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Behaviour of Walls Constructed using Kelempayan (*Neolamarckia cadamba*) Wood Wool Reinforced Cement Board

(Tingkah Laku Dinding yang Dibina menggunakan Papan Simen Bertetulang Tatal Kayu Kelempayaan (*Neolamarckia cadamba*)

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ABSTRACT

This research investigated the behaviour of walls produced from wood wool cement board (WWCB) which were reinforced with a lesser known commercial timber, Kelempayan, when subjected to compression load. Kelempayan timbers were shredded into wood wool and used as reinforcement agent in this study. WWCB having dimensions of 600 × 2400 × 50 mm and 600 × 2400 × 75 mm, respectively, were fabricated. Properties of the WWCB samples, namely swelling, bending and compression strength were tested. 75 mm WWCB has higher fracture toughness but lower strength compared to 50 mm WWCB. Four types of wall systems with different type of configuration were produced and the test results were compared focusing on their value of ultimate load and failure mode. Walls that constructed without application of link and plaster displayed the poorest performance. Plastered and linked wall had the highest ultimate load and comparable with other load bearing walls. The results suggested that walls constructed using WWCB reinforced with Kelempayan wood wool are suitable for load bearing as they exhibited comparable properties when compared to the other load bearing walls such as masonry and straw bale wall.

Keywords: Failure; Kelempayan; reinforced cement; wall system; wood wool

ABSTRAK

Penyelidikan ini mengkaji kelakuan dinding yang dihasilkan daripada papan simen tatal kayu (WWCB) yang diperkuat dengan kayu komersial yang kurang dikenali, iaitu kayu Kelempayan, apabila dikenakan daya kompresi. Kayu Kelempayan dipotong menjadi tatal kayu dan digunakan sebagai agen pengukuhan dalam kajian ini. WWCB yang berdimensi 600 × 2400 × 50 mm dan 600 × 2400 × 75 mm telah dihasilkan. Ciri seperti perubahan dimensi, kekuatan lenturan dan mampatan WWCB telah diuji. 75 mm WWCB mempunyai ketangguhan retak yang lebih tinggi tetapi kekuatan yang lebih rendah berbanding dengan 50 mm WWCB. Empat jenis sistem dinding dengan konfigurasi yang berbeza telah dihasilkan dan keputusan ujian dibandingkan dengan penilaian nilai beban muktamad dan mod kegagalan. Dinding yang dibina tanpa penggunaan pautan dan plaster mempamerkan prestasi terendah. Dinding yang mempunyai pautan dan plaster mempunyai beban muktamad tertinggi. Berdasarkan keputusan yang didapati, ia menunjukkan bahawa dinding yang dibina menggunakan WWCB yang diperkuatkan dengan tatal kayu Kelempayan adalah sesuai untuk penanggulan beban kerana ia mempamerkan sifat yang setanding berbanding dengan dinding penanggulan beban yang lain seperti tembok batu dan dinding jerami.

Kata kunci: Kegagalan; Kelempayan; simen diperkukuh; sistem dindang; tatal kayu

INTRODUCTION

Shortcomings of cement boards such as brittle and low tensile strength have long been surmounted by reinforcement using materials with a higher tensile strength, for example, wood fibre. The product, called wood-cement composite, has served as construction and building material for over 60 years (Ashori et al. 2011). As one of the main types of wood-cement composites, application of wood–wool cement board (WWCB) as a construction material is becoming increasingly prevalent, mainly as a substitution for asbestos-based cement products. Wood-wool, a type of ribbonlike particle called excelsior, is the main component of WWCB. The wood-wool was first coated with cement and a small amount of additives was then added as catalyst and finally followed by pressing them into panel (Ashori et al. 2011). The application of WWCB is economically and environmentally beneficial as wood wool is a renewable material which is available at relatively low cost (Onuaguluchi & Banthia 2016). Wyborn (2013) reported that the application of WWCB has reduced the cost of housing components to a great extent since raw materials with low commercial value could be used for fabrication.

In addition, one of the many advantages of WWBC is that it can be conveniently produced from locally available wood such as Kelempayan (*Neolamarckia cadamba*), a lesser known commercial timber in Malaysia. It is a lignocellulosic material with high tensile strength that are suitable for WWBC production. Kelempayan is a light hardwood with inferior durability and is commonly used in light construction, plywood and pulping industry. Kelempayan offers high economic and environmental value owing to its fast-growing characteristic which guarantees an economic return within eight to ten years (Lai et al. 2013). In 2005, Kelempayan was selected together with seven other species under a soft loan programme managed by Malaysian Timber Industry Board for the development of forest plantations (Zaini 2010). This programme aimed to ensure the sustainability of wood resource for the domestic timber industry while relieving the burden of natural forest being the only source of wood supply. For the next 15 years, a total of 375,000 ha of forest plantation will be planted at an annual planting rate of 25,000 ha (Ministry of Plantation Industries and Commodities 2005). Five million cubic meters of timber could be produced for every 25,000 ha of planted land. Optimistically speaking, the availability of Kelempayan timber as a raw material in WWBC production would not be a cause of concern for several years to come.

To construct a building, the wall is a very important component. The desirable properties of a board or panel suitable for wall application are high durability, dimensional stability, toughness, fire resistance, good acoustic and thermal insulation properties, good biological resistance, rapid production and low production costs. WWCB matches all the favourable properties (Del Menezzi et al. 2007). Non-renewable, high carbon emission and labor-intensive masonry clay brick and sand cement brick are the typical materials that are used for wall construction (Goverse et al. 2001). In the view of greener materials, WWCB can be a substitute to the aforementioned materials for wall components. Unfortunately, lack of design standards and guidelines pertaining to the application of WWCB has shaken the confidence of designers and contractors in Malaysia to use WWCB (Manalo 2013). Scarcity of literature on the structural behavior of wall systems using WWCB has promoted the implementation of the current study. The purpose of this study was therefore to investigate the behaviour of non-load bearing wall with different type of configurations constructed using WWCB which has been reinforced with Kelempayan wood wool.

MATERIALS AND METHODS

PREPARATION OF WOOD WOOL

8-years-old Kelempayan timber was shredded into wood wool. The debarked Kelempayan logs were cut into blocks of 50 cm length. After storage, the logs were cross-cut into billets and shredded on a cutting machine (Wadkin 26" BSW) to produce wood wool. Wood wool strands used in the manufacture of WWCB in this study were approximately 3.5 mm wide and 0.5 mm thick with lengths of up to 40-50 cm. After collection, the wood wool was soaked in the water in a pit for 5 min and then removed from the pit for WWCB manufacturing.

MANUFACTURING OF WOOD WOOL CEMENT BOARD

The collected wet wood wool, together with cement powder, were fed into a continuous mixer. The ratio of the combination of Portland cement with water and wood wool was 2:1:1. After mixing, the mixture was transported to a distribution machine for the forming process. A continuous mat of mixture was spread onto plywood moulds with dimensions of 600 × 2400 × 50 mm and 600 × 2400 × 75 mm, respectively. The moulds with the mixture were stacked in an empty space prior to pre-press. Three concrete slabs were used to pre-press the mixture and later conditioned in a chamber for a few hours for setting. After setting, the boards were removed from the moulds for further curing.

PROPERTIES EVALUATION OF WOOD WOOL CEMENT BOARD

The density and moisture content of WWCB were measured and recorded. For the swelling test, test pieces with a dimension of 100 mm × 100 mm × thickness of the board were prepared using Sears CRAFTSMAN 10" Radial Arm Saw and immersed in fresh clean water at a temperature of 27 ± 2°C. After 24 h immersion, the test samples were removed and the thickness was remeasured. The thickness swelling was calculated as in (1):

$$S\ (\%) = ([T_2 - T_1])/T_1) \times 100 \qquad (1)$$

where S is the swelling value after 24 h immersion in water (%); T_1 is thickness of sample before water immersion (mm); and T_2 is thickness of sample after water immersion (mm).

The bending strength (modulus of rupture and modulus of elasticity) of the WWCB samples was determined using Instron Universal Testing Machine (UTM) according to procedures specified in Malaysian Standard specifications for Wood Cement Board, MS 934:1986. The compression strength parallel to the surface was conducted in accordance with ASTM D1037. Five samples were used for every property testing.

FABRICATION OF WALLS FROM WWCB

Four types of wall with different configurations as shown in Table 1 were set up using the produced WWCB. Three types of wall were produced using WWCB with a 75 mm thickness, namely: WWCB connected with mortar only, WWCB connected with mortar and links and WWCB connected with mortar, links and plaster. Another type of wall was constructed using WWCB with a 50 mm thickness for comparison purpose. The WWCB was connected with mortar, links and plaster.

Basically, all the walls were set up using three layers of WWCB. The height and width of the produced walls were 1800 and 1000 mm, respectively. Two WWCB with a size of 250 × 600 mm and five boards of 500 × 600 mm were used to set up each wall. For wall type A, WWCBs were glued by mortar only and was about 10 mm thickness. In

TABLE 1. Walls configurations

Wall	Thickness	Mortar	Links	Plaster
A	75 mm	√		
B	75 mm	√	√	
C	75 mm	√	√	√
D	50 mm	√	√	√

order to set up the wall, a mortar called 'Pyepremix Plaster 921' supplied by Duralite was used to glue the boards. The wall was set up as illustrated in Figure 1.

For wall type B, the board arrangement to construct the wall was similar to wall A. 300 mm long steels with a diameter of 6 mm were attached vertically and horizontally to the wall. Two types of steel were used, namely hooked link for external attachment and embedded steel for the internal attachment.

Twenty hooked links were inserted into the boards to connect them at both sides of the wall as shown in Figure 2(a). There were also external links attached at the surface of the wall as shown in Figure 2(b).

For wall type C, the wall with a thickness of 75 mm were attached with mortar and also linked in a similar way to wall B. Additional plaster of 10 mm thickness was coated to the surface of the wall. The schematic diagram is shown in Figure 3. The duration for the plaster curing was seven days. For wall type D, the set up was similar to wall C except the thickness of WWBC used was 50 mm. Two walls were produced for each type of configuration, denoted as A1, A2, B1, B2, C1, C2, D1 and D2. A total of eight walls were produced using WWCB in this study.

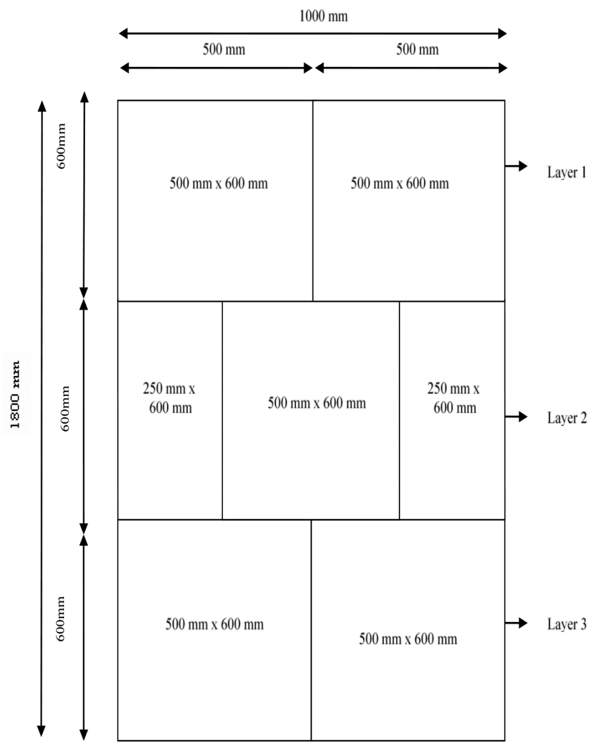


FIGURE 1. Schematic diagram of wall type A

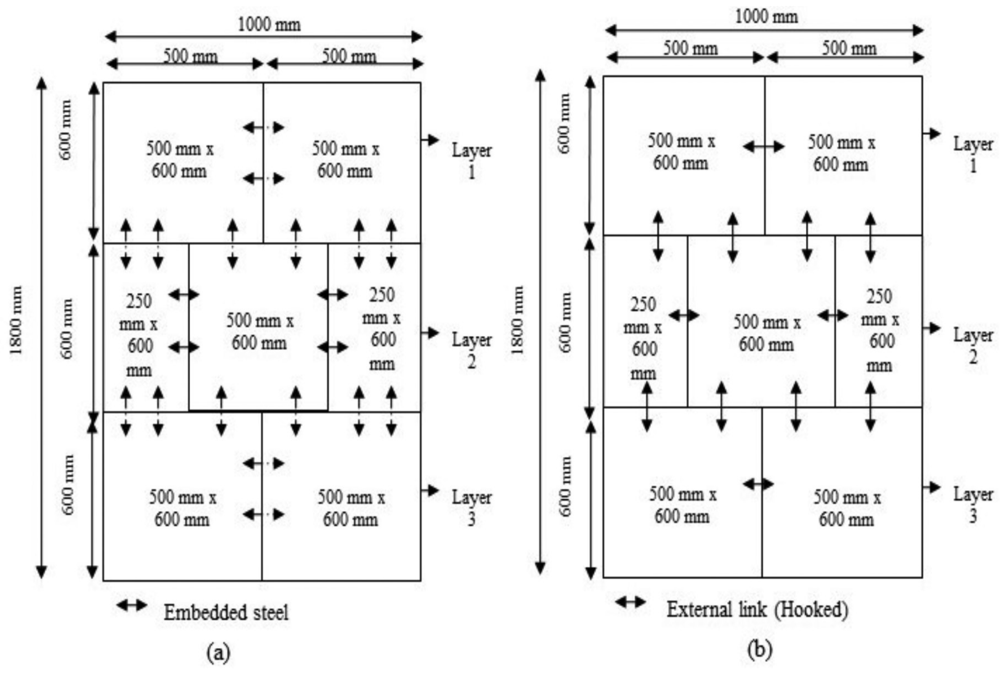


FIGURE 2. Schematic diagram of wall B with internal link (embedded) (a) and external link (hooked) (b)

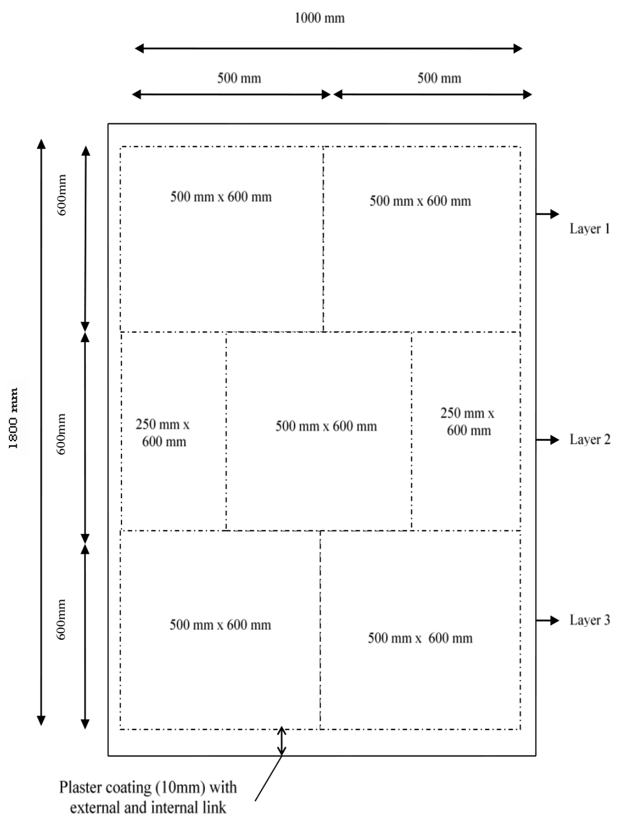


FIGURE 3. Schematic diagram of wall type C & D

COMPRESSION TEST ON THE WALL

All the walls were subjected to compression load at the top of the wall by using a hydraulic jack. The jack was used to generate a compressive force with maximum load of 1000 kN and the value was recorded by the load cell. There were four Linear Voltage Displacement Transducers (LVDT) used to measure the displacement of the wall during testing. One LVDT was placed at the actuator to measure the shortening of the wall (T1). Meanwhile on top of the wall, one LVDT was placed at the left side of the plate (T2) and the other one on the right (T3). These two LVDTs measured the vertical displacement at the side of wall. One LVDT was also placed at the center of the wall (T4) to measure the lateral displacement. The average incremental rate of loading was 0.6 kN/sec.

RESULTS AND DISCUSSION

PROPERTIES OF WWCB

Table 2 summarizes the physical and mechanical properties of the produced WWCB. From Table 2, it can be seen that the 50 mm board was denser than 75 mm board (358 kg/m^3 and 320 kg/m^3, respectively) suggesting that the 75 mm board was more porous. Since density equals mass over volume, it is reasonable that the board with a higher thickness (higher volume) resulted in lower density when the mass remained the same. The percentage of swelling of the 50 mm board (1.09%) were higher than 75 mm board (0.64%) due to its higher density. The 75 mm board had a lower density and therefore contained more gaps between the wood wool and cement. Consequently, the absorbed water was extended into and filled the gaps and led to a lower percentage of swelling (Lee et al. 2015).

As regards to the mechanical properties, the graph of load versus displacement is shown in Figure 4.

The convex shape of the graphs represents the brittle fracture behaviour. Based on Table 2, one can see that the MOE value for 50 and 75 mm board was 314 and 195 N/mm^2, respectively, suggesting that 50 mm board was stiffer due to its higher density. This finding was consistent with Soffi et al. (2014), which found that 50 mm board (444 N/mm^2) have higher MOE than 100 mm board (239 N/mm^2). However, the ductility for a 75 mm board was higher where a displacement value of 9.2 mm was recorded compared to that of a 50 mm board with a displacement value of 4.62 mm. On the other hand, the modulus of rupture (MOR) value for 50 and 75 mm board was 0.32 and 0.23 N/mm^2, respectively. The bending strength of the board increased along with the increasing density as a denser wall could sustain a higher load before it failed. According to Pablo (1988), the minimum requirement for bending strength of for 50 and 75 mm WWCB according to DIN 1101-2000-06: Wood wool slabs and sandwich composite panels for use as insulating building material - Requirements and testing is 0.5 and 0.4 N/mm^2, respectively. Unfortunately, the bending strength of the WWCB produced in this study was lower than the standard requirement. This finding could be attributed to the wood species used in the production of WWCB as wood species is one of the vital parameters that

TABLE 2. Properties of wood wool cement boards

Properties	Thickness	
	50 mm	75 mm
Density (kg/m^3)	358 ± 18	320 ± 11
Moisture content (%)	8.6 ± 0.4	7.9 ± 0.4
Swelling (%)	1.09 ± 0.10	0.64 ± 0.05
Modulus of elasticity (N/mm^2)	314.47 ± 16.09	194.94 ± 17.17
Modulus of rupture (N/mm^2)	0.32 ± 0.07	0.23 ± 0.04
Fracture toughness (N/mm^2)	162.76 ± 3.96	415.76 ± 16.16
Compressive strength (N/mm^2)	1.37 ± 0.12	0.96 ± 0.05

*Value after ± is standard deviation

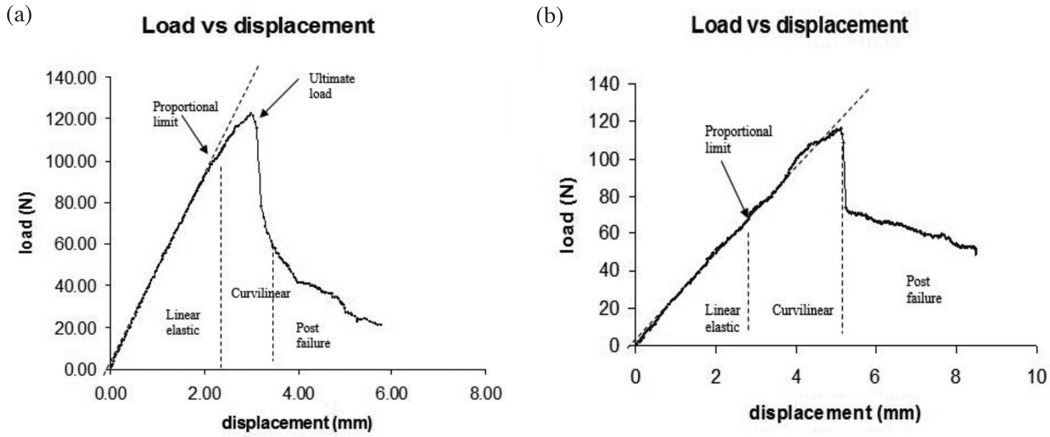


FIGURE 4. Load versus displacement of bending test for (a) 50 mm wood wool cement board and (b) 75 mm wood wool cement board

affects the bending strength of WWCB (Lam et al. 1997). The compressive strengths of the boards were 1.37 and 0.96 N/mm^2 for 50 and 75 mm, respectively. As reported by Al Rim et al. (1999) and Frybort (2008), the compressive strength is strongly related to the density. The higher the density, the higher the compressive strength. From observation, most of the specimens failed by shearing at the top part. The maximum strain for the 50 mm board was higher (2.54%) than the 75 mm board (2.04%) due to the larger cracked line.

Basically, toughness is a measure of the energy capacity of a material and is represented by the area under the load versus the displacement curve. The toughness value was calculated using Simpson's 3/8 rule and the results showed that the toughness for 75 mm board was 415.76 N/mm^2, while the value for the 50 mm board was 162.76 Nmm^2. The higher value of thickness increased the toughness of the board although it was lower in strength and exhibit brittle failure. Hence, the 75 mm board is more suitable for structural applications as it can dissipate more energy especially in earthquake prone areas (Wolfe & Gjinolli 1999).

PROPERTIES OF WALLS CONSTRUCTED USING WWCB

The ultimate load and displacement of walls produced are summarized in Table 3. It was observed that wall A1 was separated between the second and third layer at the mortar connection. Meanwhile, wall A2 was buckled between first and second layer. Figure 5(a) and 5(b) shows the schematic diagram of failure mode for both walls.

The graph of load versus displacement is illustrated in Figure 6. For wall A1, it can be seen that the load increased until it reached the initial failure at 5.7 kN. The wall started to bend while the mortar at the bottom layer cracked at this point. The lateral displacement also increased drastically after the initial failure. The load was continuously applied until it reached the maximum value of 12.8 kN when it failed, broke apart and separated at the lower layer. Then, the applied load dropped with a significant increase in deformation. For wall A2, the initial failure observed started at 3.2 kN while the mortar started to crack. The side displacement (average of T2 and T3) showed a higher value than the displacement at the top of the center (T1). The displacement increased until it reached the ultimate load of 9.6 kN. The wall buckled at the top between the first and second layer. The lateral displacement increased tremendously after the initial failure. The wall started to bend at the top until it reached the ultimate failure by local buckling.

For both walls B1 and B2, it was observed that the walls buckled between the first and second layer. They exhibited similar failure mode which was local buckling at the top layer. The mortar also cracked and the link was displaced between the layers. However, all the layers were still intact while the bottom plate was also still attached to the base. Signs of cracking were observed at the wall surface as shown in the schematic diagram of Figure 7.

TABLE 3. Ultimate load and displacement of walls produced

Wall type	Average load (kN)	Actuator displacement (mm) T1	Average displacement (mm) T2 & T3	Center displacement (mm) T4
A	11.2	2.60	3.22	5.20
B	7.7	3.18	2.10	5.15
C	112.6	3.27	1.35	-0.33
D	110.3	0	1.09	1.34

*Note: Value is average of two wall panels for each wall type

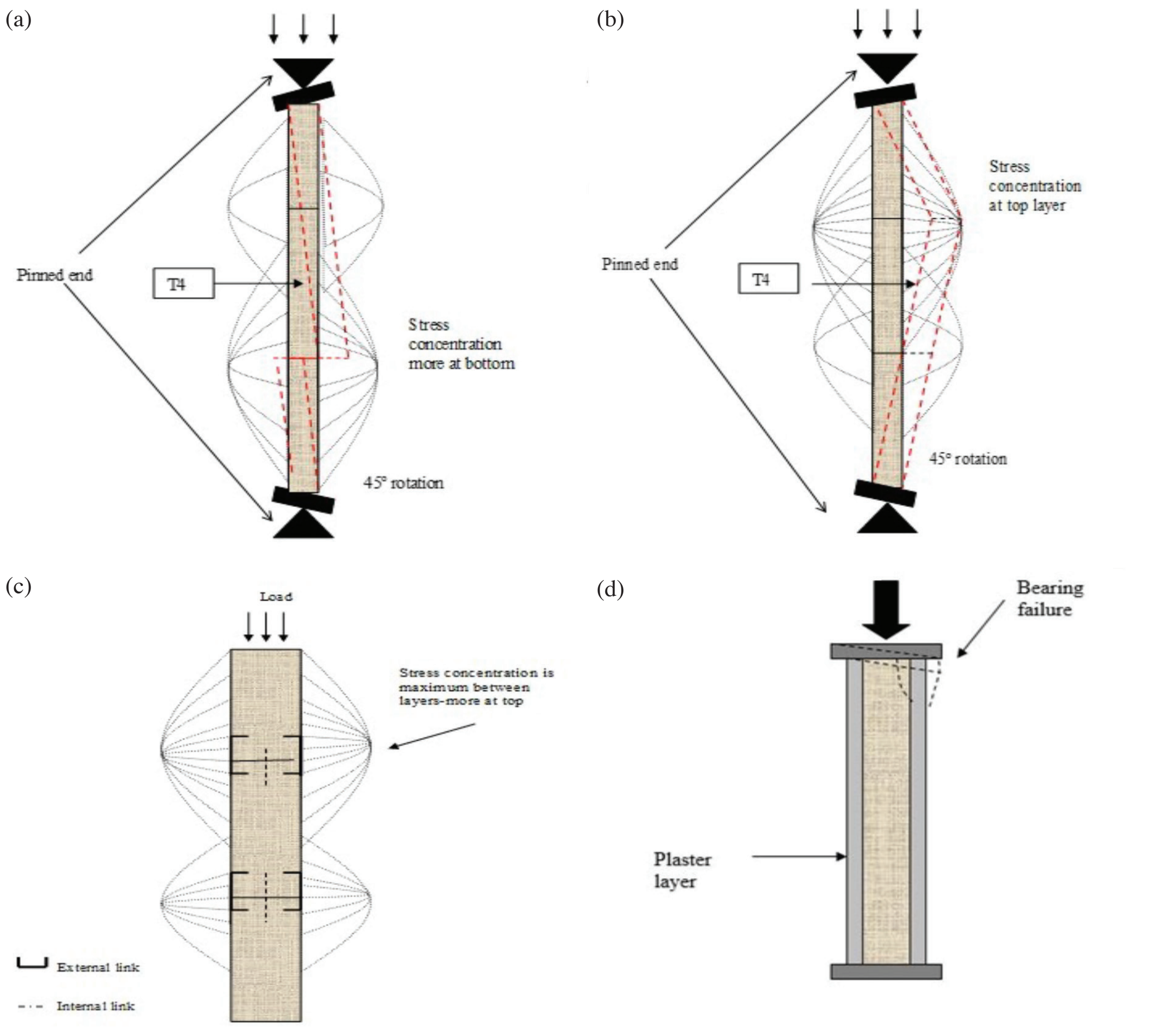
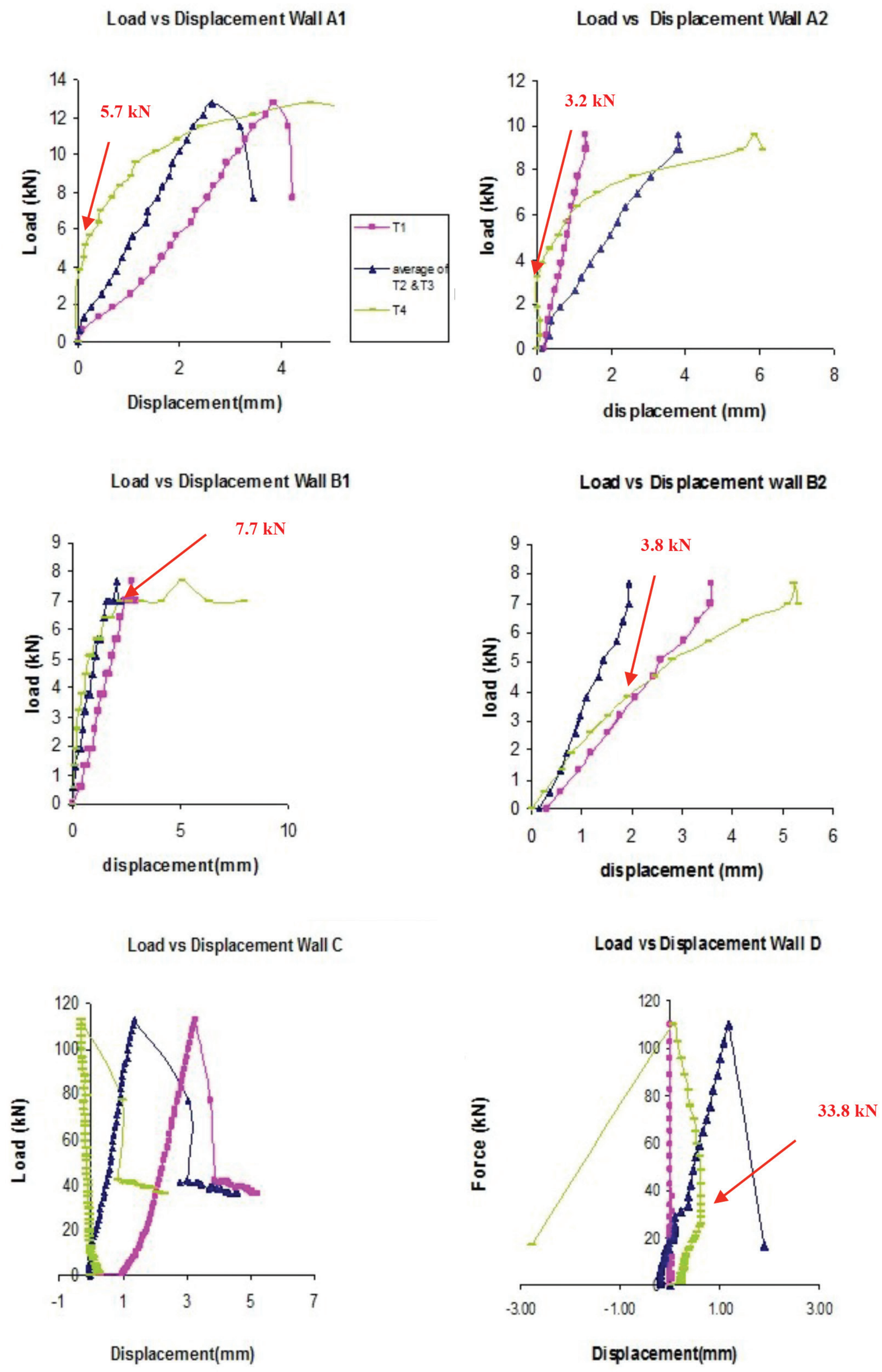


FIGURE 5. Schematic diagram of failure mode for walls produced: (a) wall A1, (b) wall A2, (c) wall B and (d) wall C & D

The graph of load versus displacement for wall B1 was plotted as shown in Figure 6. The graph shows that the displacement increased as the load increased. Initial failure occurred when links started to be displaced and the mortar cracked at the upper layer. The ultimate load was 7.7 kN and failed by local buckling at top. For wall B2, the initial failure was seen when the load reached 3.8 kN. The wall surface started to crack and the link got displaced at the top part. The wall started to lose its stiffness at that point. When the load continued to be applied to its maximum i.e. 7.7 kN, the wall buckled at top. There was a high vertical displacement of 3.59 mm measured by T1 at the top surface compared to the side edge of the wall. This indicates that the wall had not only shortened but had also caused local buckling at the top part. The maximum displacement was the lateral displacement of 5.20 mm. The wall bent towards the right direction. The mechanical properties of the wall had change due to material inhomogeneity which contributed to very high stress concentration between the layers, especially at the top part. This is shown in the schematic diagram of Figure 5(c). The wall could only withstand a very low load because of its inhomogeneity property.

Walls C also showed the same failure mode as Wall B. When the compression load was applied to wall C to its maximum load, the wall did not collapse but only some plaster fell off at the top part of the front side of the wall. No buckling was observed but bearing failure occurred at the top during post failure. The plaster cracked vertically on both sides of the wall although it was only at the top. The WWCB layers were still intact to each other. There was no cracking at the surface of the wall. As shown in Figure 6, the ultimate load capacity of the wall was 112.9 kN. For lateral displacement (T4), the negative and positive reading indicated that the wall moved inward and outward when subjected to the compression load. The wall did not buckle as the lateral displacement was very low which was 0.33 mm. The maximum displacement of 3.27 mm at the maximum load was measured by T1, which indicated a vertical shortening of the wall. The bearing failure of wall C is shown in the schematic diagram of Figure 5(d). The failure mode was quite similar to those of walls constructed using straw bales. According to King (2003), the bearing failure of straw bales occurs when the skin (plaster layer) crushes under the top or bottom plate and/or when the top



*red arrow indicates the load when initial failure occurred

FIGURE 6. Graph of load versus displacement for walls produced

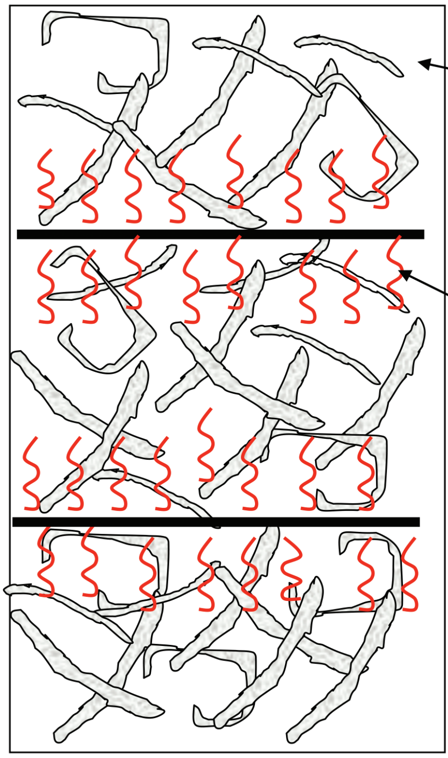


FIGURE 7. Cracked pattern at the surface for wall B1 and B2

or bottom plate crushes under the edge of the skin. The wall components have not been designed or built to sustain the focused stress at the joint.

On reaching the ultimate load, there was a horizontal plaster cracked at the front top of wall D. Bearing failure occurred and the plaster cracked vertically at the top side. However, the WWCB layers were still intact to each other. The plaster peeled off at the edge of the wall and slightly buckled during post failure. No cracking was observed at the center and the bottom part of the wall. The graphs of load versus displacement were plotted as shown in Figure 6. The initial failure occurred when the load reached 33.8 kN. The wall started to crack at the top until the ultimate load of 110.3 kN was reached. At this point, the wall was obviously cracked at the edge of the top part, indicating bearing failure. The load then dropped significantly to 16.6 kN as it entered the post failure stage. The plaster peeled off and the wall was also slightly buckled during this stage. It can be seen that the deflection had slowly increased until it reached the maximum load. The maximum displacement was only 0.04 mm at the ultimate failure. However, during the post failure stage, the displacement significantly increased and the wall buckled to the left side. The maximum displacement was 1.34 mm which was measured by transducer T2 and T3. Both transducers were located at both sides of the edge of the wall. It can also be seen that the displacement measured by T1 was almost zero, indicating that no wall shortening was observed.

Generally, the most observed failure mode was at the top of wall and the failure mode was dominated by the buckling of the wall board. Walls with a plaster coating (wall C and D) also exhibited bearing failure which cracked vertically at the top of the wall. Based on own observation, the upper layer was near to the applied load, thus causing most failure to occur at the top part. No other failure occurred at the center and bottom of the wall except for wall A, where layers of WWCB were separated at the bottom part. Theoretically, links or reinforcements could enhance the strength of the wall when subjected to loading. However, wall B with links attached exhibited a lower value in comparison to wall A that had no links (7.7 and 11.2 kN, respectively). The links, however, had prevented the wall from being broken and caused buckling only. The material inhomogeneity between the board and links of wall B induced stress concentration at the mortar layer compared to wall A which was homogeneous. Thus, the wall could not sustain a high load, however, the value of displacement was reduced because wall B was stiffer than wall A (5.09 and 5.20 mm, respectively) which was held tightly by the attached links.

It is interesting to note that the ultimate load of walls with plaster coating, walls C and D (112.6 and 110.3 kN, respectively) had significantly increased in comparison to wall A and B. Both vertical and lateral displacements were also lower than the walls without plaster. This proves that plaster coating had enhanced the strength of walls and reduced deflection. The plaster coating had transformed the wall into a homogeneous wall that was able to withstand a higher compression load. As reported by Faine and Zhang (2001) and Walker (2004), walls that were constructed using straw bales rendered with plaster exhibited significantly stronger strength. Therefore, it can be interpreted that the bonding between WWCB and plaster also plays a similar role in increasing the bending resistance of the wall.

Other than the difference in the set-up configuration, the slenderness ratio (length/width of the wall) also affected the behaviour of the wall (Himasree et al. 2017). The higher the slenderness ratio of the wall panels, the lower the ultimate load that can be withstood by it. Therefore, it is understandable that wall D with a slenderness ratio of 36 had a lower ultimate load than wall C which possessed a slenderness ratio of 24. A research on masonry walls constructed using concrete by Seangatith (2005) also produced the similar results. The difference in ultimate load between walls D and wall C was slight, at only 2%. However, the toughness value for a 75 mm wall board was higher, implying that it could dissipate a lot of energy as it failed when encountering natural disasters. Therefore a 75 mm wall is preferable for housing construction especially in less developed countries that are located in the seismic region or regions which are prone to heavy winds.

Table 4 shows the comparison of walls constructed using WWCB with other wall systems. The ultimate load of the wall located between the straw bale wall and masonry wall had an ultimate load of 41.1 and 180.3 kN, respectively. The results suggested that the wall constructed using WWCB reinforced with Kelempayan wood was suitable for load bearing although it had been designed for

TABLE 4. Comparison with previous studies on walls with different systems and materials

Wall system	Material	Ultimate load (kN)	Reference
Composite wall- non-load bearing	Cement bonded wood with papercrete infill	25	Masjuki et. al (2008)
Load bearing	Straw bale with hazel pinned and plaster	41.1	Walker (2004)
Masonry-Load bearing	Soil cement brick with addition of ground ceramic waste	180.3	Lima Junior et al. (2003)
Composite wall- Load bearing	Concrete and steel sheeting	566	Hossain et al. (2015)
Non-load bearing	WWCB with links and plaster	112.6	Current study

non-load bearing. The wall configuration could be modified in future research in order to enhance the strength of the wall. As no established design standard is available in designing a wall using WWCB, further research needs to be done to attain this design standard. Consistent research of this material will provide more insights into the behaviour of the structural elements.

CONCLUSION

In terms of the WWCB produced, those with 50 mm thickness has higher density, swelling, MOE, MOR and compressive strength but lower fracture toughness compared to that of the WWCB with 75 mm thickness. 75 mm WWCB was chosen for the fabrication of wall due to its higher fracture toughness that are able to dissipate more energy. Wall with different configuration was produced and the results showed that under compression load, wall constructed using WWCB without links and plaster demonstrated the poorest behaviour by showing a large displacement, separation between layers and tilted. Wall types that have links or plaster display better performance with only buckling and minor cracks observed. The highest ultimate load of 112.6 kN was recorded in plastered and linked wall with a thickness of 75 mm (Wall C). The application of plaster significantly strengthens the WWCB wall. The bond between the plaster coating and WWCB enables load transfer and subsequently improved the compression resistance of the wall. Therefore, WWCB wall reinforced using Kelempayan wood wool coated with plaster and links can act as a load bearing wall as the ultimate load was found comparable with other load bearing walls such as masonry and straw bale wall.

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