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FIRE SAFETY STUDIES IN THE RESTORATION OF A HISTORIC WOODEN TOWNHOUSE IN KYOTO - FIRE SAFETY EXPERIMENTS ON JAPANESE TRADITIONAL WOOD-BASED CONSTRUCTIONS

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ABSTRACT

Until recently, sufficient research was not conducted on the fire performance of the traditional construction method utilizing soil walls. In this paper, fire performance of a traditional soil wall is examined by loaded fire resistance tests. Fire performance of traditional surface treatment of wood-based material is also studied through heat release measurements. The test results suggest high feasibility of traditional timber frame reinforced soil wall construction to urban buildings. This indicates an encouraging prospect for the rational fire safety assessment of historic buildings and further development of fire-safe traditional constructions for the restoration of historic buildings.

Keywords: Quasi-fireproof test, soil wall, traditional construction method, traditional wood-base material.

INTRODUCTION

Until recently, research and development on the fire performance of wooden buildings has been advanced mainly on industrial timber construction such as frame wall and prefabricated constructions[1,2]. However, research on the understanding and improvement of the fire performance of traditional construction methods using soil walls has not been sufficient. In the Building Standards Law of Japan, there are a variety of traditional wall constructions including “Dozo”, wooden frame walls protected with Japanese traditional plaster layer, and “Shinkabe”(earth-plaster wall with bare timber frames) construction with back soil coating. These are merely rated as Fire Protective Constructions. This is not because the fire performance of the traditional soil wall is proven to be inferior, but rather because research and data on the fire performance of traditional wood-based construction are insufficient. The traditional wooden soil wall construction has recently begun to be revalued from the viewpoint of building resource recycling. When consideration is given to preservation of a historic townscape, and the preservation and utilization of historical buildings, improvement of fire resistant performance of traditional wooden construction methods is very important.

BACKGROUND

In Kansai District, especially Kyoto, there are several voluntary groups specializing in the investigation of ways of preserving “Machiyas”, historic traditional style town houses. Kansai Association for the Research in Traditional Housings (KARTH) is one such groups and the authors are its members. Recently KARTH carried out shear stress tests and fire resistance tests on a timber frame reinforced soil wall in order to study the technical feasibility of the traditional timber frame construction method. In this paper, the focus is limited to the fire resistance test. The origin of this research can be traced to the restoration by KARTH of a town house over 150 years old in the Nishijin district of Kyoto, west of the Imperial Palace. The preservation effort did not need a permit to meet the Building Standards Law due to the small scale of the restoration work. However, under the Building Standards Law, many of the traditional construction methods such as the wooden soil wall construction are not permitted in urban districts. The government has chosen to restrict these methods in favor of modern construction that is deemed to be safer. However, this decision was carried out without sufficient data or research on the traditional methods. It has resulted in the loss of authenticity in preserved historical buildings as original methods have had to be replaced by modern construction permissible under the Building Standards Law. KARTH carried out fire resistance tests in order to make it possible to use such traditional construction methods for the restoration of historic buildings and new construction of traditional style buildings.

Loaded fire resistance tests of a traditional soil wall

In the present study, test specimens were manufactured using the traditional wooden soil wall construction method. The loaded fire resistance tests were carried out according to the Japanese Quasi-Fireproof Construction test protocols. This test protocol was chosen because previous furnace tests on modern wood based wall assemblies[1,2] had shown signs that a sufficiently thick soil wall would survive the Fire Protective Construction test which is less strict than the Quasi-Fireproof Construction test. The Fire Protection Construction test examines if thermal penetration occurs in 30 minutes against the ISO 834 standard heating. It was also anticipated from the results of previous experiments that the fire safety performance of timber frame walls may be determined by the collapse of the frame rather than flame penetration. In order to investigate the effect of seismic damage on the fire safety performance of external wall assemblies, the loaded fire resistance tests were repeated using two specimens, the first without any pretest deformation and the second with pretest horizontal deformation simulating a large earthquake.

After Restoration Before Restoration

Photo 1: The Restored town house in Nishijin district of Kyoto.

Test specimens

Two replicas were produced for two different specifications of soil walls as shown in Figure 1. Mr. Koichi Kinosita, master of Sukiya-style traditional wooden constructions, produced these specimens. One specification was to reproduce the external wall of the restored town house in Nishijin district (seen in the left, Photo 1). These specimens A and B, are referred to as KN type in this paper. The other specification, test specimens C and D, were prepared essentially according to the soil wall method widely used in Kyoto, and was further strengthened with a 20 mm thick external mortar layer. These will be referred to as the “common type”.

THE EXPERIMENTAL METHODS

The horizontal (shear) loading test

Horizontal loading was given to one specimen of each specification before conducting the furnace test. The loading was repeated three times with the deformation angle ±1/100 radian on the specimen fixed in the loading frame. The distortion angle was returned to 0 after the horizontal press and before the loaded fire resistance test.

The loaded fire resistance test

The test specimens were installed in the center of the loading frame attached to the heating furnace. Photo 2 depicts the test scene. The heating was made from the “external” side of each specimen.

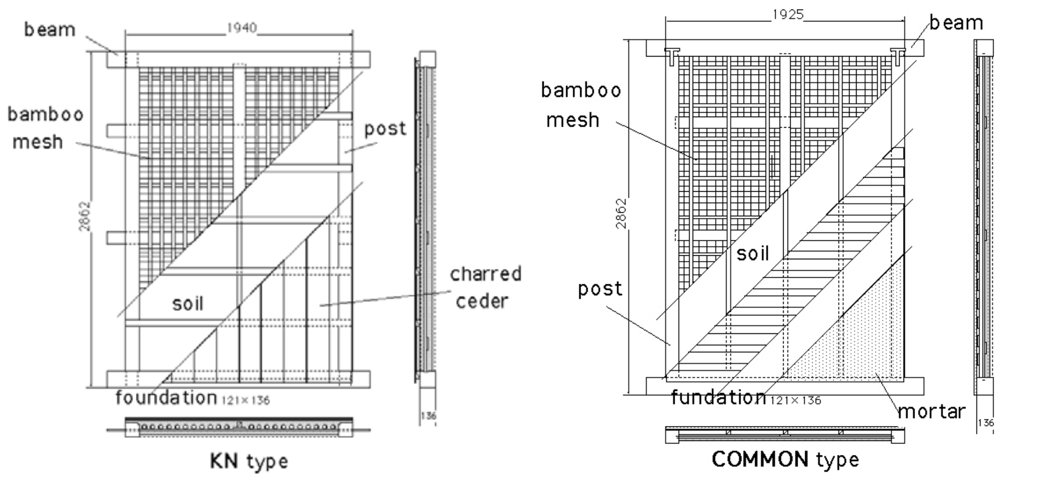


Figure 1: The test specimens.

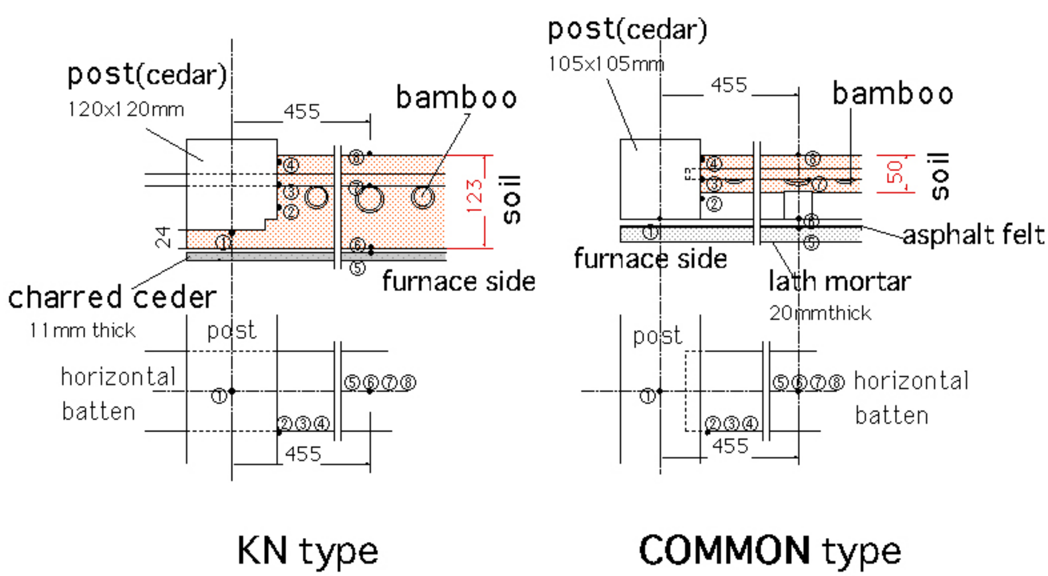


Figure 2: The thermometry position (section and elevation).

Photo 2: The loaded fire resistance test.

The loading

The specimen was loaded vertically with the predetermined level of stress being applied to the loaded bearing members (the two side posts for the present specimens). The loading level was determined from either the allowable unit stress for sustained loading or sinkage proof stress. Sinkage proof stress was adopted as the controlling stress for the present specifications. (KN type: 56.5 kN, Common type: 43.4 kN)

The heating method

The furnace temperature was controlled according to the ISO834 Standard Time-Temperature curve.

Reference criteria

Although the present tests were not conducted for approval purposes, it still should be useful to refer to the approval criteria for the then effective regulatory Quasi-Fireproof Construction test protocol. Quasi-Fireproof Construction is required for three story urban buildings and so on, and needs to be built with load-bearing members and fire separations of 1 hr (collective housings) and 45 min (others) Quasi-fireproof performance. The judgment of the Quasi-fireproof performance is made according to the following three criteria*[1]:

Any crack through which flames could permeate appear during heating;

The average and the maximu

The maximum axial contract ... ollowing

T_a140+T_0 T_m 180+T_0

In these formulae, T_a, T_m, and T_0 represent the following values.

T_a : Average temperatures (^{0}C)

T_m : Maximum temperatures (^{0}C)

T_0 : Initial temperatures (The lowest of the following three temperatures when the test started: average temperature of the back surface, average temperature inside the specimen, and the ambient temperature of the laboratory)(^{0}C) formulae:

$\delta_l \; h/100$

$\nu_l \; 3h/1000$

In these formulae, δ_l, ν_l, and h represent the following.
δ_l: Maximum axial direction contraction (mm)
ν_l: Maximum rate of axial direction contraction (mm/min)
h : Initial length of the specimen (mm)

*1 Details of the test protocol have been changed after the present test. T_a 160^{0}C, and T_m200^{0}C are used in the current effective protocol.

However, the present aim was to examine the capability of traditional wooden soil walls to withstand fully developed fires. The tests were continued until any clear sign for either fire penetration or collapse of the specimen arose. Performance of the Quasi-Fireproof Construction is evaluated by the time at which the maximum axial contraction exceeded $h/100 = 25.9$ mm or the time in which the maximum rate of axial contraction exceeded $3h/1000 = 7.77$ mm/min or the back surface temperature exceeded the criterion (where h is the height of the part which receives the heating from the furnace).

The measurements

Temperature was measured with 0.2 mm diameter K(CA) thermocouples at 8 points from the surface to the back surface of the 6 locations (total 48 points) with the interval of 30 s (Figures 2 and 3). Axial contraction was measured using 3 gauges installed at the bottom with the 30 s interval. Deformation of the specimen normal to the wall surface was measured with 3 gauges installed in the front face of the test specimen. In addition, the following were also carried out: measurement of the furnace pressure, visual observations of the surface and back surface of the specimens, the VTR image record, temperature distribution measurement by infrared camera of the test specimen back surface and measurement of the charred layer depth of the wooden frame after each test. Visual observations of the specimen surfaces from the furnace side were conducted through the pyroglass window of the furnace.

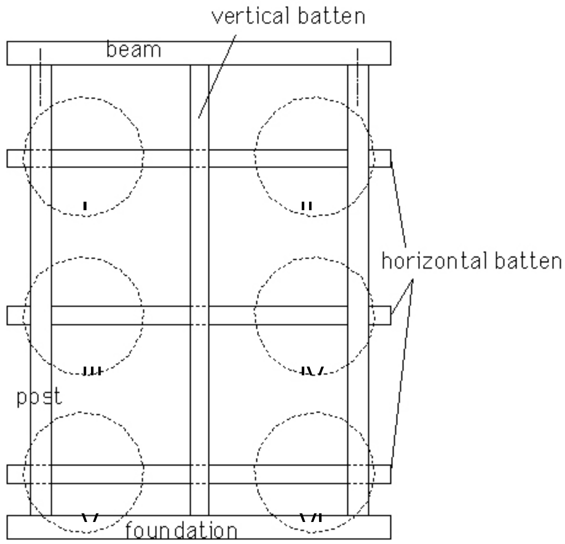


Figure 3: Thermocouple installation layout.

Photo 3: KN type specimen (furnace side).

The test results

The horizontal (shear) loaded test results

As a result of giving test specimens B and D a horizontal force, the following phenomena were observed.

(1) KN type (specimen B)

No crack was observed on either the furnace side surface (the charred cedar board) or the back surface (soil wall).

(2) Common type (specimen D)

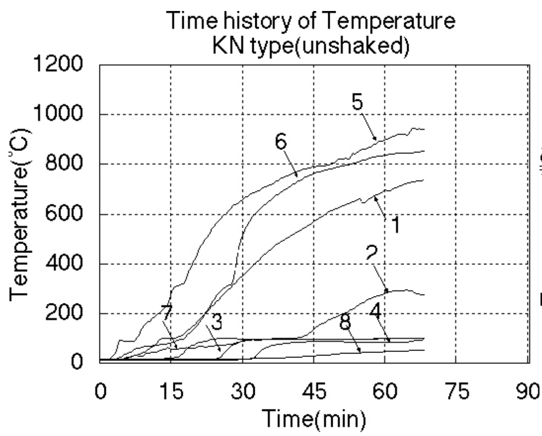
Before the loading test, there had already been 1 crack in the middle of the furnace side surface (mortar) and 1 vertical crack on the back side (soil wall). These were attributed to some shock during the transportation to the laboratory. The horizontal loading did not seem to cause any visible change on the furnace side surface of the specimen. However, the observed crack (maximum width: 0.2 mm) radially expanded when the horizontal loading was repeated. A gap appeared on both test specimens between the upper beam and the soil wall, and between the foundation and the soil wall.

The loaded fire resistance test results

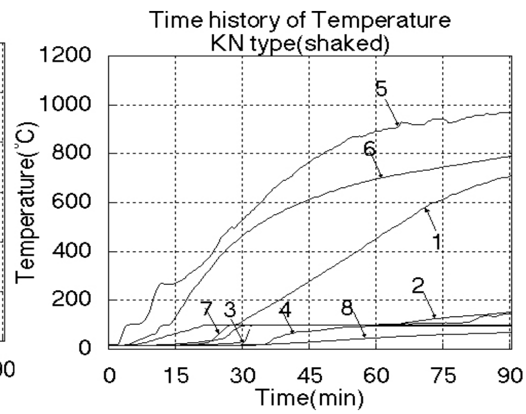
Figure 4 is the time history of the temperature at measurement position (III in Figure 3) obtained from all the four tests. Figure 5 and Figure 6 are the axial contractions and deformations of the specimen normal to the wall surface respectively. The observations during and after each test can be summarised as follows:

(1) KN type (specimen A, B)

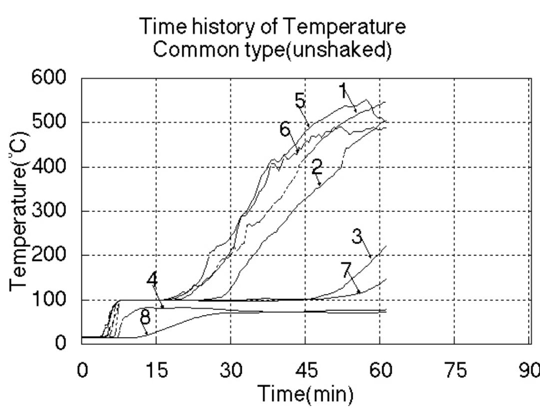
After a few minutes from the start of heating, “yakisugi-ita”, charred cedar board on the furnace side began to burn. After13 to 14 min, the charred cedar board finally burned down and began to fall into the furnace. Vapour began to generate from the gap between the post and the soil. Significant increase was not observed in the back surface temperature, axial contraction nor deformation of the specimen normal to the wall surface until the end of each test.



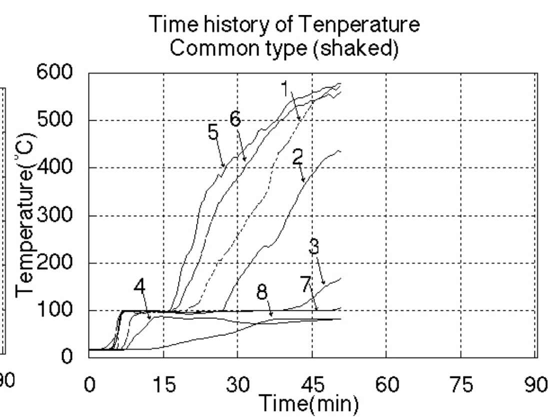
Specimen (A)



Specimen (B)



Specimen (C)



Specimen (D)

Figure 4: Time history of temperature of each specimen (for numbers, refer to Figure 2).

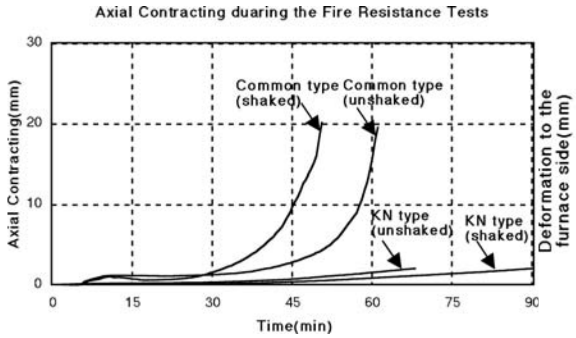


Figure 5: Axial ontraction during the Fire Resistance Tests.

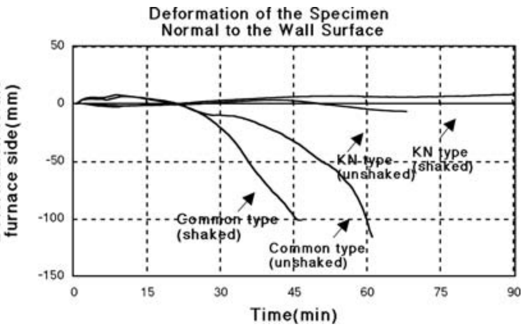


Figure 6: Deformation of the Normal to the Wall Surface.

Figure 7: Carbonization depth of the post around part of each specimen (mm).

The heating was terminated at 68 min for specimen (A), and at 90 min for test specimen (B), dictated by damage to the gasket filling the gap between the specimen and the steel frame of the equipment. From these results, it is evident that the time of the termination for this specification in the present tests does not indicate its fire resistance. The specimens could have survived longer heating if only the flame had not penetrated the gasket. According to the post-test investigation of the specimens, the posts were carbonized to the depth of about 23 mm on average for each specimen (Figure 7). The furring strips had charred but still survived (A: Almost all, B: Partially). The vertical bamboo of the inside survived (A: Almost all survived, B: The surface charred, and a crack partially generated).

(2) Common type (specimen C, D)

After 5 to 6 min from the start of the heating, the mortar layer on the furnace side surface exploded (about 1). Flame began to eject to the furnace side from this "crater" after 20 min (C), and 17 min (D). The mortar layer around the "crater" began to float after about 30 min, and cracks were generated and gradually expanded. Almost simultaneously, axial contraction and deformation of the specimen normal to the wall began to increase and the wall began to bend toward the furnace. The loaded fire resistance test was finished after 61 min (C), and 51.5 min (D) when the axial contraction began to rapidly increase. After the heating ended, cracks were generated in the mortar of the furnace side surface. However, the mortar layer was still supported by the lath. The posts were carbonized with the depth of about 22 mm on average for each specimen. The asphalt was lost. The vertical bamboo of the inside survived (C: Partially surface charred, D: Almost all survived).

Implication of the test results

From these experimental results, it has been proven that the KN type specification has Quasi-fireproof performance longer than 1 hour, even if the large deformation corresponding to a large earthquake is given. Also, the "common type" specimen has Quasi- fireproof performance longer than 1 hour. The Quasi-fireproof performance of these constructions was found to not be controlled by the flame penetration but by the deformation of the timber frame due to the decrease of the load bearing area. Although there is not yet any traditional wood frame soil wall construction rated as the Quasi-Fireproof Construction, these test results demonstrate a good capability of soil wall construction to achieve very high fire resistance. This result further suggests a high possibility of various weaker specifications of the wood frame soil wall construction to be rated as the Fire Protective Construction, which is less strict than the Quasi-Fire Proof Construction. Fire Protection Construction is the essential requirement for the external wall of single or two story common wooden buildings in urban districts.

Heat release measurements of traditional treated and untreated wood based materials

"Yakisugi-ita", charred cedar board, is used for the external wall finish of the KN type specimen and the restored town house. In the traditional construction community it has been long believed that charred cedar board and coating with natural materials, principally applied to improve the durability, may also be effective for fire protection. However, the effectiveness and burning behavior of such treatments has not been verified experimentally. In order to examine the fire hazard of traditional wood-based materials with such surface treatment as "yakisugi-ita" (charred cedar board), "tonoko" (polishing inorganic powder painting), and "bengala" (red iron oxide), heat release measurements were carried out with the ISO 5660 Cone Calorimeter. The heat flux level 50 kW/m² was chosen to reproduce typical flame heating in a city fire scenario.

It is widely known that wood based materials generally make a characteristic peak heat release just after ignition. The peak heat release rate for "yakisugi-ita" (charred cedar board) was lower than 100 kW/min while the peak heat release rate for all other materials exceeded 160 kW/min. This drastic suppression of the first peak with the charred cedar board is believed to be because the surface treatment charring, has already "cut-off" combustible contents near the surface. Since the sharp peak heat release just after the ignition is the principal driving force of concurrent flame spread of wood based materials, the suppression of the peak is believed to reduce fire spread on this material. The charred layer is also believed to function as a form of thermal insulation for the virgin wood beneath the char layer at the beginning of the surface burning. Effectiveness of this treatment naturally becomes insignificant with time.

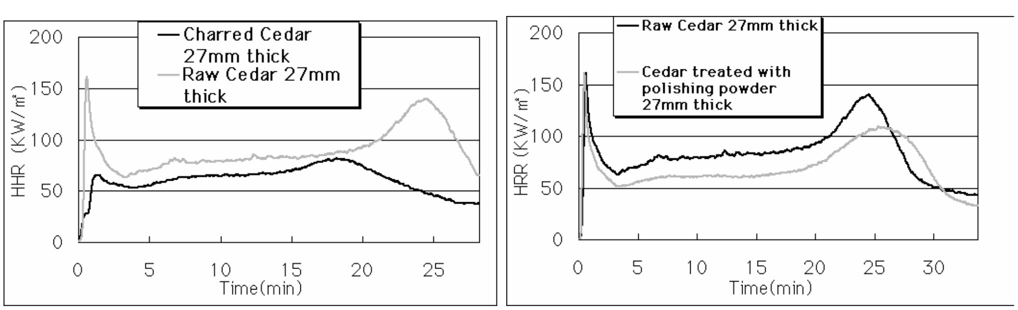


Figure 8: Heat release rate (raw Cedar, 27 mm thick, charred Cedar, 27 mm thick, Cedar treated with "tonoko", 27 mm thick).

Table 1: Experimental results.

specimen	surface treatment	thickness (mm)	ignition time (sec)	burning time (sec)	peak HRR(kW/m²)		total HRR(MJ/m²)			penetration time (sec)
					first	second	5min.	10min.	15min.	
cedar	char one side	9	13	495	86.0	105.3	22.4	33.3		290
cedar	char one side	15	21	710	74.9	150.0	35.6	46.6	56.0	500
cedar	char one side	18	20	975	90.9	149.5	16.2	41.6	71.2	720
cedar	char one side	27	32	1543	70.8	112.9	16.9	37.7	60.1	1110
cedar	char both sides	27	23	1241	63.2	121.7	13.8	30.4	51.8	900
red cedar	none	27	15	1791	175.7	146.2	17.9	36.9	55.9	1500
red cedar	bengala coating with tonoko and kakishibu	27	10	1875	181.7	135.7	23.4	43.8	65.9	1500
chestnut	none	27	19	1848	159.6	100.0	18.6	32.4	46.9	1800
chestnut	bengala coating with tonoko and kakishibu	27	17	2082	172.3	99.3	21.0	35.1	48.2	1620
zelkova	none	27	28	1996	159.4	180.4	22.3	50.0	59.7	1760
zelkova	bengala coating with tonoko and kakishibu	27	26	1935	221.4	177.5	20.8	37.4	53.9	1780

Natural covering materials such as “bengala” (red iron oxide), “tonoko” (polishing inorganic powder), and “kakishibu” (persimmon tannin) were also examined. Although it has been said that these treatments are effective in fire, the test results do not demonstrate any notable improvement in the heat release rate.

CONCLUSIONS

From these results the following can be concluded:

1. Charring of a wood surface, with a sufficient charred layer on the surface, is effective for slowing the spread of fire along the wood surface.

2. Application of natural coatings does not make notable improvement on the wooden burning behavior.

3. When the material thickness is increased, the time to penetration increases significantly. Therefore, if thick charred cedar boards are utilized as the external cover of wall, it could further improve its fire resistance.

The fire performance of traditional construction methods utilizing soil walls has been proven to be quite good. However, in order to improve the administrative treatment of traditional wooden construction, it is necessary to establish quality control standards to reproduce the performance demonstrated by testing in on-site constructions. In order to realise this, leaders of traditional wooden construction should cooperate to establish a self-regulating organization to provide guidance, and education. It is more important that as much data as possible is collected and further experiments are carried out to improve and standardise the traditional wooden construction methods. For more details of the Quasi-fireproof tests, readers are suggested to see[3].

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