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Study of the Mechanical Behavior of Traditional Japanese Mud Wall on Bamboo Lath

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Abstract: Mud wall on bamboo lath is a traditional Japanese method for constructing walls. Although the use of mud walls is environmentally friendly, it is necessary to evaluate the performances of the walls, especially their structural resistance, for broader and safe application. However, the performances of mud walls vary widely with various factors, including the locality, the natural materials used, the construction method adopted, and the quality of workmanship. In this study, the combinations of factors expected to improve the initial stiffness and toughness of mud walls were first determined based on previous studies. Subsequently, to reveal the influences of the bamboo lath configuration and properties of the wall mud on the structural resistance, structural experiments were conducted using full-section-sized specimens, the mechanical behavior observed, and characteristic values calculated. The results indicate that a mud wall of high initial stiffness can be practically achieved by avoiding gaps between the load-bearing elements and using wall mud with large elastic modulus and compressive strength. However, such walls tend to have reduced toughness because of marked delamination at the interface of the layers.

Key words: Mud wall, bamboo lath, mechanical behavior

1. Introduction

Mud wall on bamboo lathing, also referred to as "mud-bamboo wall construction", is a traditional Japanese method of constructing walls using a timber framework, bamboo lathing, and plaster produced by mixing mud and straw. Although the use of mud wall on bamboo lathing is environmentally friendly, it is necessary to evaluate the performance of the walls, especially their structural resistance, so that they can be used widely and safely. However, the structural resistance of mud walls varies widely depending on factors such as their location, the natural materials used, the construction method adopted, and the quality of the workmanship. Furthermore, the influence of wall mud properties and plastering methods on their structural resistance mechanisms is unclear. This study investigated the fracture behavior and resistance mechanisms of mud–bamboo walls subjected to horizontal forces and clarified the factors that influence their mechanical properties.

2. Methods

2.1 Mud Wall Specimen Types Employed

The specimens employed had the same cross-sectional dimensions of framework members as those used in real buildings, but were proportionally smaller. The timber framework was assembled using columns, a sill, a beam, and a batten. To create the bamboo lathing, which forms the bed required for the plastering of mud, split bamboo was woven into a grid-like pattern. This bed was created using two types of bamboo. The first type, called "bamboo furring", was inserted into holes in the sides of neighboring framework members every 30 cm. The other type, called "flying bamboo strip", was secured with rope ties at the points where the ties intersect the bamboo furring. The mud-bamboo wall comprised mud layers,

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including two base-coat and two middle-coat layers in general (Fig. 1). All layers were completely dried before the loading tests were performed.

The specimens are listed in Table 1. Based on the findings of previous studies [1, 2], the combinations of factors expected to improve the initial stiffness, Specimen No. 1, and toughness, Specimen No. 6, of the mud walls were determined. The factors are described below.

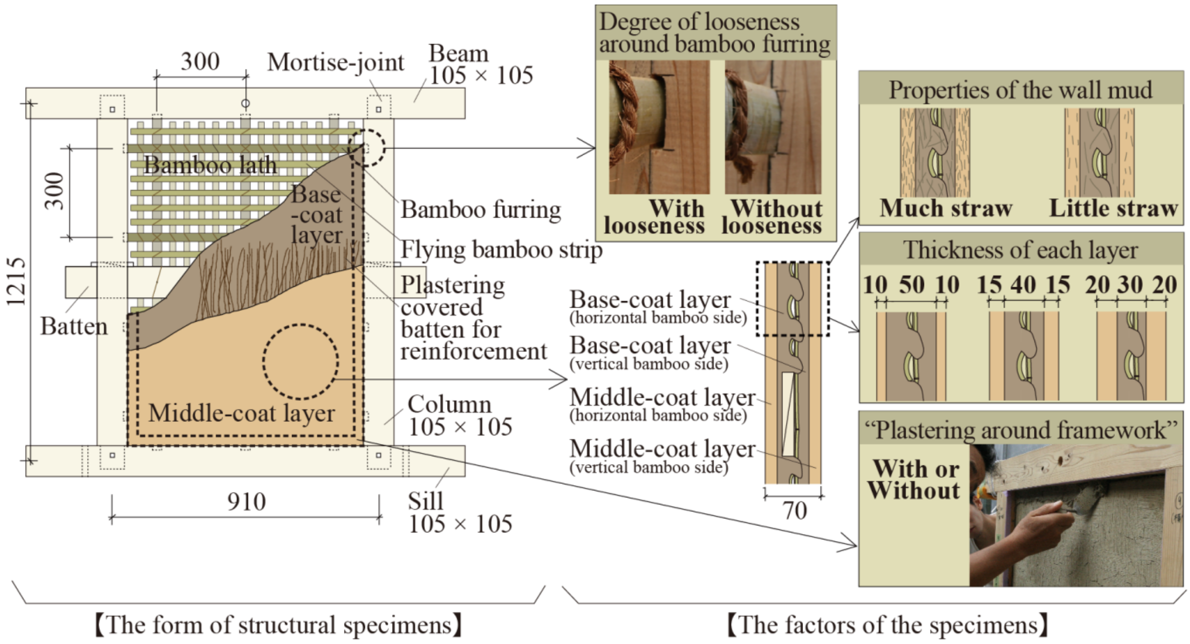

Fig. 1 Mud-bamboo wall construction for a real building and for structural specimens.

Table 1 Types of specimens.

<table>
<tr><th rowspan="2">Specimen No.</th><th rowspan="2">Thickness of batten</th><th rowspan="2">Looseness around the end of bamboo furring</th><th colspan="2">Properties of the wall mud</th><th colspan="2">Thickness of each layer (mm)</th><th rowspan="2">With or without "Plastering around framework"</th></tr>
<tr><th>Base-coat layer</th><th>Middle-coat layer</th><th>Base-coat layer</th><th>Middle-coat layer (with both side)</th></tr>
<tr><td>1</td><td rowspan="5">15</td><td rowspan="3">with some looseness</td><td rowspan="2">Much straw (2.0%)</td><td rowspan="2">Much straw (2.0%) without sand</td><td>50</td><td>10</td><td rowspan="4">without</td></tr>
<tr><td>2</td><td rowspan="4">40</td><td rowspan="4">15</td></tr>
<tr><td>3</td><td rowspan="4">Little straw (1.0%)</td><td rowspan="4">Little straw (1.0%) with sand</td></tr>
<tr><td>4</td><td rowspan="3">without looseness</td></tr>
<tr><td>5</td><td rowspan="2">with</td></tr>
<tr><td>6</td><td>10</td><td>30</td><td>20</td></tr>
</table>

(1) Difference in degree of looseness around the end of bamboo furring

Two types of specimens were prepared, as shown in Fig. 1: (i) with some looseness, Specimen Nos. 1-3; and (ii) without looseness, Specimen Nos. 4-6.

(2) Difference in properties of the wall mud

Previously, we investigated the compression properties of wall mud [1] and found that in the case of the base coat, the elastic modulus and compressive strength decreased with increasing straw content, whereas the absorbed energy increased. For the middle coat, in which the mud possessed a higher viscosity and water retentivity, the elastic modulus and compressive strength decreased, whereas the absorbed energy increased because the wall mud required a higher straw content to avoid cracking.

Based on these results, two combinations of wall mud, sand, and straw were adopted for the base and middle coat: (i) both base and middle coat had a large amount of absorbed energy, Specimen Nos. 1-2, (ii) both possessed a large elastic modulus and high compressive strength, Specimen Nos. 3-6. The compositions are detailed below.

(a) Base coat wall mud: we used mud from Kyoto and rice straw cut to a length of approximately 6 cm. Two types of straw content were used: 2.0, labelled “Much straw”, and 1.0%, labelled “Little straw”, in terms of mass of dry mud.

(b) Middle coat wall mud: the same mud as the base coat was used. The mud was sieved and lumps of fine mud removed, with the resulting mud coarser than the base coat. The straw used was shorter and finer. Two compositions of sand and straw were used: 2.0% straw without sand, labelled “Much straw”, and 1.0% straw with sand, labelled “Little straw”.

(3) Specimens with differing ratios of layer thickness

Three combinations of thickness, constituting a total thickness of 70 mm, were adopted. As shown in Fig. 1, the thicknesses of the base-coat layer and both middle-coat layers were, respectively, (i) 50 mm and 10 mm for Specimen No. 1, (ii) 40 mm and 15 mm for Specimen Nos. 2-5, and (iii) 30 mm and 20 mm for Specimen No. 6.

(4) Difference in the plastering method “Plastering around framework”

The plastering method called “Plastering around framework” was investigated to determine whether the wall mud filled the gap between the base coat layer and the framework after shrinkage of the base coat layer. Two types of specimens were prepared (with and without “Plastering around framework”), Specimen Nos. 1-4 and Nos. 5-6.

2.2 Loading Methods

Fig. 2 gives an overview of the apparatus used for the loading tests. The beam of the specimen was a joint actuator; the sill was a fixed reaction base. Axial force of 9 kN was applied to the two columns. Horizontal

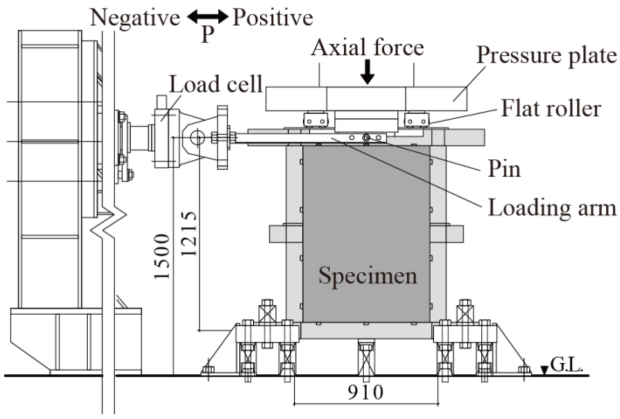

Fig. 2 Overview of the loading test apparatus.

force was loaded to the positive and negative sides, alternating every three cycles until the deformation angle, 1/600, 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, 1/50, 1/30, 1/20, 1/15 and 1/10 radian, was reached.

2.3 Calculating the Characteristic Values

The characteristic values were calculated in conformity with the methods for evaluating the structural resistance required by building regulations in Japan [3]. The skeleton curve of the load-deformation relationship replaced perfect elastic plastic straight lines, and the initial stiffness and the absorbed energy until yield point and ultimate deformation were calculated.

3. Results

3.1 Load-deformation Curve, Fracture Behavior, and Mechanical Characteristics

Fig. 3 shows the skeleton curves of the positive side, and Fig. 4 shows the state of fracture after loading. The skeleton curves and state of fracture differed with the types of specimens. The state of fracture had two types: with and without shearing crack.

Fig. 5 shows the mechanical characteristics values. It was established that the specimen that increased the initial stiffness had a high “K value,” which is the index of initial stiffness, and that the specimen that would improve the toughness would have high absorbed energy until yield point deformation. The absorbed

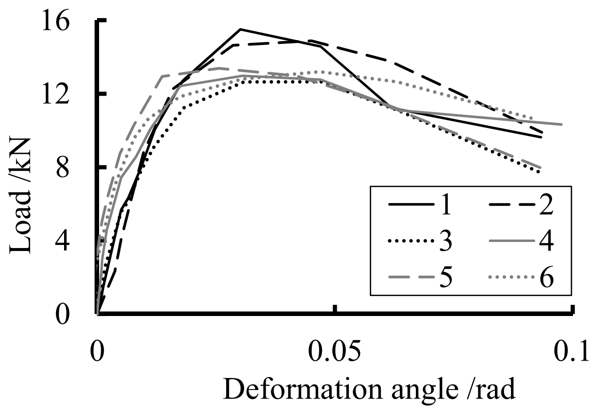

Fig. 3 The skeleton curves.

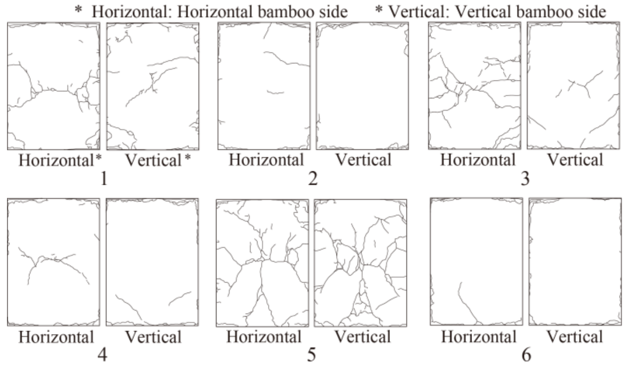

Fig. 4 State of fracture after loading test.

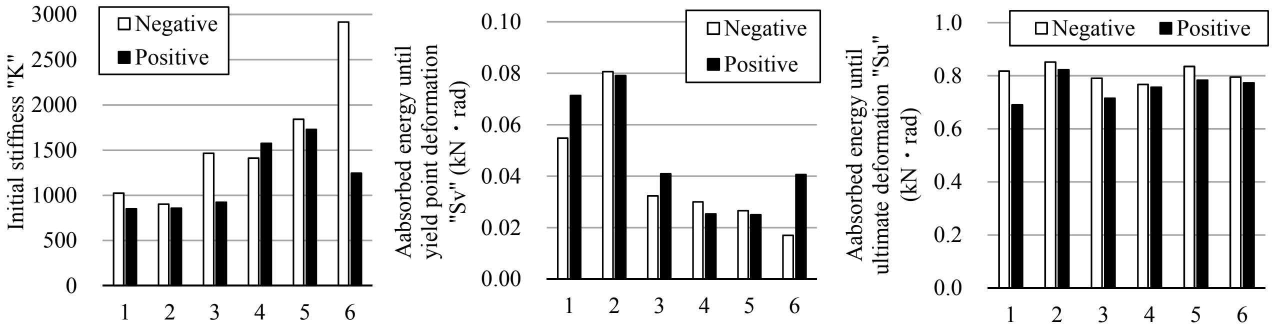

Fig. 5 Mechanical characteristics values.

energies until ultimate deformation did not differ significantly among the specimens.

3.2 Resistance Mechanisms

From the distresses observed during and after testing, we confirmed that four elements contributed to the resistance to the horizontal force observed in previous studies [4]. Fig. 6 shows the four elements. First, in the initial stage, even when the framework tilted because of the horizontal force, the plastered mud-wall layer rotated inside the framework without shear deformation. Consequently, the four corners of the mud-wall layers were found to have consolidated (I). Similarly, the mud-wall layer around the upper and lower sides of the batten was consolidated (II). After the rotation increased, the bamboo furring touched the edge of the hole made in the timber, which prevented further rotation. At that point, the bamboo furring began to separate the base-coat layer into the face and back layers (III). As the frame deformation angle increased, the flying bamboo strips began to prod against framework members, at which point the flying bamboo strips similarly caused the front and back sides of the base-coat layer to separate (IV).

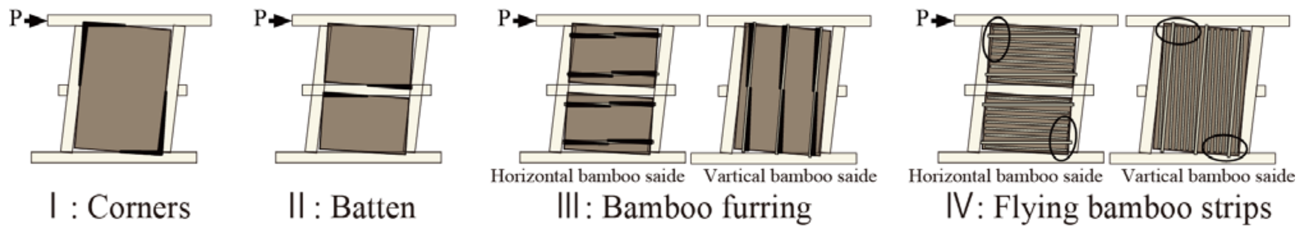

Fig. 6 Types of resistance elements.

A notable point is that there was a degree of looseness around the four resistance elements. For example, gaps related to load-bearing elements I and II were found because of drying shrinkage of the mud. In the case of III, looseness existed between the end of the bamboo furring and the hole. In the case of IV, clearance existed between the end of the flying bamboo strip and the framework member. Furthermore, as shown in Fig. 1, the mud wall comprised four layers. Therefore, the resistance elements that exist in each layer should differ. Table 2 shows the types of resistance elements in each layer.

Table 2 Types of resistance elements in each layer.

	Types of resistance element			
	Ⅰ : Corners	Ⅱ : Batten	Ⅲ: Bamboo furring	Ⅳ: Flying bamboo strips
Base-coat layer (horizontal bamboo side)	○	○	○	○
Base-coat layer (vertical bamboo side)	○	-	○	○
Middle-coat layer (both side)	○	-	-	-

4. Discussion

The influence of the factors were considered with reference to Figs. 3, 4, and 5.

(1) Influence of the properties of the wall mud (Comparison between Nos. 2 and 3)

The initial stiffness (Fig. 5) of Specimen No. 3 was higher than that of No. 2 for the mud layer labelled “Little straw”, which had a large elastic modulus and compressive strength. The other side, the absorbed energy until yield point deformation (Fig. 5) of “Little straw,” significantly decreased because of the low absorbed energy of the wall mud.

(2) Influence of looseness of the bamboo furring (Comparison between Nos. 3 and 4)

The initial stiffness (Fig. 5) of No. 4 was higher than that of No. 3 owing to resistance at the start by bamboo furring (the load-bearing element III). Although shearing deformation of No. 4 happened earlier to resist bamboo furring (III), shearing crack did not appear after the loading test (Fig. 4). This may be because larger delamination between the face and back of the base-coat layer is created without looseness, than that with looseness.

(3) Influence of “Plastering around framework” (Comparison between Nos. 4 and 5)

The initial stiffness (Fig. 5) of No. 5 was higher than that of No. 4 for initial resistance corners (the load-bearing element I) earlier with “Plastering around framework.” Shearing crack appeared with No. 5 in contrast to non-appearance with No. 4 (Fig. 4). This may be because larger delamination between the face and back of the base-coat layer of No. 4 is created by bearing bamboo furring (III) before start to bear corners (I).

(4) Influence of thickness of each layer (Comparison between Nos. 1 and 2, and 5 and 6)

Mechanical characteristics (Fig. 5) showed little difference between Nos. 1 and 2, and 5 and 6. On the other hand, the state of fracture of Nos. 1 and 5 appeared with shearing crack, in contrast to 2 and 6 (Fig. 4). This may be because delamination between the layers occurred before shearing crack was created when the middle-coat layer was thicker.

In summary, a mud wall possessing a high initial stiffness can be achieved by avoiding looseness around the resistance elements and using materials with large elastic modulus and compressive strength. However, such walls tend to develop delamination between the face and back of the base-coat layer, that are difficult to repair, because the behaviors of adjacent layers differ significantly in terms of the different load-bearing elements of each layer. In contrast, the advantage of toughness of mud walls can be maximally exploited by increasing looseness around the resistance elements and using materials that absorb large amounts of energy. Such walls tend to resist serious damage, namely delamination.

5. Conclusions

In this study, we conducted structural experiments to investigate the influence of various factors on the mechanical properties of traditional Japanese mud walls on bamboo lathing. The results obtained show that the mud walls developing initial stiffness tend to become seriously damaged because of delamination between the face and back of the base-coat layer. Originally, the Japanese mud walls can keep soundness for a long time period by repairing the slight damages such as around framework and finishing layer, which can easily repair. Accordingly, we should avoid the delamination between the face and back of the base-coat layer, for creating looseness around the bamboo lath.

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