to make the house stronger at a lower cost. So, it was very natural for people to start building their built environment conventionally. The typology of houses and joint systems that developed in Aceh concerning their performance in facing earthquakes is shown in Table 1.

TABLE I
THE TYPOLOGY OF HOUSES AND JOINTS SYSTEM RESPONSE TO EARTHQUAKE

Typologi of houses	House Characteristics	The joints response
 Type 1, when the spread of Islam - 1950s. Spread in inland plains, East coast, West coast	 • Wooden stilted house • Lightweight and elastic materials • Round post • Mortise-tenon joints	 This mortise-tenon joint reduces earthquake energy by following the earthquake's shake
 Type 2, 1950s – 1970s Spread in the inland settlements of Aceh Besar	 • Wooden stilted house • Lightweight and elastic materials • Round post • Mortise-tenon joints	 This mortise-tenon joint reduces earthquake energy by following the earthquake's shake
 Type 3, 1950s – 1970s Spread in the East coast	 • Wooden stilted house • Lightweight and elastic materials • Square post • Mortise-tenon joints	This mortise-tenon joint reduces earthquake energy by following the earthquake's shake
 Type 4, 1950s - 1970s Spread on the swampy settlements/estuaries	 • Wooden stilted house • Square post • Mortise-tenon joints with bolt	 The joint system is less elastic against earthquakes
 Type 5, 1970s – today Spread throughout the province of Aceh	 • Landed house • Reinforced concrete, rigid frame joints	Experienced structural failures in several major earthquakes in Aceh

The joint system has undergone a change from earthquake-resistant mortise-and-tenon joints to rigid frame joints that, in principle, resist seismic forces, but it is not in reality [20]. This is evidenced by the cracks and collapse of conventionally reinforced concrete buildings in several fairly strong earthquake disasters in Aceh that had a magnitude between 6.5 and 9.0. These disasters reportedly caused many people to lose their lives as a result of being crushed and buried under collapsed buildings, as shown in Fig. 3. There is no information about a house with a mortise-and-tenon connection that has collapsed due to the earthquake. The joint system has flexible properties and can respond well to forces caused by earthquakes so that no fractures occur, like building structures using concrete.

Fig. 3 Samples of two houses constructed of reinforced concrete with rigid frame joints which collapsed during the Pidie Jaya earthquake

B. Stepping Towards Sustainability

Vernacular architecture is still under-appreciated regarding modern construction in Aceh, although the natural environment faces serious challenges in terms of environmental impact and natural resource management. Knowledge should be built to include traditional culture in technological principles that are built over time through a continuous process.

Using factory materials, we can apply the essentials of the vernacular structure to a more modern one. Discussions to understand sustainability in contemporary architectural design suggest that dialogue with past traditions is necessary. The author believes this can be done because Hărmănescu and Enache [21] said that vernacular technology could adapt to changes in the natural environment and is sustainable because it is contextual to the local climate, materials, and culture.

Japanese architecture uses paper and other lightweight traditional materials but has now adjusted to use fabricated materials, such as steel and glass, in its structures. This means that the traditional values in construction have been transformed to create a new traditional habitat in the present that is original and authentic and still upholds traditional values and is also free from the logocentrism of the past.

C. Essential Transformation of Mortise-and-Tenon Joints

The ideal approach to earthquake-resistant house design is not by strengthening the structure of the building but by reducing the earthquake forces acting on the building. The main structure that resists the horizontal force must be elastic. Therefore, mortise-and-tenon joints with new technology must be found and applied to homes in earthquake-prone areas. Concrete, brick, and iron materials are used as a substitute for wood, but the joints must apply the mortise-and-tenon performance principle to make it an elastic clamp. Of course, this must also be supported by other earthquake-resistant building criteria.

Earthquake-resistant economical housing is needed in developing countries like Indonesia, especially in Aceh. Several interlocking brick products have been developed and implemented in building construction, replacing conventional load-bearing and solid masonry systems. This can be considered as an alternative solution for earthquake-resistant houses in Indonesia.

Several studies related to the interlocking system were reviewed and discussed as an essential transformation process for a mortise-and-tenon joint system that could be applied to housing design in the Aceh province. The interlocking bricks made from a mixture of clay, concrete, sand, and compacted cement are environmentally friendly because they do not undergo a burning process like the red brick material that has been used for building houses in Aceh. They lock together and serve as structural walls and partitions for the house, offering lower construction costs comparable to red bricks [22]. Malahayati *et al.* [23] reported that this material could also be used as a substitute for reinforced concrete structures such as sloof, column, and ring balk. It does not need to be plastered because of its attractive appearance. The function of interlocking bricks is differentiated for structural and non-structural use based on the laboratory's compressive strength test for 28 days. Cost analysis is done by simulating the need for interlocking bricks in type 36 of house building that is resistant to structure and non-structure. The use of interlocking bricks can be considered as an alternative to other environmentally friendly building materials at a low cost.

As supported by Al-Fakih *et al.* [24], the shape of the interlocking bricks varies with simplicity, which results in easy and fast production and assembly in a masonry system. In addition, the locking mechanism of all types of interlocking bricks is sufficient to connect the assembled bricks in different directions. The interlocking bricks can be used as either a load-bearing wall or a non-load-bearing system.

Cold-formed steel is preferred for knockdown structures because it is flexible (strong, easy, fast to install and dismantle) and also has an anti-rust coating proven in the presalt test. It can use conventional foundations or precast foundations in the form of concrete blocks if the building has a semi-permanent concept [25]. This material is suitable for housing construction in the coastal area of Aceh. The interlocking concrete block model provides better strength than ordinary clay bricks for masonry walls [26].

Various additions of natural ingredients to increase toughness and strength, including the addition of nacre [27], the addition of coconut coir ropes [13], the addition of Typha-fibers waste [28], the addition of Sugarcane Bagasse [29], have started to be researched and show promising results. The use of lightweight foamed concrete for building walls indicates the energy-saving potential of the building in the tropics and its low cost [30], [31]. This is an opportunity for the development of materials that support the transformation of essential mortise-and-tenon as a sustainable earthquake-resistant housing joint system.

The Aceh vernacular house is a construction of interlocking poles and beams. The facade is observed to be composed of the letter H. This H-profile is an essential form that can be translated into a concrete interlocking-brick profile for housing design in Aceh. Fig. 4 shows the essential transformation process of Aceh vernacular houses construction towards the design concept of an H-profile of interlocking bricks.

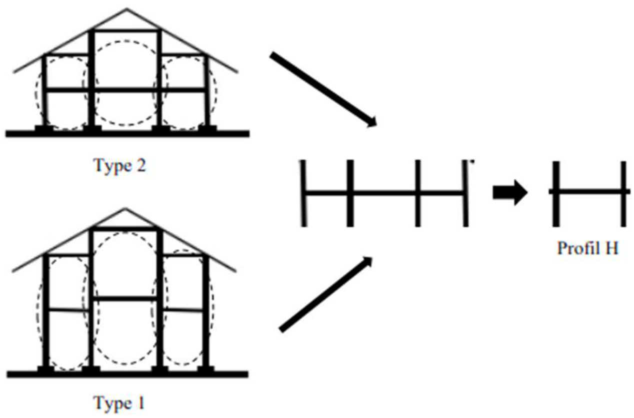


Fig. 4 An essential transformation process of Aceh vernacular houses

This paper also recommends using traditional Aceh colors in this interlocking brick product to support the uniqueness of its interlocking shape. This product is conditioned to be able to withstand lateral forces from two directions, and the depth of the locking tongue should be considered so that the hooks are not easily released when the ground moves. Thus, this product is recommended, taking into account the aesthetics and strength of the building. This product of an H-profile of interlocking bricks is ready to be produced in Banda Aceh, after laboratory tests, as a material for structures and infill walls. As a wall filler panel without interlocking concrete bricks, it also acts as an energy dissipation device. Fig. 5 shows a mortise-and-tenon transformed in material and technology as an H profile of interlocking brick, both of which have essentially the same connection principles for earthquake-resistant house construction.

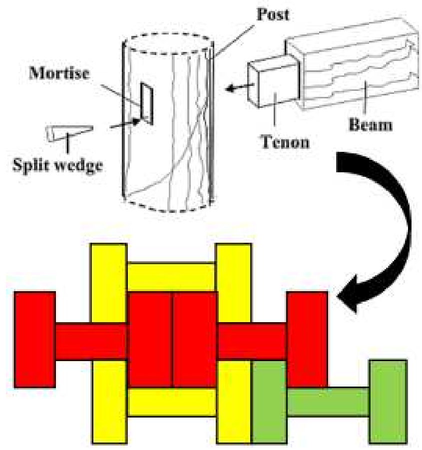


Fig. 5 An essential transformation from the traditional joint system to contemporary technology resulted in a unique interlocking system of the H brick profile shape with traditional Aceh colors

The H-profile aims to create an interlocking system against forces parallel to the direction of the wall, resulting in each wall segment interlocking so that the shape of the wall does not change when resisting the back-and-forth force earthquake. The interlocking-brick system is very suitable for contemporary housing development in Aceh as a construction that is earthquake-resistant, ecological, cost-effective, and saves construction time. Cost savings will occur if the material is used for housing construction in large quantities.

IV. Conclusion

In earthquake-resistant construction, the main structure must withstand the horizontal forces that are elastic. Mortise-and-tenon joints are essential and must be used with new technology. Other criteria of earthquake-resistant buildings must also support this. Various additions of natural materials to increase the toughness and strength of interlocking bricks have been researched and are showing promising results. This is an opportunity to develop materials that support the essential transformation of mortise-and-tenon into sustainable housing because they are earthquake-resistant and low-cost. The H-profile of interlocking bricks aims to ensure that each wall segment is interlocked so that the shape of the wall does not change while resisting the alternating earthquake forces. The interlocking-brick system with the colors commonly used in vernacular Acehnese houses is very suitable for contemporary housing developments in Aceh.

Acknowledgment

This research was funded by the Directorate of Research and Community Service (DRPM) DIKTI and Syiah Kuala University. We express our gratitude to these two institutions.

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