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Article

Seismic Retrofitting of Indonesian Masonry Using Bamboo Strips: An Experimental Study

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Abstract: Unreinforced masonry (UM) is well known as a vulnerable structure against earthquakes. However, it remains a popular structural system for low-rise residential housing in many high-seismicity areas, particularly in developing regions due to its low cost and easy construction. In the present study, a retrofitting strategy using locally available material, bamboo strips, was proposed. In addition to its fast-growing rate, the tensile strength of bamboo is considered high, nearly comparable to its steel counterpart. A series of experimental tests were performed in this study, including the bamboo tensile test, the mortar flexural test, the diagonal compressive shear test on the masonry assemblages, and the in-plane pushover test on masonry wall specimens without and with bamboo reinforcement. The retrofitted specimens with different volumes of bamboo reinforcement were also considered. The results show that the application of bamboo reinforcement, at a proper volume, significantly increases the ultimate strength and the ductility of the masonry wall. Such results indicate that the brittle failure of UM structures can be avoided by means of bamboo retrofitting.

Keywords: unreinforced masonry housing; bamboo retrofitting; pushover test; diagonal compressive shear test; ductility; seismic retrofitting

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1. Introduction

During many earthquakes that occurred in Indonesia, many low-rise buildings, mainly confined masonry (CM) or unreinforced masonry (UM), collapsed and caused thousands of casualties [1,2]. This fact indicates the importance of developing low-cost seismic retrofitting strategies for residential buildings, widely applicable in developing countries with high seismicity.

Masonry is a widely preferred material for housing in developing regions due to its low cost and easy construction. However, it is well known that the shear strength of unreinforced masonry structures is very low compared to reinforced concrete (RC) frames. The seismic resistance of masonry structures is provided only by the in-plane shear and flexural strength of piers and spandrels [3,4]. Thus, a brittle failure of UM buildings during strong earthquakes is likely to happen due to the absence of ductile reinforcement. In Indonesia, masonry typically consists of single-layer clay bricks arranged in the longitudinal direction and bonded by mortar joints with low strength, commonly made with the cement-to-sand ratio of 1:4. Masonry often presents a large uncertainty of the mechanical properties because it relies on the locally produced materials such as clay bricks and sand and the traditional mortar mixing by the workers.

In many developing countries, the problem may arise from the administrative procedures of building construction. For instance, in Indonesia, there is no obligation for the housing owners to submit their structural design documents if the buildings have two stories or less. In fact, the government has published a general guideline for the construction of single-story housing. However, it is not mandatory to follow and not well socialized. Consequently, thousands of low-rise buildings have been built without proper design [5].

In Figures 1–3, the photographs of damaged or collapsed UM or CM housing after the Malang earthquake (East Java, Indonesia) in April 2021 are shown. Figure 1 presents heavy damage on a substandard two-story CM housing with a large opening on the first floor and too small columns with cross section dimension of 15 × 15 cm^2. In Figure 2, a collapsed single-story building with a heavy concrete roof deck is shown. Several drawbacks of the structure were observed: heavy mass of the roof, reduced column cross area due to the placement of a PVC drainage, poor lap splice, and poor confinement. In Figure 3, two neighboring UM housing are depicted. The building on the left remained intact, while the building on the right was heavily damaged. Since the dimension and the floor plan of both buildings were almost similar, the difference in material quality, particularly the mortar joint, may be the main reason why those two buildings performed very differently against the same earthquake.

Figure 1. Heavy damage on a two-story confined masonry (CM) with a large opening and substandard RC frame.

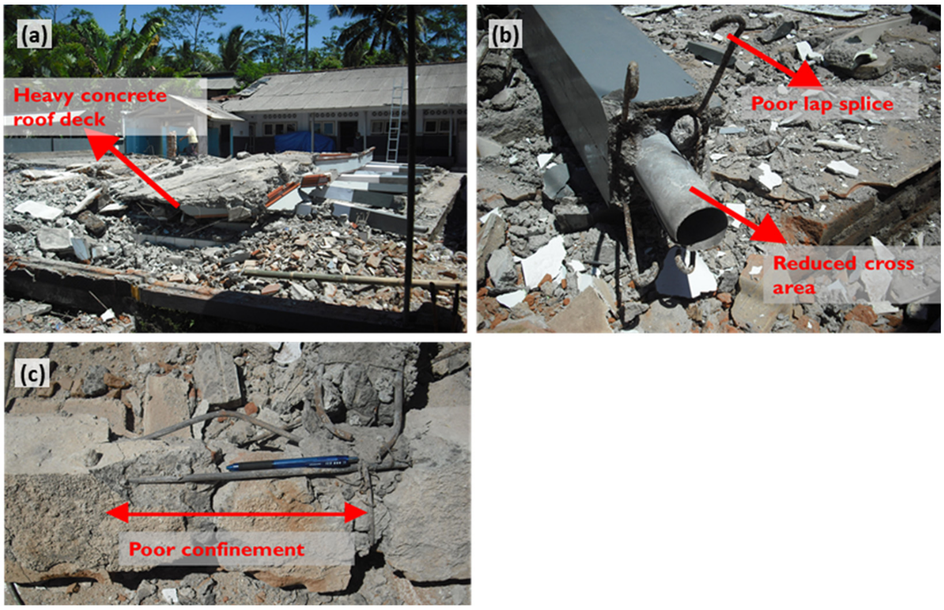


Figure 2. (**a**) Collapse of a single-story CM building with (**b**) poor column design and lap splice, and (**c**) low confinement.

Figure 3. (**a**) Two neighboring UM housing after an earthquake: (**b**) heavy damage on the right house, while (**c**) no remarkable damage on the left house.

Investigations on the retrofitting of masonry structures have been conducted by many researchers. In reference [6], FRP was used for the strengthening of the masonry wall. The results of dynamic in-plane tests show that the seismic capacity of the retrofitted masonry using FRPs was significantly increased. In reference [7], FRP was used for strengthening ancient masonry arches and vaults. The retrofitting system was found efficient in significantly increasing the ultimate strength of the ancient masonry arch.

A comprehensive analytical study to investigate the seismic behavior of existing curved masonry structures retrofitted with FRP was conducted in reference [8]. The proposed method, which was based on an assumption that the masonry and FRP strips were modeled with separate interacting elements, was able to predict the actual failure mode of the considered structure. Pretensioned aramid fiber-reinforced polymers (AFRP) were proposed in reference [9] as the retrofitting material of non-ductile RC structures. The results present that the retrofitting procedure improved the global seismic performance and significantly reduced the probability of collapse.

In reference [10], FRCM retrofitting was considered to recover the capacity of a masonry wall after damage and to improve the seismic response of the masonry building. The results presented that the external FRCM retrofitting was effective to avoid a brittle failure. In reference [11], a numerical approach was proposed to predict the behavior of FRCM-reinforced masonry structures. Accurate results were presented to predict the global behavior and damage pattern of the FRCM retrofitted masonry walls.

Steel bar reinforcement and shotcrete were used in reference [12] for full-scale masonry wall retrofitting. Specimens without reinforcement, with one-side, and two-side reinforcements were subjected to cyclic shear loads. It was found that the one-side retrofitting was not effective and did not present significant improvement compared to the two-side reinforcement. In the latter case, a significant improvement resulted, in terms of ductility and energy dissipation.

In reference [13], wire mesh and cement mortar were used for retrofitting a scaled masonry housing subjected to a shaking table test. The results show that the retrofitted housing showed the reinforcement effectivity and significant delay of total collapse due to the Kobe earthquake.

In reference [14], a bamboo mesh was used for masonry housing retrofitting. The proposed retrofitting method was considered easy and low cost such that unskilled workers can be used for small housing retrofitting after short training. The results of the shaking table test show that the proposed retrofitting method can considerably increase the seismic resistance of the housing so that casualties due to sudden collapse can be prevented.

In reference [15], masonry walls with different configurations of bamboo strips and mat reinforcement were investigated through cyclic shear tests. The bonding between the bamboo mat and the masonry wall was provided by a mixture of epoxy resin, cement, and dry sand. The results showed that the external bamboo mat reinforcement can notably improve the strength, deformability, and energy dissipation of masonry walls. It was also found that no significant slip between the bamboo mats and masonry thanks to the adhesive agent.

Implementation of a base isolation system for existing historical masonry structures was considered in the numerical study [16–18]. The results from the nonlinear time history analysis showed that the proposed isolation system can significantly reduce the damage to the masonry structures due to considered ground motions. In reference [19], a proposal to evaluate the performance of retrofitted masonry, taking into account the structural and thermal-energy aspects were presented. The study was meant to optimize several categories of costs related to the retrofitting strategy.

In reference [20], a review investigated various retrofitting methods of UM structures based on the nature of the structures and possible availability. The advantages and shortcomings of the retrofitting methods were presented in terms of cost, sustainability, and buildability. Based on the available literature on masonry retrofitting, indeed, steel bar reinforcement was found to result in the largest additional strength on masonry. However, such retrofitting strategy is considerably expensive, so it is not suitable for application in low-class housing, particularly in developing countries. PP band or bamboo retrofitting can be considered as optimum alternatives regarding the cost constraint and required ultimate strength to avoid a deadly collapse of housing under earthquakes.

Bamboo is one of the potential materials for structural reinforcement thanks to its high tensile strength, even though a broad range of strength variation was reported in the literature. Based on experimental studies in references [21–23], the modulus of elasticity and tensile strengths of bamboo were reported 1.5–2.0 × 10^4 MPa and 31.6–95.8 MPa, respectively. Such variations strongly depend on the part of bamboo that was tested. The strongest part is the peel part which has significantly higher tensile strength compared to the inner part. Based on the literature [24,25], the outer layers which have a thickness of about 1 mm present a maximum tensile strength of about 340 MPa, while for the inner layers, the tensile strength was found 54 MPa. Meanwhile, the compressive strength of bamboo was reported about 79.4 to 86.4 MPa. Table 1 summarizes the reported properties of bamboo from several works of literature.

Table 1. Mechanical properties of bamboo materials as reported in the literature.

Properties	Value
Density	0.2–0.85 kg/cm^3 [23]
Modulus of elasticity	1.5–2.0 × 10^4 MPa [21]
Ultimate compressive strength	79.4–86.4 MPa [21]
Ultimate tensile strength	31.6–95.8 MPa [22]
Ultimate tensile strength (outer part only)	290–342 MPa [24,25]

The lightweight and flexibility of bamboo material are suitable for earthquake-resistant small structures. It is also considered a sustainable material because the growth rate of bamboo is incredibly fast. Certain bamboo species can grow up to 91 cm/day [26]. In laminated products, bamboo shows high resistance against deterioration.

In the present study, experimental tests on retrofitted masonry panels using bamboo were performed, taking into account the effect of retrofitting volume. The study starts with the mechanical characterization of brick and mortar, bamboo, and masonry assemblage. Then, pushover shear tests were performed to evaluate the effectiveness of proposed retrofitting methods in increasing the shear strength of masonry panels.

2. Materials and Methods

2.1. Bamboo Preparation and Tensile Test

The bamboo material used in this study was locally available, growing in the side river in Madura, East Java, Indonesia. The bamboo is then cut into strips, as shown in Figure 4, with a cross-section dimension of about 0.5 × 2.5 cm^2. In fact, the strongest part of the bamboo is the outer layer, which has a thickness of about 1 mm. However, for the simplicity of the retrofitting work, the inner part of the bamboo was also included, so that the cutting process would be easier. No pre-treatment of the bamboo reinforcement was performed in this research.

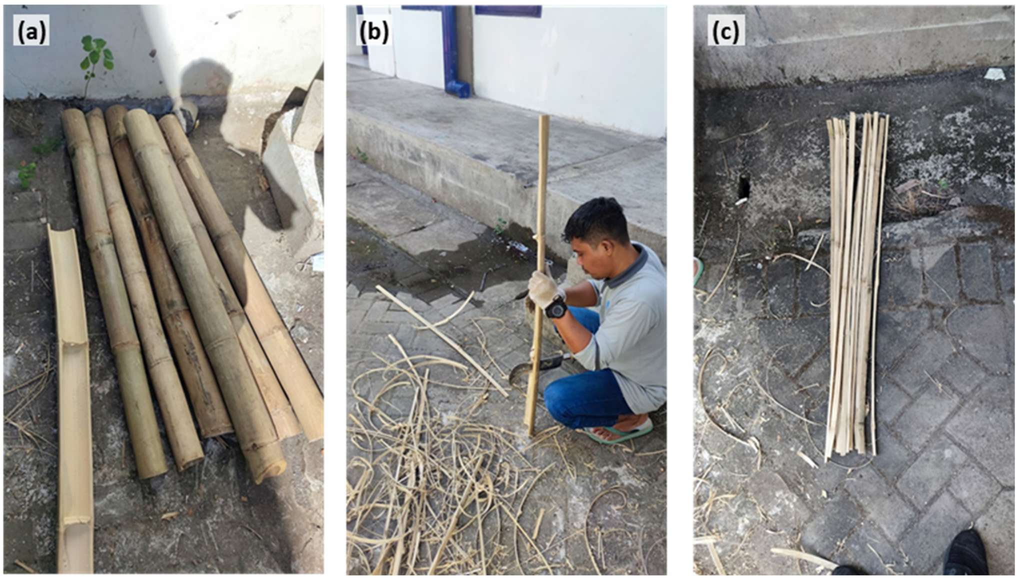


Figure 4. Preparation of bamboo strips for masonry retrofitting: (**a**) bamboo rods cut from the tree, (**b**) slicing the bamboo into strips, (**c**) bamboo strips used for retrofitting.

A uniaxial tensile test was performed to evaluate the tensile strength of the bamboo under study. The dimensions of the bamboo specimen and the tensile test method are shown in Figures 5 and 6, respectively.

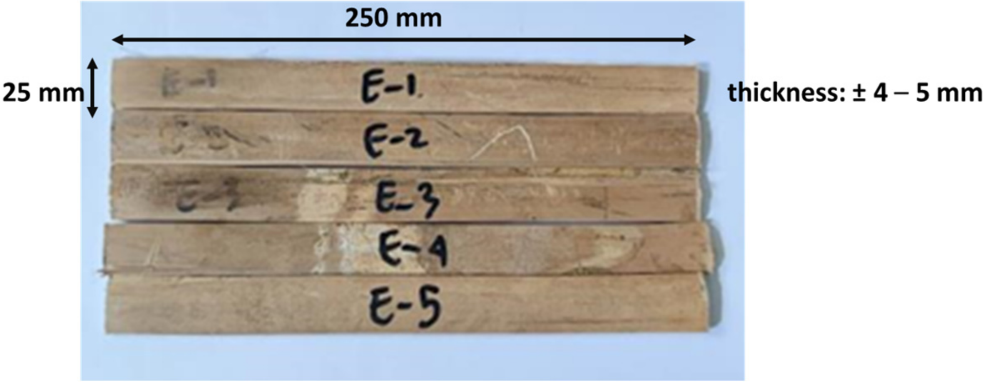


Figure 5. Bamboo specimens for tensile test.

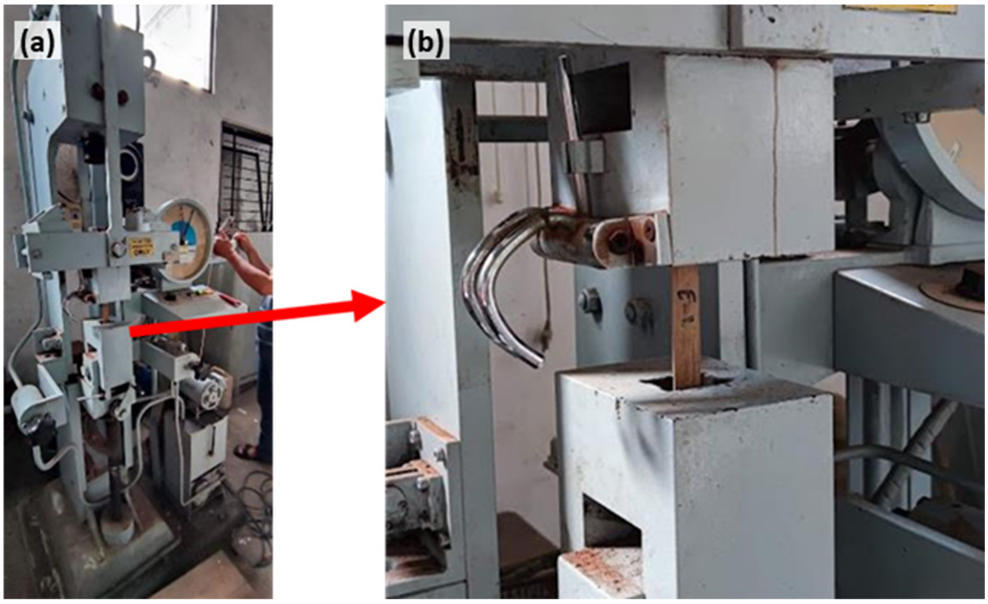


Figure 6. (**a**) Universal testing machine for the tensile test of bamboo and (**b**) the bamboo specimen during the tensile test.

2.2. Flexural Test on Mortar

In the present study, the mortar joints of the masonry were made with the cement-to-sand ratio of 1:4. Such composition is common to use in masonry construction in Indonesia. In order to investigate the mechanical properties of the mortar joint, particularly the flexural or tensile strength, flexural tests are performed on three mortar samples with the dimension of 40 × 40 × 160 mm^3, as shown in Figure 7. The flexural or tensile strength of the mortar joints plays the most important role in the shear strength of the masonry structures.

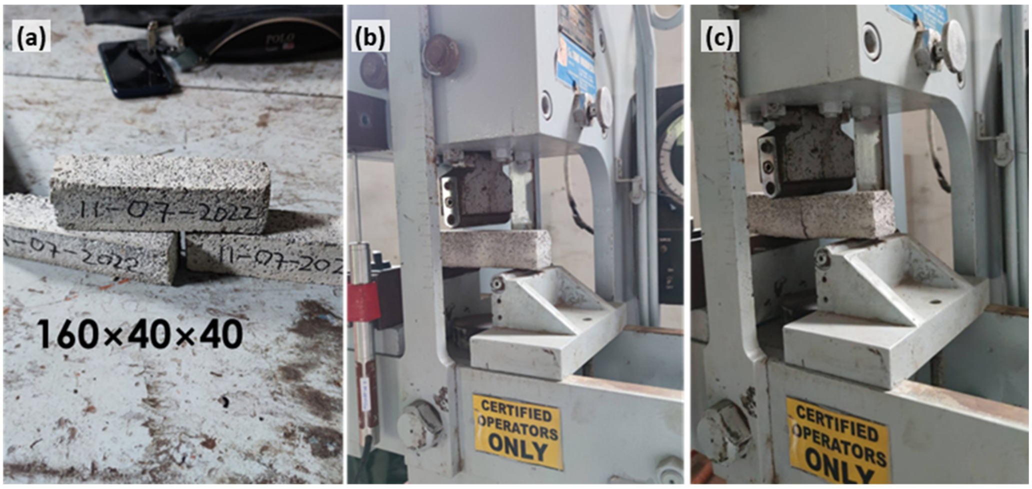


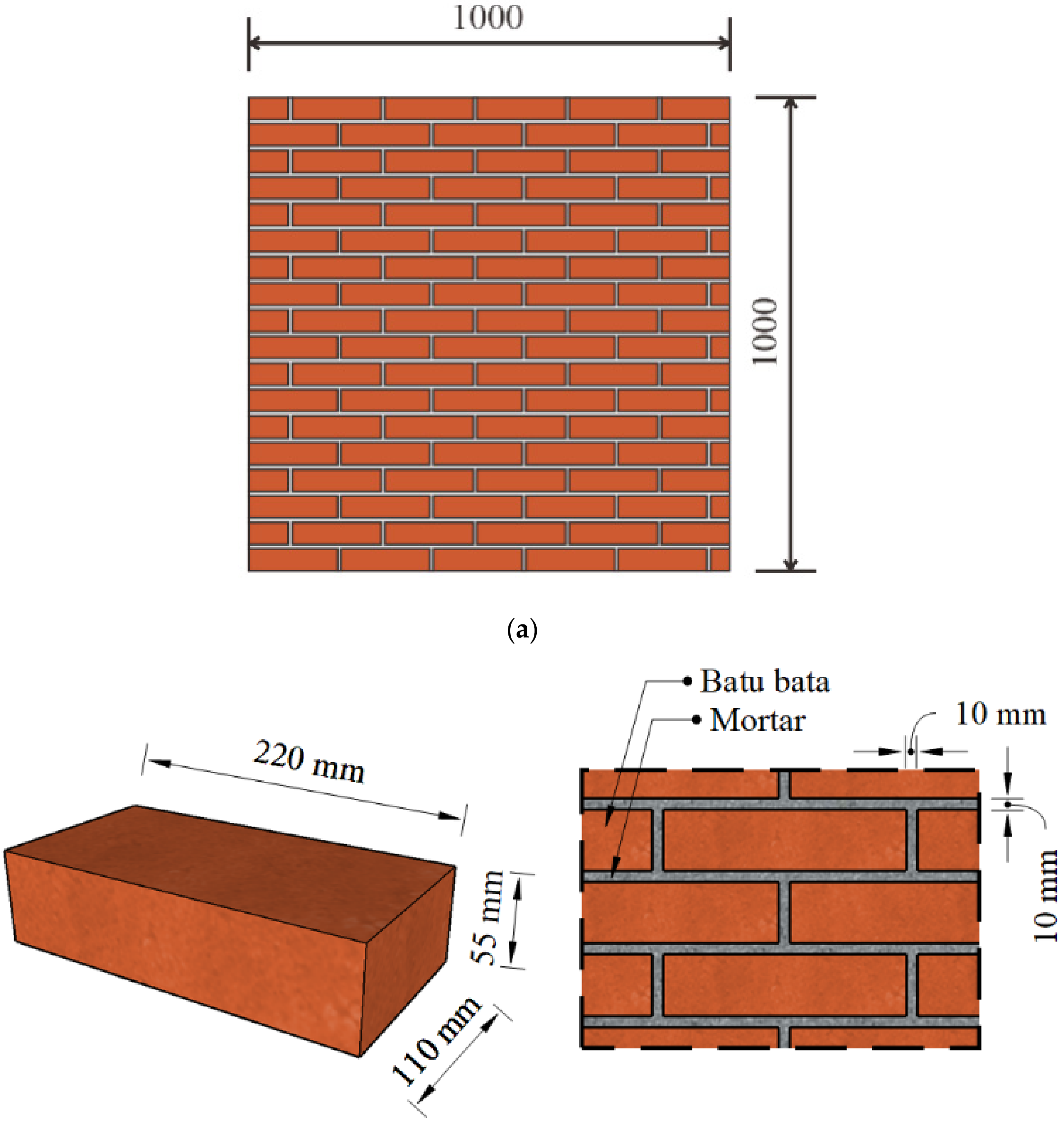
Figure 7. (**a**) Mortar specimens, (**b**) the flexural test on the mortar specimen, and (**c**) the flexural failure of the mortar.

As shown in Figure 7, the flexural test was performed on 30-day-old samples using a one-point load method. The flexural strength (Sf in MPa) of the mortar for the given dimension can be evaluated through Equation (1) [27], where P (in N) is the maximum load.

$$Sf = 0.0028\,P \quad (1)$$

2.3. Diagonal Compressive Shear Test on Unreinforced Masonry Panel

The masonry assemblages were made for two experimental tests: diagonal compressive shear test and pushover shear test. For the diagonal compressive shear test, 1 × 1 m^2 masonry panels, as presented in Figure 8a were constructed. The clay bricks used in this experimental study were traditionally fabricated with the dimension of 200 × 150 × 50 mm^3, as shown in Figure 8b. The UM panels were built from single-layer bricks arranged in the longitudinal direction and bonded by mortar joints with a thickness of 10 mm, as seen in Figure 8c.



(a)

(b) (c)

Figure 8. (**a**) The dimension of the masonry panel for the diagonal compressive test, (**b**) the dimension of the brick unit, and (**c**) the thickness of the mortar joint.

The diagonal compressive test was performed according to ASTM E519 [28]. Such a test was meant to evaluate the shear strength of the masonry assemblage. Three samples were tested as stated in the standard. Upper and bottom loading supports were constructed from steel plates and ribs, with the dimension as shown in Figure 9.

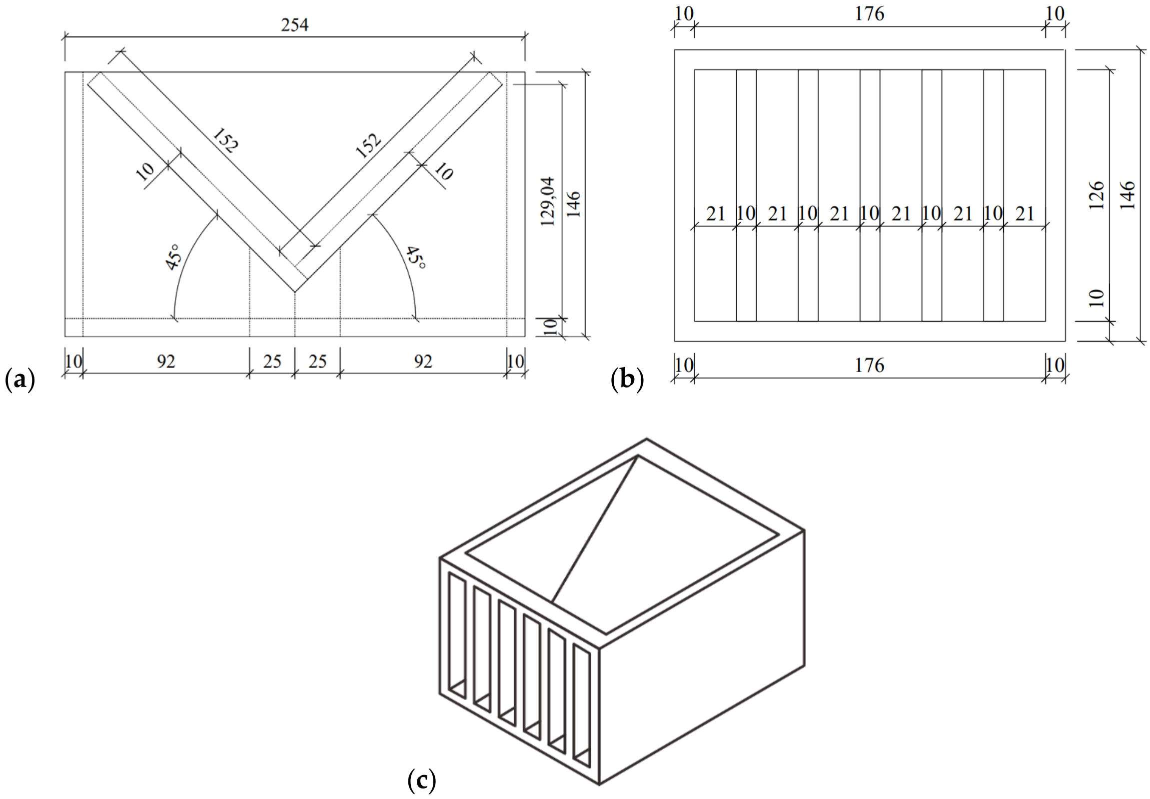


Figure 9. Loading support for the diagonal compressive test: (**a**) Cross Section view; (**b**) Bottom view; (**c**) Isometric view. Units are in mm.

The samples with the supports were placed in the universal testing machine (UTM), as shown in Figure 10, and were incrementally loaded until they reached the ultimate loads. Visual observation was also conducted to observe the crack propagation during the compressive test. LVDTs were used to monitor the vertical and horizontal deformations of the masonry panels. The shear strength of the masonry panel can be evaluated through Equations (2) and (3).

$$S_s = \frac{0.707P}{A_n} \tag{2}$$

$$A_n = \left(\frac{w+h}{2}\right)tn \tag{3}$$

where:

S_s = shear stress at net cross area
P = compressive load
A_n = net cross section,
w = width of the panel
h = height of the panel
t = thickness of the panel

2.4. Pushover Shear Test on Unreinforced and Retrofitted Masonry Walls

Six masonry wall specimens with the dimension of 1 × 1 m^2 were constructed in this study for the pushover shear test, with the configuration as presented in Figure 11. Two samples of unreinforced masonry (UM), two samples with a 2.88% volume ratio of bamboo retrofitting (RM1), and two samples with a 1.44% volume ratio of bamboo retrofitting (RM2). Such percentages were computed as the volumetric ratio of bamboo to the masonry wall.

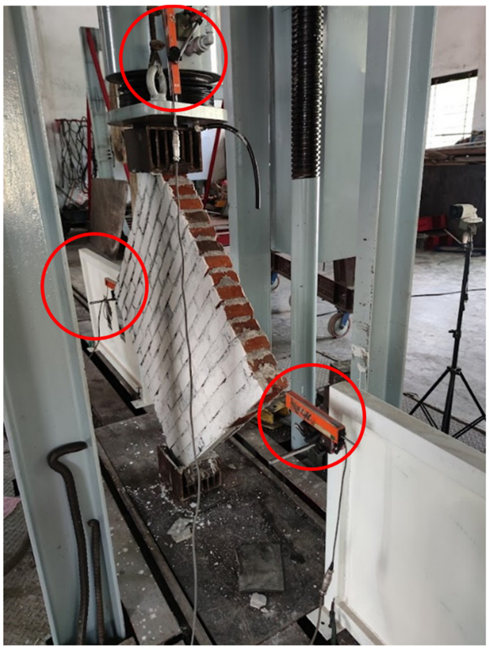


Figure 10. Masonry panel under compression test and LVDTs for displacement measurements.

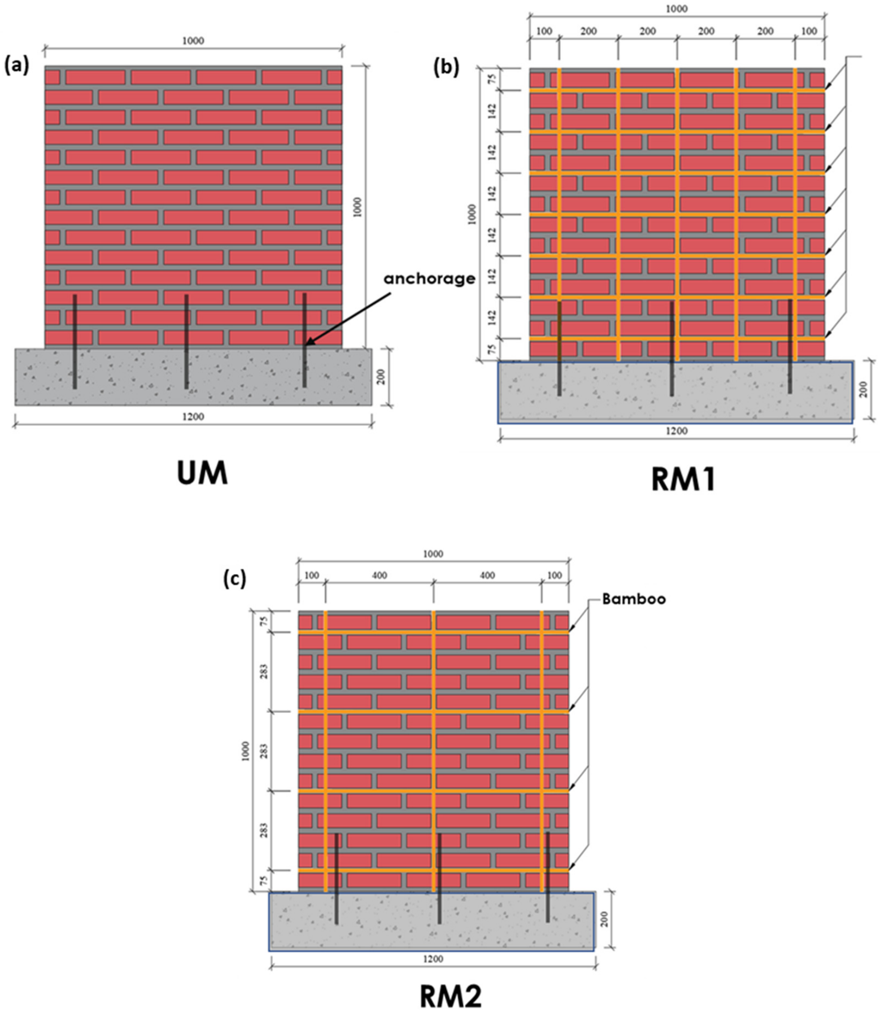


Figure 11. Sketches of three masonry panel models: (**a**) without retrofitting, (**b**) with 2.88% of bamboo retrofitting, (**c**) with 1.44% of bamboo retrofitting.

The masonry specimens were built on reinforced concrete beams with a cross section dimension of 150 × 150 mm^2. Steel bars with a diameter of 10 mm as vertical anchorage at every 380 mm were used to avoid a premature sliding failure between the RC beam and masonry panel. In order to reduce further the construction cost, the steel bar anchorages can be replaced by bamboo bars.

For retrofitted specimens, as shown in Figure 12, some small holes with a certain distance were prepared (using a straw) during the construction of the masonry wall. Please note that the proposed retrofitting method was intended to strengthen existing UM structures. Thus, in such a case the holes can be made through drilling. The small holes were required for the application of transversal wires, which would act as shear connectors so that the integrity of the outer and the inner bamboo layers of bamboo reinforcement can be preserved.

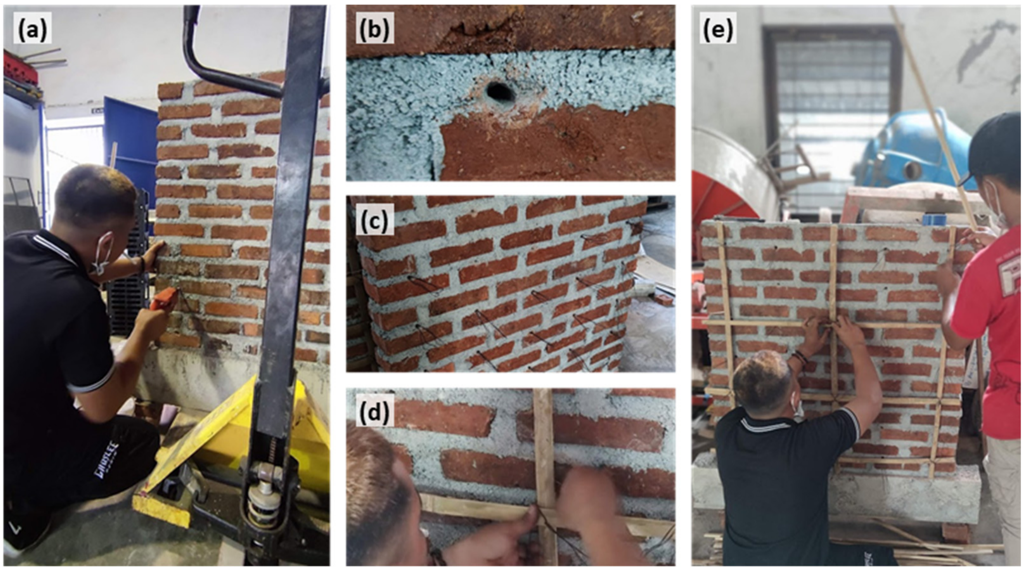


Figure 12. Preparation of the masonry panel with bamboo retrofitting: (**a**,**b**) boring holes on the mortar joint with specified distance, (**c**) placement of transversal wires into the holes, (**d**,**e**) placement of the bamboo strips on two sides of the wall and fastening using the prepared transversal wires.

The bamboo reinforcements should be arranged such as the shear and flexural capacity of the masonry wall can be enhanced. A uniform arrangement of horizontal and vertical bamboo strips was considered in this study, as shown in Figure 11b,c. The horizontal bamboo strips would act as the shear reinforcement, while the vertical ones would act as the flexural reinforcement.

To consider only the effect of bamboo reinforcement in this experimental study, no finishing mortar layer was applied to the masonry panels. On the other hand, in real applications, the finishing mortar layer may increase the shear strength of the panels.

In this study, a modified universal testing machine (UTM) was used to perform the pushover shear test, as shown in Figure 13. The pushover shear load was generated by a tension force through the metal strand. A tension load cell was used to measure the generated tension load. LVDTs were used to monitor the deformation of the masonry panel. The masonry panel was incrementally loaded up to the failure of the panel. No compressive load was applied to the masonry wall. In addition to the limitation of the testing device, it is considered that in a common one-story UM housing in Indonesia, the amount of the compressive load is generally very low due to the use of a light roof system. The proposed retrofitting method in this study is indeed intended for application on single-story UM housing.

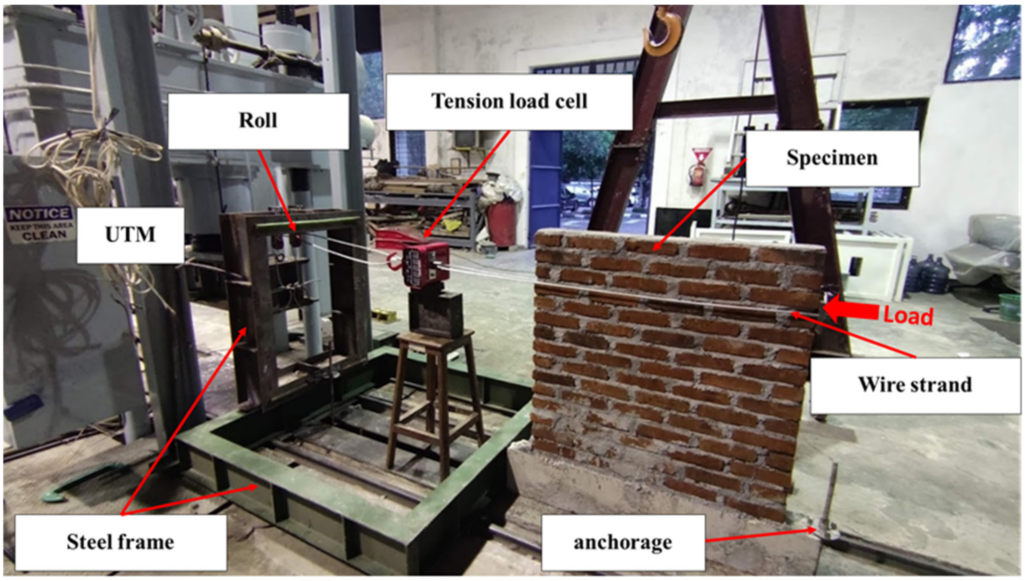


Figure 13. Pushover shear test on the masonry wall.

3. Results and Discussions

The results of the uniaxial tensile test on bamboo are presented in Table 2. The average tensile strength was found 164 MPa, which is nearly comparable to steel reinforcement. The tensile strength obtained in this study was found higher compared to the available data in the literature [22]. A broad range of bamboo strengths can be caused by the different parts of bamboo which were tested, the variance of the species, local weather, and age.

Table 2. Result of bamboo tensile test.

Specimen	Ultimate Tensile Load (N)	Ultimate Tensile Strength (MPa)
1.	17,542	140
2.	22,638	181
3.	20,972	168
4.	25,676	205
5.	15,876	127
Average		164

The results of the flexural test on mortar are presented in Table 3. The average flexural strength was found considerably low, about 0.1 MPa.

Table 3. Results of flexural test on mortar.

Specimen	Force at Crack (kgf)	Flexural Stress (MPa)	Average (MPa)
1	3.50	0.100	0.11
2	4.50	0.120	
3	4.00	0.110	

Diagonal compressive tests were performed on two masonry assemblages. In Figures 14 and 15, the crack pattern of the panels and the force–vertical displacement curves during the test are shown, respectively. The forces at the crack were found about 20 kN and 25 kN, respectively. Table 4 shows the resulting shear strength of the masonry panels under the diagonal compressive test through Equation (2). The average shear strength was found 0.13 MPa. Such value is much lower compared to the data obtained from the experimentation in Europe [29] and India [30], 1.678 and 0.220 MPa, respectively.

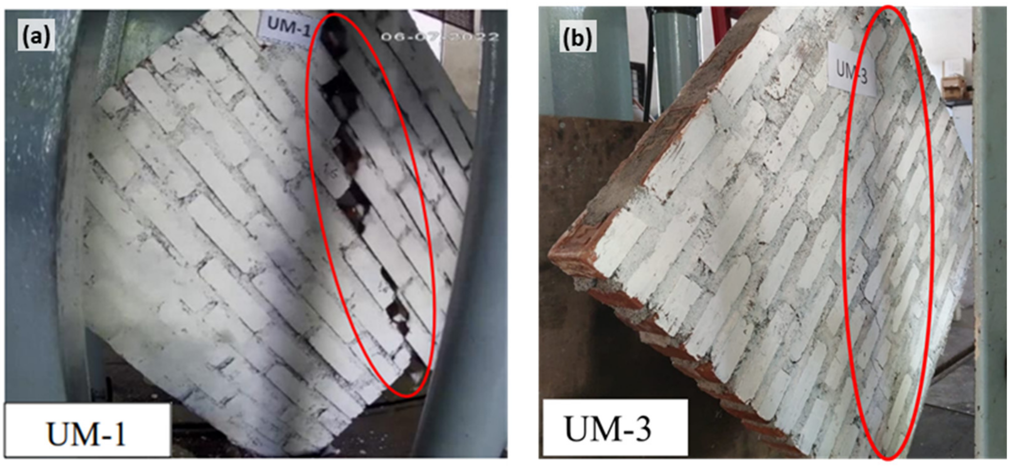


Figure 14. The crack patterns of the two masonry panels, (**a**)UM-1, and (**b**) UM-3, under diagonal compressive tests.

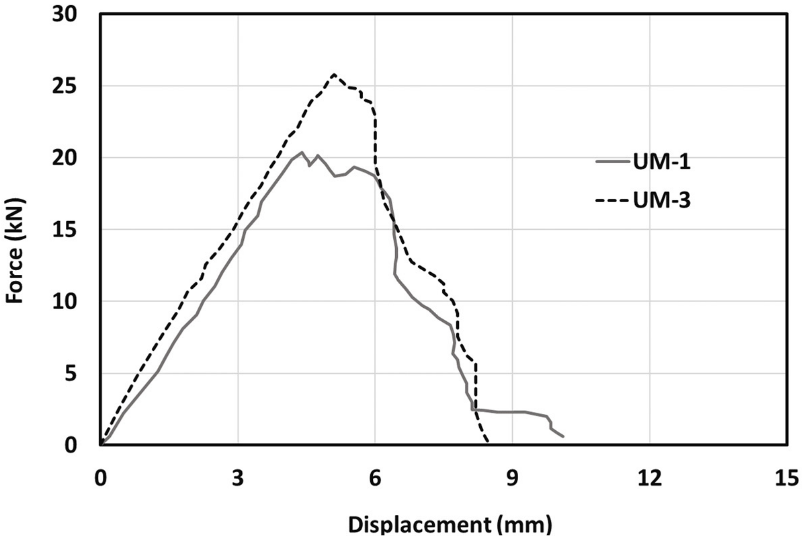


Figure 15. Force–displacement curves of two UM panels under diagonal compressive test.

Table 4. Results of diagonal compressive tests on unreinforced masonry (UM) panels.

Specimen	Maximum Load (kN)	Shear Strength (MPa)	Average (MPa)
1	20.35	0.14	0.16
2	25.75	0.18	

Regarding such very low masonry shear strength, it seems required for the authorities to publish a guideline on the mortar specification, particularly used for the construction of unreinforced (UM) or confined masonry (CM) housing. In fact, in Indonesia, where almost all the engineering codes adopt the American ones, the structural design codes for UM or CM buildings are not available since they are not permitted. However, thousands of UM or CM housing have been built without proper design and construction supervision.

The results of the pushover shear test on the unreinforced and strengthened masonry wall are presented in Figures 16–18. Figure 16 shows the crack and failure of the UM model under the pushover shear test. A horizontal crack starting from the right part, the one under tension, was observed, which indicates a dominant flexural failure of the wall. The crack propagates horizontally along the third bed joint, where it was the end of the anchorage length.

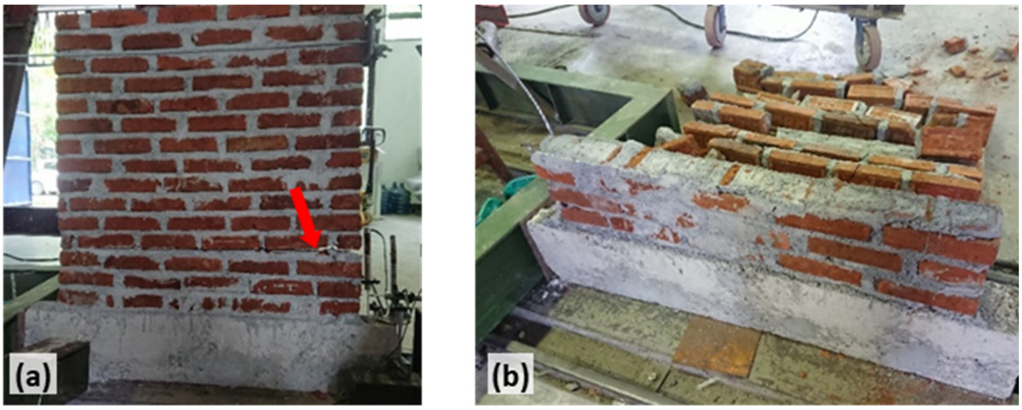


Figure 16. (**a**) The crack patterns of the UM panel under pushover shear test, and (**b**) the collapse of the UM panel.

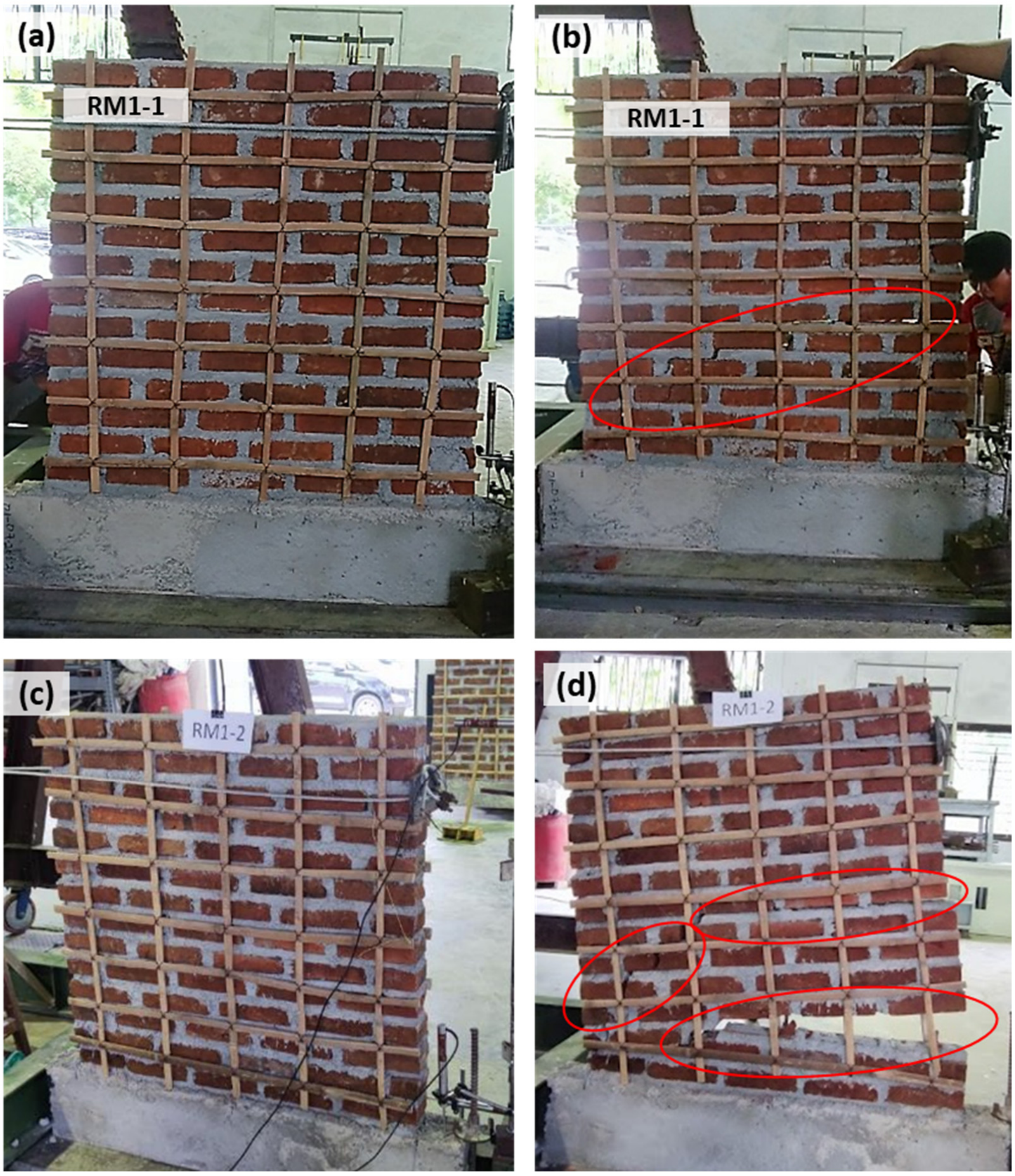


Figure 17. The pushover shear test and crack patterns of the retrofitted masonry panels with 2.88% of bamboo retrofitting: (**a**,**b**) RM1-1, and (**c**,**d**) RM1-2.

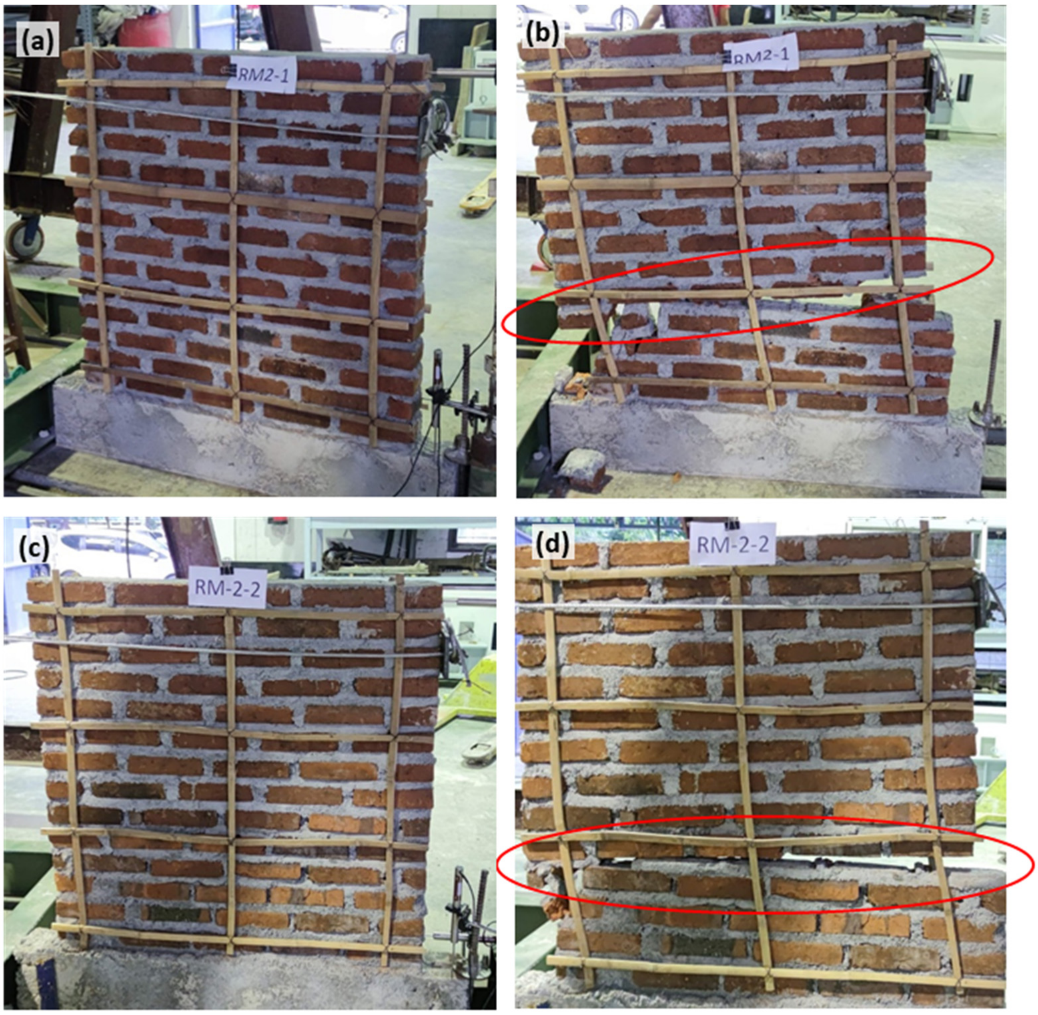


Figure 18. The pushover shear test and crack patterns of the retrofitted masonry panels with 1.44% of bamboo retrofitting: (**a**,**b**) RM2-1, and (**c**,**d**) RM2-2.

The force–displacement curves of the pushover test on the UM walls are presented in Figure 19a, where the crack forces of the two identical UM specimens were reported at about 280 and 120 kgf, followed by a brittle failure deformation due to the lack of reinforcing element. However, when compared to the five other specimens, the specimen with a crack load of 120 kgf might experience a premature failure. Thus, it is excluded from the performance comparison in Table 5.

Table 5. The summary of the pushover shear test results.

Spec.	Bamboo Ratio (%)	F_{cr} (kgf)	Δ_{cr} (mm)	F_{ult} (kgf)	Δ_{ult} (mm)	Average Increase in F_{ult} (%)	Ductility (μ)
UM-1	-	270	2.70	270	2.70	0.00	1.00
UM-2		-	-	-	-		-
RM1-1	2.88	293	3.08	464	41.62	64.07	13.51
RM1-2		315	2.80	422	47.05		16.80
RM2-1	1.44	270	2.23	270	4.25	−9.26	1.91
RM2-2		219	1.85	220	1.85		1.00

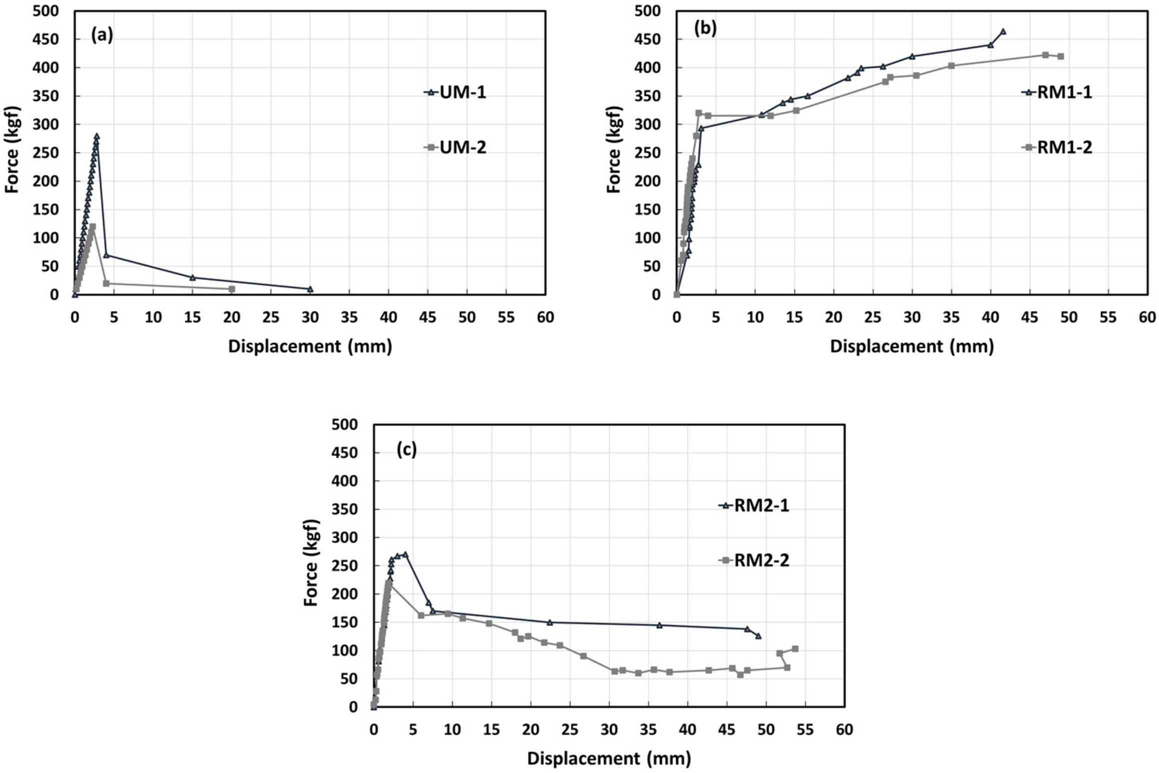


Figure 19. Force–displacement curves of three masonry models under shear test: (**a**) unreinforced masonry, (**b**) retrofitted masonry using 2.88% of bamboo, and (**c**) retrofitted masonry using 1.44% of bamboo.

In the case of reinforced specimen RM1, as presented in Figure 17, one specimen presented shear crack patterns (see Figure 17b), while the other one showed a combination of a shear crack pattern followed by a flexural crack pattern (see Figure 17d). When compared to the result of the unreinforced specimens, as shown in Figure 16, the bamboo reinforcement tends to change the failure mode from flexural failure to shear failure.

Regarding the force–displacement curves of the specimens RM1 presented in Figure 19b, the bamboo reinforcement seems to not significantly increase the force and deformation at the crack. However, such reinforcement seems to be very effective to increase ductility. Hence, the life safety performance of the masonry housing could be achieved. Up to the horizontal displacement of 40 mm, the specimens still resisted the applied load. Such a large displacement capacity is clearly beneficial in preventing a brittle collapse of masonry housing due to an earthquake.

A similar trend of crack patterns was also presented in specimen RM-2, in which the volume of bamboo reinforcement was half of the reinforcement in specimen RM-1. Both specimens RM-2 showed a transition between shear and flexural failure mode, as presented in Figure 18.

Regarding the force–displacement curves of specimen RM2 in Figure 19c, no significant change in the load at the crack was observed. When compared to the performance of model RM-1, the post-elastic zone of model RM-2 presented inferior resistance against lateral load.

During the test of the retrofitted models, no notable damage on the bamboo strips was observed. However, at large displacement, remarkable slips on the bamboo wire ties were reported, as clearly seen in Figure 17d. Even though such a failure seems to not significantly decrease the performance of the retrofitted models (RM1), the application of an adhesive agent between bamboo and masonry is recommended to eliminate the slip failure mode, as reported in reference [15]. In real construction, the finishing mortar may also improve the integrity of the masonry and bamboo reinforcement.

The performances of the tested masonry specimens were summarized in Table 5. The increase in the ultimate load was computed based on the increase in the average values. The ductility μ is the ratio of the ultimate displacement Δ_{ult} to crack displacement Δ_{cr}. It is shown that using 2.88% of bamboo reinforcement increased dramatically the ultimate load by 64.07% and the ductility factor up to 16.80. On the other hand, the application of 1.44% of bamboo reinforcement did not improve the ultimate strength, while the ductility was slightly increased up to 1.91.

Another issue regarding bamboo reinforcement is its durability against weather exposure. As reported in some references [31,32], resin laminations on bamboo can prevent deterioration due to weather exposure. In addition, when applied in real construction, the bamboo will be covered by mortar finishing, which can further protect the bamboo from weather exposure.

4. Conclusions

A series of experimental tests were conducted to evaluate the characteristic of common Indonesian masonry and the effectiveness of bamboo retrofitting on the masonry wall. Based on the obtained results, several conclusions can be drawn:

1. The application of 2.88% bamboo reinforcement (model RM-1) resulted in a significant increase in ultimate strength and ultimate deformation. Hence, a sudden collapse could be avoided. Meanwhile, the application of 1.44% bamboo reinforcement (RM-2) barely improved the ultimate strength of the masonry wall under study.
2. While the ultimate strength of the reinforced models was improved with the application of the bamboo reinforcement, the crack load and the deformations at the crack were barely increased. It indicates that the elastic mechanical properties of the masonry wall were not affected by the application of bamboo reinforcement, in particular, when the finishing mortar or adhesion is not applied.
3. No damage on the bamboo strips was observed until the end of the test. However, at large displacement, notable slips on the bamboo wire ties were observed. The application of an adhesive agent on the masonry–bamboo interface would eliminate this slip failure mode.

The above conclusions may apply only to the considered specimens in the present study. Therefore, in the design of a building retrofitting, the volume of the reinforcement should be designed based on the site's seismic demand and the cost–benefit analysis. In particular, when dealing with the assessment or strengthening of non-engineered buildings, there are wide variations in the building's material quality, depending on the local materials and economy. In any case, the results of the present experimental study can be used as a validation for numerical analysis in a real retrofitting design.

Furthermore, as the present study investigates only the in-plane behavior of the bamboo-strengthened masonry, the investigation of the out-of-plane performance needs to be carried out in future research. The effect of the arrangement of bamboo reinforcement is also interesting to investigate.

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