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Assessment of fire resistance performance of composite bamboo shear walls

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ABSTRACT

This study is aimed to examine which configurations of mortar covering give the best fire protection for the composite bamboo shear wall system. The research is done in two stages, first is the non-standardized pre-test stage, which results will become the basis for determining the specimen specification. In the second stage, the specimen with the best fire resistance level is tested with standardized tests referred to as SNI 1741-2008 and ISO 834-1-1999. Fire resistance performance was measured according to integration and insulation level expressed in minutes. In the pre-testing stage, bamboo-wall configurations with flattened bamboo and mortar plaster on one-sided and two-sided are evaluated according to the burning time, and the highest temperature reached on the unexposed side. The pre-testing result shows that the chipped and cracked mortar conditions affect the high temperature of the specimen and the burning of the flattened bamboo, and vice versa. In the standardized test in the second stage, it was found that the specimen with one-sided mortar had an insulation and integration level of 30 minutes, while the specimen with two-sided mortar was 120 minutes. These results indicate that mortar condition and location affect the bamboo-plaster wall's fire resistance performance.

Introduction

Bamboo is one of the green building materials because it is a sustainable natural material. Bamboo is accessible, affordable, and easy to construct. It is known that bamboo fiver has a strength that is almost equivalent to steel (Harison, Agrawal, and Imam 2017; Rahim et al. 2020; Kumar et al. 2019). Bamboo is now widely used in modern buildings as a roof frame, columns, walls, and floors (Lobovikov et al. 2007).

Composite bamboo shear walls have been used for a long time and have become more prevalent in recent decades. Engineered bahareque houses, successfully built in many countries worldwide, are one type of bamboo housing that uses composite bamboo shear walls, such as in Colombia, Nepal, and the Philippines. Engineered bahareque housing comprises small-diameter bamboo, organic matrix of cane, bamboo laths, or bamboo mats that are fastened to the frame and reinforced with galvanized steel chicken mesh. After that, the walls are finished with cement mortar covering to produce solid walls (Kaminski, Lawrence, and Trujillo 2016). Techniques like bahareque were also developed in Indonesia and named plaster bamboo houses. This wall construction is made of flattened bamboo or palupuh, then plastered with mortar

(Widyowijatnoko and Mustakim 2015). Composite Bamboo shear wall construction is widely used, mainly in developing countries. The Indonesian government has proclaimed using houses with plaster bamboo walls in affordable housing programs (detikFinance 2011).

Bamboo is flammable and can easily catch fire. It burns at temperatures between 250 °C-300 °C (Lu and Chen 2015). At 200 °C bamboo retains 20% of its compressive strength, 42% of tensile strength, and 70% of its modulus of elasticity (Gutierrez and Maluk 2020), and at 160 °C the properties of bamboo panels change (Wang et al. 2022). Research on the performance of bamboo against fire is not as extensive as research on the performance of wood. Furthermore, several studies on the fire resistance of bamboo have focused on engineered bamboo products such as GluBam (glue-laminated bamboo) and laminated bamboo lumber. It is known that engineered bamboo generally has better fire performance than some wood species and wood-based products (Mena et al. 2012; Xu et al. 2020; Solarte, Hidalgo, and Torero 2018; Huo, Ma, and Xiao 2021; L. Chen et al. 2019).

Several studies recommend utilizing fire retardants or other protective techniques to increase the fire retardancy of bamboo. For example, using boric acid or borax and MgAl-LDH coating on a bamboo surface (Yu et al. 2017; Guo et al. 2019; Yao et al. 2019), use of charring in extending the burning time and lowering the round bamboo temperature to its auto-ignition temperature (Fitriana and Tsai 2017), or use of insulation to the inner parts of the cross-section of laminated bamboo (Gutierrez et al. 2019). These previous studies gave an overview that further research is still needed to find the proper method to improve the fire resistance performance of bamboo.

Houses with plastered flattened bamboo (*palupuh*) have become one of the cheapest house wall construction options. However, no research has been conducted on the fire resistance level and the effectiveness of using mortar as a protector on plastered bamboo walls. Mortar is a mixture of sand, binders such as cement and lime, and water, which is applied as a paste and then cured. The water-to-cement ratio affects mortar porosity and hydration (X. Chen and Wu 2013). Most mortar is somewhat fire-resistant; however, when mortar is exposed to high temperatures, the heat generated by the fire changes the structure and pore density of the mortar (Kim, Yun, and Park 2013), causing contraction and thermal expansion, which eventually generates cracking. Thermal expansion in mortar is usually much less than at lower temperatures (Cruz and Gillen 1980; Rodriguez et al. 2011). Thermal expansion and thermal deformation are strongly influenced by porosity, with thermal expansion decreasing as porosity increases (Zeng et al. 2012).

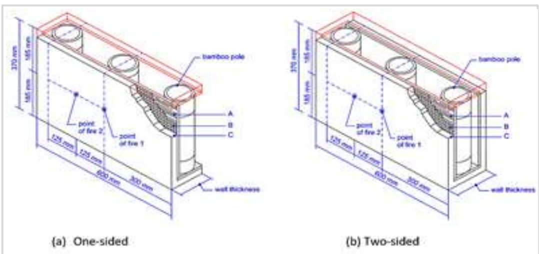
Cracks or cavities in the mortar layer cause heat to spread through the flattened bamboo by convection and igniting the wall. The burning of flattened bamboo inside the wall indicates the dynamics of a fire occurring in a compartment. These weaknesses can significantly affect the fire resistance performance of composite bamboo shear walls. Standard procedures for passive protection systems planning for fire prevention in buildings require wall components of residential buildings that carry loads to have a Fire Resistance Level of 90/90/90 minutes (SNI 03-1736-2000). However, there has been no research on using mortar as a protector on composite bamboo shear walls to achieve fire resistance according to standard requirements. Hence this research aims to understand the performance of the mortar layer in protecting bamboo against fire and increasing the fire resistance of the composite bamboo shear wall.

Method

The test was done in two stages; the first is the non-standardized test stage aims to identify which wall configuration has the best fire resistance. The best configuration was tested in the second stage using the standardized test method based on SNI 1741-2008 and ISO 834-1-1999. The non-standardized testing method refers to the same standards with some modifications and simplification, particularly on the furnace type and temperature. This was done considering the unavailability of equipment to test small-size specimens (less than 105 cm x 106 cm) as required by SNI.

Pre-test

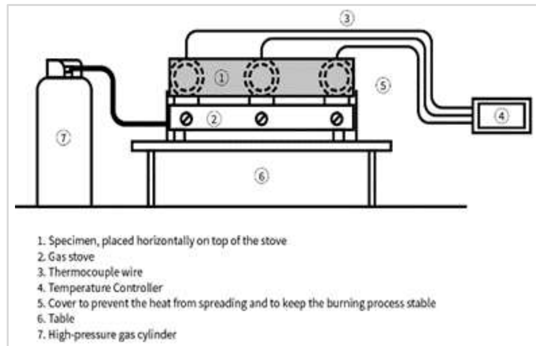
The bamboo wall was constructed of three bamboo stalks (*Gigantochloa apus*) with a diameter of 80-90 mm, strengthened with steel plate bracing with a thickness of 3 mm and a width of 30mm. The iron plate was installed diagonally on one side of the bamboo stalks arranged parallel to each other. The specimen length is 600 mm, height 300 mm, and thickness 150 mm. Bamboo stalks and bracing were covered with mortar (1PC : 3sand) with a thickness of 25-35 mm. There are two variations of specimens with different kinds of mortar covering using flattened bamboo and chicken wire/metal lath.: one-sided (code 1P-1, 1P-2) and two-sided (code 2P-1, 2P-2). The specimen was kept for 2-3 weeks until the mortar was completely dry. The detailed construction of the model is seen in figure 1.



(A = Flattend bamboo; B = Chicken wire; C = Mortar)
Figure 1. Construction of specimen

Two gas stoves with a maximum heat of 800°C and two 12 kg gas cylinders were used as test furnaces. Six thermocouples were used to read the temperature of the specimen and the furnace. The specimen was placed in the furnace at a horizontal position (figure 2). Software LabVIEW Measurement ver. 0.92 was used to read the data from thermocouples. A digital thermometer was also used to identify specific points in the specimen that could have a higher temperature than other points. The variety of burning temperatures ranges from 200 °C to 800 °C. The temperature was recorded every 5 minutes, and every change in the specimen was recorded, e.g., fire, water, or crack emission. The test is stopped when the temperature of the unexposed side of the specimen exceeds 100°C or the maximum burning time of 120 minutes, respectively.

(a)



(b)

Figure 2. Position of thermocouples on the specimen (a) and position of the specimen during the test (b)

Standardized test

Two specimens measuring 2640 mm x 2640 mm made of flattened bamboo covered with mortar with a thickness of 20-25 mm, on one-sided (M1) and two-sided (M2), are used (figure 3).

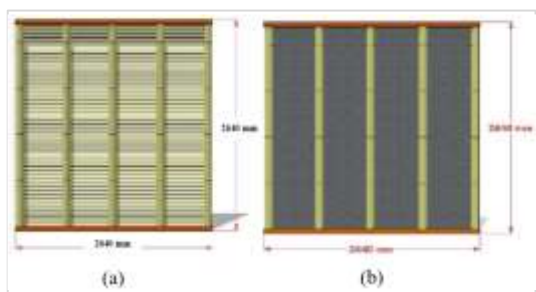


Figure 3. One-sided specimen (a), two-sided specimen (b)

The furnace temperature was measured using nine thermocouples (TC1-TC9) evenly distributed in the furnace. The back-surface temperature of the specimen was measured using nine thermocouples (TC10-TC18) mounted on the not exposed to fire surface (figure 4).

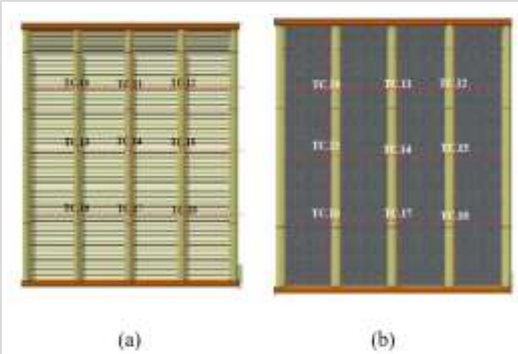


Figure 4. The position of the thermocouple on the unexposed side of the specimen M1 (a) and specimen M2 (b)

Fire resistance is measured based on integrity and insulation level. In this study, no stability test was carried out because it was not required for non-structural components. Integrity means that there is no smoke/fire fine crack on the surface of the specimen exposed to fire during the combustion period, and insulation means that the average surface temperature of the back side of the specimen is not more than the average temperature limit required. Burning time is set to 120 minutes. The test stops when insulation temperature limits are exceeded or cracking occurs. The fire resistance rating is determined based on the burning duration when either of these conditions occurs.

The average temperature limit for the M1 test is 140 °C + 23.1 °C (initial temperature) = 163.1 °C, and the maximum temperature limit is 180 °C + 23.1 °C (initial temperature) = 203.1 °C. Meanwhile, the average temperature limit for the M2 test is 140°C + 24.1°C (initial temperature) = 164.1°C, and the maximum temperature limit is 180°C + 24.1 °C (initial temperature) = 204.1 °C. The time it takes the M1 and M2 specimens to reach the required temperature limits is used to calculate the level of fire resistance.

Result and discussion

Test results of the pre-test stage for all specimens are shown in figure 5 and table 1.

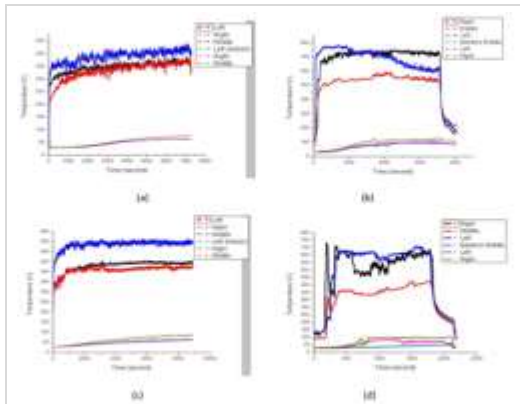


Figure 5. Time-temperature curves result of pre-test for specimen (a)1P-1, (b) 1P-2, (c) 2P-1, and (d) 2P-2

Table 1. Results of pre-test

Specimen	Plaster position	Average furnace temperature	Burning time	Specimen temperature
1P-1	One-sided	386 °C	120 min	75 °C
1P-2	One-sided	567 °C	36 min	102 °C
2P-1	Two-sided	674 °C	67 min	126 °C
2P-2	Two-sided	477 °C	120 min	87 °C

From the results in table 1, it is known that in terms of time, the higher the furnace temperature, the shorter the time required to increase the temperature of the two specimens to exceed 100 °C. The burning time of specimen 1P-1 is longer than that of specimen 1P-2, with a lower combustion temperature of 1P-1 than specimen 1P-2. The burning time of specimen 2P-1 is shorter than that of specimen 2P-2, with a higher burning temperature of specimen 2P-1 than specimen 2P-2. At the end of the combustion, the temperature of specimen 2P-1 is higher than that of 2P-2. The physical condition of the specimen on the flame-exposed and non-flame-exposed sides after the test is shown in table 2.

Table 2 shows that in the specimens with one-sided mortar (1P-1 and 1P-2), the mortar layer exposed to fire did not crack or peel off, and the bamboo mat behind the mortar only blackened, as well as the bamboo poles behind the bamboo mat. At the end of the combustion, the temperature of the 1P-1 specimen is lower than that of the 1P-2 specimen. On the side exposed to fire, the condition of the flattened bamboo in the 1P-1 and

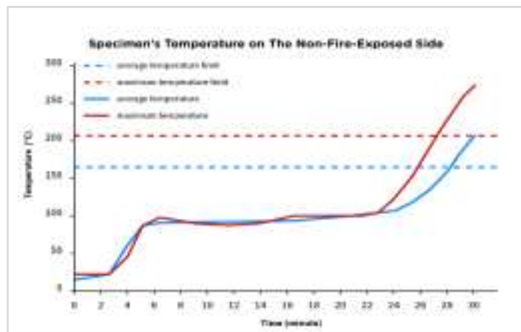
1P-2 specimens was black, but the 1P-2 bamboo pole specimens did not change colour. While on the side not exposed to fire, flattened bamboo in specimen 1P-1 blackened, but the bamboo pole did not change colour, while in specimen 1P-2, both flattened bamboo and bamboo polish did not change colour at all. In specimens with double-sided mortar, cracks and peeling occurred in specimen 2P-1 on the side exposed to fire. The flattened bamboo on this side was scorched and shattered, while the bamboo poles were blackened. The same condition occurred on the side that was not exposed to fire, even though the mortar layer was not cracked or peeled off.

Table 2. Physical specimen condition after pre-test

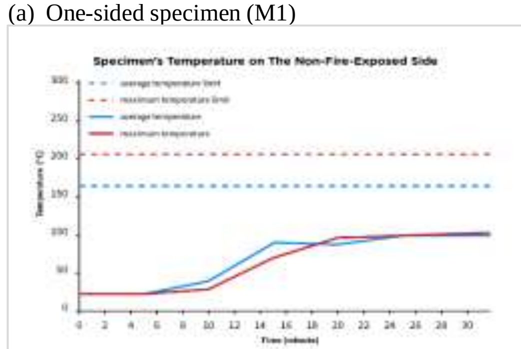
Specimen	Exposed side				Non-Exposed Side		
	Mortar		Flattened bamboo	Bamboo poles	Mortar	Flattened bamboo	Bamboo poles
	Peeled (Y/N)	Cracked (Y/N)	Changes	Blackened (Y/N)	Cracked (Y/N)	Changes	Blackened (Y/N)
1P-1	N	N	Blackened tip	Y	-	Blackened tip	N
1P-2	N	N	Blackened tip	N	-	No changes	N
2P-1	Y	Y	Scorched-mostly Shattered	Y	N	Scorched-mostly Shattered	Y
2P-2	Y	N	Blackened tip	N	N	No changes	Y

Meanwhile, the mortar layer of the 2P-2 specimen was peeled off on the fire-exposed side, but there were no cracks on either the fire-exposed or non-fire-exposed side. Unlike in specimen 2P-1, the condition of the flattened bamboo in specimen 2P-2 only blackened in part exposed to fire, but there was no change in colour on the side not exposed to fire. The flattened bamboo did not change colour, either on the fire-exposed or non-fire-exposed side. The temperature of specimen 2P-2 is slightly higher than the specimen temperature of 1P-1 and not exceeding 100 °C, although both of the specimens have the same combustion time, and there is a significant difference in furnace temperature between specimens 1P-1 and 2P-2.

The standardized test result for the one-sided specimen (M1) and two-sided specimen (M2) is shown in figure 6 and table 3.



(a) One-sided specimen (M1)



(b) Two-sided specimen (M2)

Figure 6. Time-temperature curves result of standardized test for one-sided and two-sided specimen

Table 3. Results of standardized test

Specimen	Plaster position	Average furnace temperature	Burning time	Specimen temperature (average)
M-1	One-sided	858,6 °C	32 min	94.2 °C
M-2	Two-sided	1025,7 °C	119 min	154,4 °C

Like the pre-test, the standardized test results showed that the specimen temperature increased with increasing furnace temperature and combustion time. The M1 specimen test was carried out for 32 minutes, where until the 32nd minute, the average upper surface temperature of the test object was 94.2 °C, not exceeding the average temperature limit value (163.1 °C) and not exceeding the maximum temperature limit value (203.1 °C). After 32 minutes of testing, the test object was damaged by fire cracking, and the test was stopped. Thus, it was determined that the value of the insulation resistance and integration of the test object was 30 minutes (according to the value of the five-minute measurement interval). The M2 specimen test was carried out for 119 minutes, where at the 110th minute, the average back surface temperature of the test object (154.4 °C) had not exceeded the average temperature limit value (164.1 °C). However, the temperature at one point of the thermocouple reached 221.5 °C, which exceeded the maximum temperature limit value (204.1 °C). Thus, the value of the insulation resistance of the M2 specimen is 105 minutes (according to the value of the five-minute measurement interval). After 119 minutes of testing, the specimen was damaged by fire cracking, and the test was stopped. Thus, the value of the integrity criterion is 115 minutes (according to the value of the five-minute measurement interval). Table 3 shows that the insulation and integration level of the M1 specimen is lower than that of the M2 specimen. Thus, the level of fire resistance of M2 specimens is higher than that of M1.

The condition of flattened bamboo in the M1 specimen was partially burnt due to penetrating cracks. Meanwhile, at the same minute, on the M2 specimen, there was no fine crack, and the condition of flattened bamboo and bamboo polish on the side not exposed to fire did not change colour, as seen in figure 7 and figure 8.

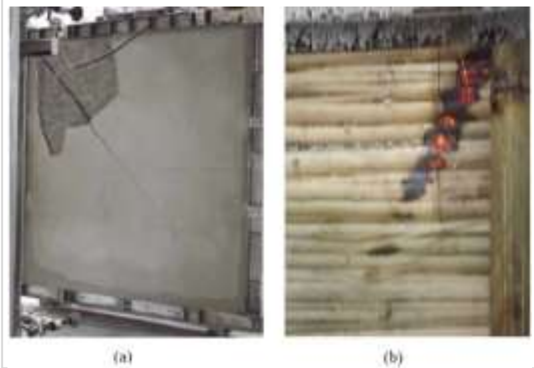


Figure 7. Mortar condition of specimen M1 after the test. Cracks and peels on the fire-exposed side (a) and a close-up of parts on the non-fire-exposed side (b)

Figure 8. Specimen M2 condition after testing on the fire-exposed side. The black line is grouted to cover hair cracks before the burning test

Conclusion

Observation of various conditions of the four specimens after the pre-testing stage found that the presence of mortar and mortar condition (peeled or cracked) on the fire-exposed side influenced the resistance of the composite bamboo shear wall against fire. It can be seen in the states of specimens 1P-1 and 1P-2, where the mortar does not peel or crack during the firing process, so there is no significant change in the flattened bamboo and the bamboo pole behind it. In contrast to the condition of specimen 2P-1, where the mortar peeled off and cracked so the fire could penetrate, and the flattened bamboo was burned. While in specimen 2P-2, although the mortar peeled off, the flattened bamboo did not burn because there was no penetrating crack. This condition occurred consistently in standardized tests where a sharp crack in the mortar layer of the M1 specimen caused damage to the flattened bamboo behind it. However, the test time was short, and the furnace temperature was lower than that of the M2 specimen. Penetrating cracks in the mortar is more dangerous than if the mortar peels off because the fire can spread through the gap.

There was a higher temperature increase in the two-sided specimen compared to the one-sided specimen; this means that the increase in the temperature is not caused by the location of the mortar but is a logical consequence of the increase in the furnace temperature. The location of the mortar layer is also not related to the insulation level; it is influenced by the presence or absence of penetrating cracks in the wall. However, this cannot be confirmed in standardized tests due to the limited number of test specimens.

The two tests show that if there is a penetrating crack in the one-sided specimen, the flattened bamboo will burn only on the back of the mortar layer with a penetrating crack. In contrast, the flattened bamboo will burn completely if a penetrating crack occurs in a two-sided specimen. This is possible because of the accumulated heat in the specimen, which is covered by mortar on both sides. This phenomenon was demonstrated in specimen 2P-1. However, if there are no cracks in the mortar layer, the fire resistance of specimens with double-sided mortar is almost 2 hours.

It is concluded that mortar can increase the insulation property of flattened bamboo wall specimens against fire. In contrast, the absence of a mortar layer significantly lowers the performance of bamboo wall fire-resistant. The most effective mortar application is on all sides of the specimen, with a thickness of 25 mm-30 mm. The effectiveness of mortar as a protector is strongly influenced by the performance of the mortar at high temperatures. Control of the quality of the mortar becomes very important in manufacturing fire-resistant flattened bamboo walls.

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Author(s) contribution

Lily Tambunan contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Luis Felipe Lopez contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Andry Widyowijatnoko contribute to methodology, supervision, and validation.

Yulianto Sulistyo Nugroho contribute to methodology, supervision, and validation.