Stealth Brace for Traditional Wooden Architecture

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Abstract

In recent years, there has been an increasing incidence of traditional wooden architecture collapsing or suffering damage as a result of earthquakes. These buildings often have open structures with few walls, making their seismic reinforcement challenging. This paper proposes a seismic reinforcement method utilizing high-strength, galvanized steel wire, which possesses sufficient yield strength, toughness, and rigidity to meet the required earthquake resistance performance. Both ends of each steel wire are processed with so-called button heads, allowing the steel wire to bear the stress through the button heads when a tensile load is applied. When a compressive load is applied, the steel wire-end escapes to avoid bearing stress. Therefore, it is expected that the stress generated in the metal-fitting body or column/beam members will be reduced. A horizontal load test has confirmed that the proposed reinforcement method yields sufficient strength and toughness. Going forward, the arrangement angle and fixing anchoring fittings will be employed as parameters to expand the scope of application.

Introduction

Japan is a highly earthquake-prone country. Since the introduction of new earthquake resistance design standards in 1981, there has been a growing demand to improve the seismic performance of buildings. However, important cultural property buildings made of wood before these standards were introduced lack sufficient seismic performance and are at high risk of collapse upon a major earthquake. There are many reports of such traditional wooden buildings suffering damage from earthquakes and losing historical value.

There are currently around 5,500 Important Cultural Properties and 14,000 Registered Tangible Cultural Properties in Japan, and it has become a major challenge to ensure they are properly preserved and to fortify them against seismic activity. Though challenging, it is critical to safety to ensure structural soundness because tourism to cultural heritage buildings has been increasing. As such, the demand for seismic retrofitting of cultural property buildings is expected to further increase.

However, there are numerous challenges associated with this task. First, obtaining permits for retrofitting plans and their execution takes a long time, making it difficult to act quickly. There have been instances in which structures have collapsed in an earthquake despite plans for seismic retrofitting being complete, highlighting the need for swift action. One such example is the Former Yubikan[1], an educational institution from the Edo period (1603-1867). Furthermore, in buildings from the late Edo period that feature openings with few walls, it is difficult to perform seismic retrofitting without compromising the landscape or architectural design. Current retrofitting methods include sacrificing the openness of a space by installing load-bearing walls, or using lattice walls and steel columns. Such alterations may be discordant with the landscape and design and thus be in opposition to the cultural elements of the structure. Thus, balancing seismic performance with the preservation of cultural assets has become a major challenge. However, new seismic retrofitting technologies have been developed in recent years to overcome this challenge. As one example, we introduce the ϕ7 Stealth Brace [Note)], a seismic retrofitting method that uses high-strength galvanized steel wire. This solution's small-diameter steel wire makes installation possible even in narrow spaces in a way that minimizes damage to existing members, such as from drilling holes. Furthermore, this product leverages the characteristics of steel wire through the use of components that bear stress during tensile loading and prevent damage to members due to buckling under compressive load.

This paper reports on the results of horizontal load testing of full-scale models, which we conducted to understand the basic mechanical properties of the proposed reinforcement method. This technology will serve as a new option for enhancing seismic performance while preserving the open layouts of historical architecture, thereby improving the safety of cultural property buildings and safeguarding their cultural value.

1. Proposed reinforcement method

The system consists of steel wires and connecting hardware (terminal fittings and anchoring fittings). **Fig. 1** shows an overview of the reinforcement method. The anchoring fittings and the timber of the foundation are secured using coach screws or bolts.

Note) "ϕ7 Stealth Brace" is a trademark of Kobelco Wire Company, Ltd.

Fig. 2 shows the behavior of the terminal fittings. Under compressive load, the ends of the steel wires slide outward and do not bear the compressive load. This action maintains the straightness of the steel wires to prevent bowing. This structure counteracts the tensile forces that occur during events such as earthquakes and should prevent damage to shoji (traditional Japanese sliding paper doors) and structural framework. Since the terminal fittings may protrude as the steel wire extends during high-angle compression, they are tapered to ensure a smooth return to their original position.

This paper proposes three structures of reinforcement methods. The structures of the different anchoring fittings are shown in **Figs. 3**[2], **4**[2], and **5**.[2]

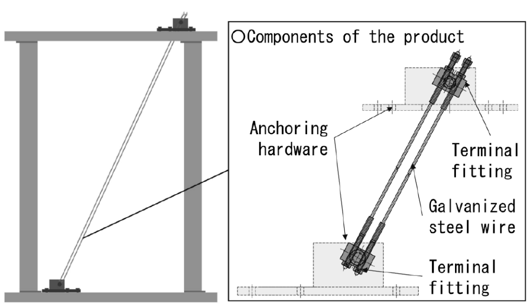

Fig. 1 Overview of reinforcement method

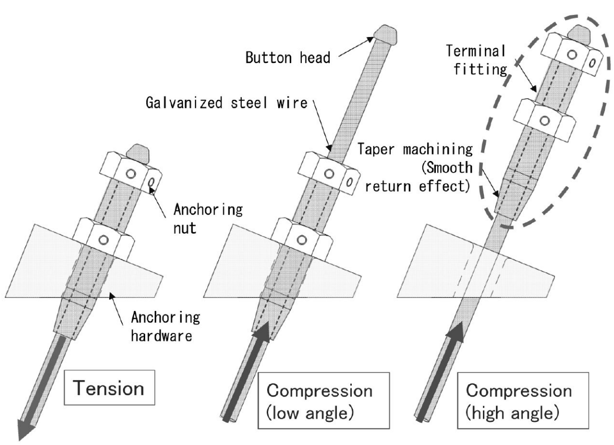

Fig. 2 Behavior of terminal fittings under tensile and compressive conditions

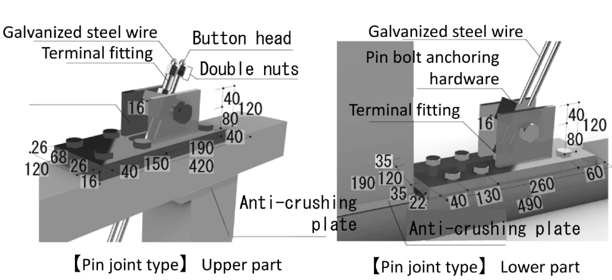

Fig. 3 Structures of Anchoring Fittings [pin joint type]

1.1 Characteristics of galvanized steel wire

Galvanized steel wire is a tried-and-true material typically used in bundles in applications such as cable-stayed bridges. Such cables possess excellent mechanical properties, which we exploited in developing a construction method that uses individual strands. **Fig. 6** and **Table 1**, respectively, show the stress-strain curve and

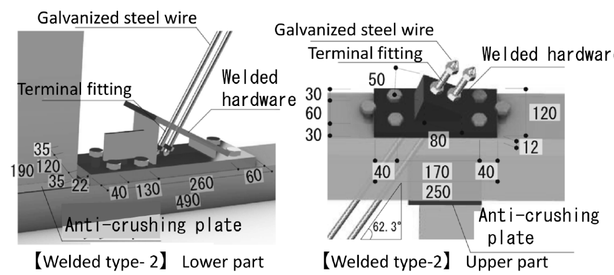

Fig. 4 Structures of anchoring fittings [welded type – 2 wires]

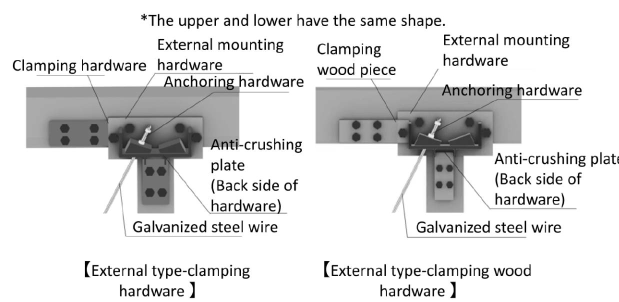

Fig. 5 Structures of anchoring fittings [External type – clamping hardware], [External type – clamping wood hardware]

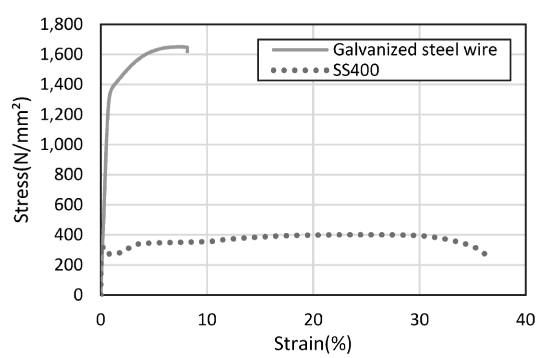

Fig. 6 Stress – strain curve

Table 1 Mechanical properties of galvanized steel wire

Property			Value
Nominal cross-sectional area		(mm^2)	38.48
Unit mass		(kg/km)	301
Tensile strength	Tensile load	(kN)	(60.3)
	Tensile stress	(N/mm^2)	1,570
Yield strength	Yield load	(kN)	(44.5)
	Yield stress	(N/mm^2)	1,160
Elongation at break	Elongation	(%)	4.0
	Gauge length	(mm)	250
Elastic modulus		(N/mm^2)	(196,000)

mechanical properties of galvanized steel wire. Its yield strength is approximately five times that of SS400, and its tensile strength is approximately four times that of SS400. Further, its elongation at break of approximately 4% means it can track the deformation of wood.

As a further design feature, the button head end (**Fig. 7**) anchors the ends of the steel wires. Specifically, this cold-formed protrusion provides bearing pressure for anchoring. This method eliminates the need for crimping to the terminal fitting, creating a purpose-built anchoring structure that is active only under tensile load.

1.2 Reinforcement method using pin bolt joints

This method consists of two steel wires and anchoring fittings. At the upper part of the structure, the two steel wires pass through a horizontal member and connect to anchoring fittings that have pin mechanisms. With this design, only axial forces are carried, even during deformation. This reinforcement method is called the [pin joint type].

1.3 Reinforcement method using welded fittings

The anchoring fitting of this method has a fitting welded at the same angle as the initial angle of the steel wire (62.3° in the study for this paper). The connection to the horizontal member is the same as for the [pin joint type]. The size and weight of the fittings are about 60% of those of the [pin joint type].

The steel wire penetrates the horizontal member at the top part and is secured to the fitting. This reinforcement method is called the [welded type].

1.4 Reinforcement method using external fittings

To minimize alteration of existing members and achieve simple construction, this method is designed such that the steel wire is attached to the external surface of the structure without penetrating horizontal members. It consists of one single steel wire and an external anchoring fitting, with the fitting attached to the side of the horizontal member and the foundation. Since the steel wire does not penetrate the horizontal member, this method minimizes alteration to existing members. This method also incorporates hardware or a wooden block to resist shear forces by supporting the anchoring fitting. These reinforcement methods are referred to as the [external type – clamping hardware] and the [external type – clamping wood hardware], respectively.

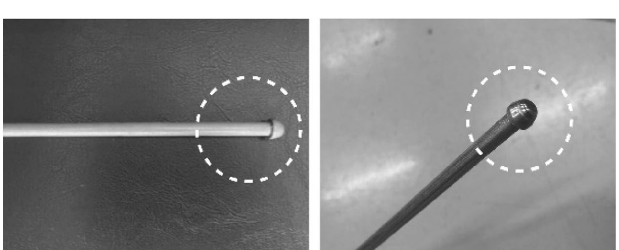

Fig. 7 Button head

2. Horizontal load testing

2.1 Test method

In the research for this paper, horizontal load testing was conducted on a timber frame to verify the structural characteristics of the proposed reinforcement method. **Fig. 8**[2)] shows a schematic diagram of the reinforcement method used for testing, **Table 2**[2)] shows the dimensions of the test specimens, **Table 3**[2)] shows the dimensions of the main elements of the test structure. The number of steel wires for each reinforcement type was based on considerations of structural stability and stress distribution. Further, we used different numbers of steel wires to elucidate how structural behavior varies depending on the number of wires used. The [pin joint type] has a two-wire configuration to ensure stability. For the [welded type], we conducted tests with one wire and with two wires to determine how the number of steel wires affects the results. For the [external type – clamping hardware] and [external type – clamping wood hardware], we only tested a single-wire configuration in the interest

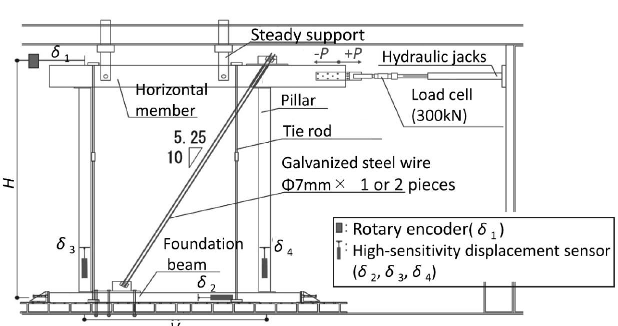

Fig. 8 Overview of reinforcement method

Table 2 Dimensions of test specimens

	H (mm)	V (mm)
【Pin joint type】	2,760	1,820
【Welded type—1】	2,730	1,820
【 Welded type—2】	2,760	1,820
【External type– clamping hardware, clamping wood hardware】	2,730	1,177

of structural preservation.

We assembled three test specimens for the pin-joint type and one each for the other types. Testing was conducted in accordance with Allowable Stress Design for Wood-Frame Residential Structures (2017 Edition), with the "tie-rod method" used to apply load.

Load was applied from a deformation angle γ of 1/450 to 1/15 in eight stages. The direction in which tensile force was generated in the steel wires was defined as the positive direction. Cyclic loading – alternating between the positive and negative directions – was performed three times per stage. Monotonic loading was then performed in the positive direction until a deformation angle of 1/10 rad was reached.

For test specimens with two steel wires, the beam height was increased from 210 mm to 270 mm to prevent the horizontal members from splitting.

2.2 Test results and discussion

Fig. 9 [2] shows the hysteresis curves for the [pin joint type]. The envelope curves for the [pin joint type], [welded type], and [external type] are shown in **Figs. 10** [2], **11** [2], and **12** [2], respectively.

Table 3 Material dimensions

	【Pin joint type】	【Welded type−1】 / 【Welded type−2】	【External type− clamping hardware, clamping wood hardware】
Foundation beam (Douglas fir/E110)	120×120×2,180		120×120×1,897
Horizontal member (Douglas fir/E110)	210×270×3,000	210×210×3,000 210×270×3,000	210×210×2,357
Right pillar (Cedar wood/E70)	120×120×2,561		120×120×2,685
Left pillar (Cedar wood/E70)	120×120×2,541		
Galvanized steel wire	ϕ7-3,280×2	ϕ7-3,126×1 ϕ7-3,207×2	ϕ7-2,926×1

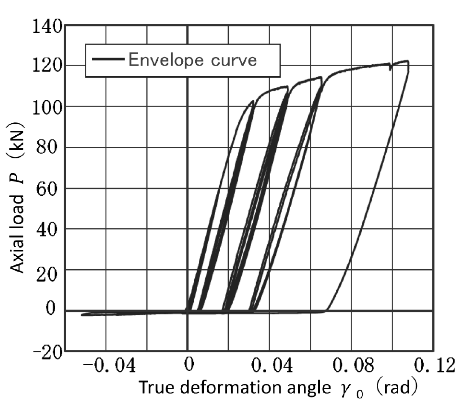

Fig. 9 Pin joint type hysteresis characteristics

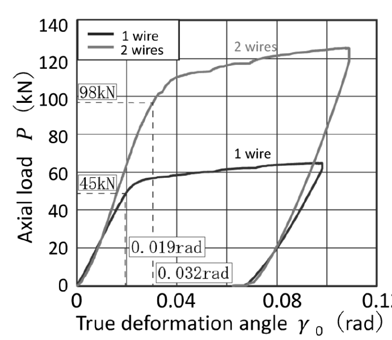

Fig.11 Welded type (1, 2 Wires) envelope curve

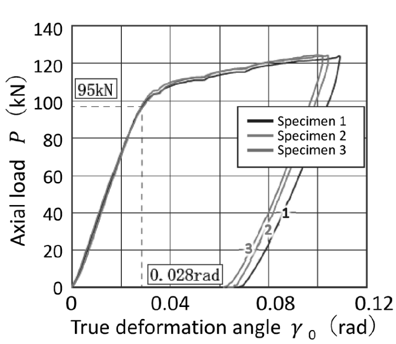

Fig.10 Pin joint type envelope curve

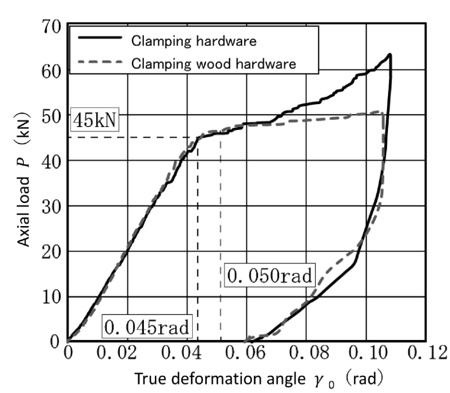

Fig.12 External type (clamping hardware, clamping wood hardware) envelope curve

A comparison and analysis of the test results for each reinforcement method revealed the common behaviors and characteristics described next.

All reinforcement methods exhibited a linear relationship between load and deformation during the initial loading phase and clearly exhibited stiffness until the yield load of the steel wire was reached. Specifically, the respective approximate values are 95 kN for the [pin joint type] (2 wires), 45 kN for the 1-wire [welded type], and 98 kN for the 2-wire [welded type]. For the [external type], yielding was confirmed at approximately 45 kN (1 wire), and it was clear that the load increased essentially linearly up to the yield load.

After the steel wires yielded, all test specimens exhibited a decrease in stiffness, indicating a transition to plastic behavior. However, none of these cases exhibited a sudden decrease in load-bearing capacity or a significant loss of structural performance due to localized failure. This demonstrates that each reinforcement method retains the capacity to bear a certain load even beyond the yield point, ensuring ductile toughness (deformation performance).

Furthermore, in the course of reaching the maximum load, even when the steel wire came near its standard breaking load, no significant damage or failure was observed in the terminal fittings, anchoring fittings, or timber members (pillars and beams). This indicates that sufficient structural safety was maintained. Regarding behavior during compressive loading, all reinforcement methods exhibited a tendency for the steel wires and bolts to extend from the joints at the anchoring points. This definitively indicates that the steel wires were no longer bearing load, thereby confirming the working mechanism of the reinforcing components.

In summary, the results above indicate that for all three reinforcement methods, there is obvious stiffness during the initial loading phase, clear yielding behavior of the steel wires, and high ductility after yielding.

3. Calculation and evaluation of characteristic values for each reinforcement method

3.1 Calculation methods and overview of characteristic values

Fig.13 [2] shows the bilinear models [3] and substitution results of horizontal load testing. **Table 4** shows the calculation results for the short-term standard shear strength and characteristic values.

3.2 Discussion of characteristic values

Fig. 13 confirms similar behavior among the [pin joint type], [welded type], and [external type] structures, as explained below.

The ultimate displacement for all structures falls between 1/20 and 1/10 rad, indicating that they satisfy the safety limits (interstory drift of 1/30 to 1/20 rad) applicable to “extremely rare earthquakes (major earthquakes).” This means it is possible to reuse these structures following repair, permitting a certain degree of damage.

In particular, the [external type] exhibited lower initial stiffness and short-term standard shear strength than other types. Possible causes include localized crushing from the initial deformation angle near the attachment points of the fittings and clamping wood hardware, and torsion and eccentricity in the top part of the horizontal member (upper beam). Nevertheless, even at a deformation of 1/10 rad, there was no significant decrease in load-bearing capacity. The structure has a high capacity to track deformation and exhibits structural properties characterized by high toughness (deformation capacity). Therefore, the method is effective for reinforcing existing timber structures in a way that limits localized damage.

4. Case study (Kobuntei)

Kobuntei [4], an ancient villa in Mito Kairakuen (one of Japan’s Three Great Gardens), is a historic building designed by Tokugawa Nariaki in the late Edo period. **Fig. 14** shows the exterior of this building. Situated near Lake Senba and Mount Tsukuba, it offers picturesque views from the third floor and is known for the open structure and delicate features of its design. This building has numerous open spaces and a correspondingly low number of walls, putting it at risk of collapse during a major earthquake and therefore prompting seismic retrofitting using ϕ7 Stealth Braces. **Fig. 15** shows a conceptual image of seismic retrofitting with lattice windows beside images of the installed ϕ7 Stealth Braces. ϕ7 Stealth Braces have accomplished seismic retrofitting while preserving the building’s original appearance. With seismic retrofitting completed in 2021 and visitor safety ensured, tea service can now be offered year-round. Similar design elements have been incorporated into two other properties, indicating that this system is gaining traction as a solution for cultural heritage buildings.

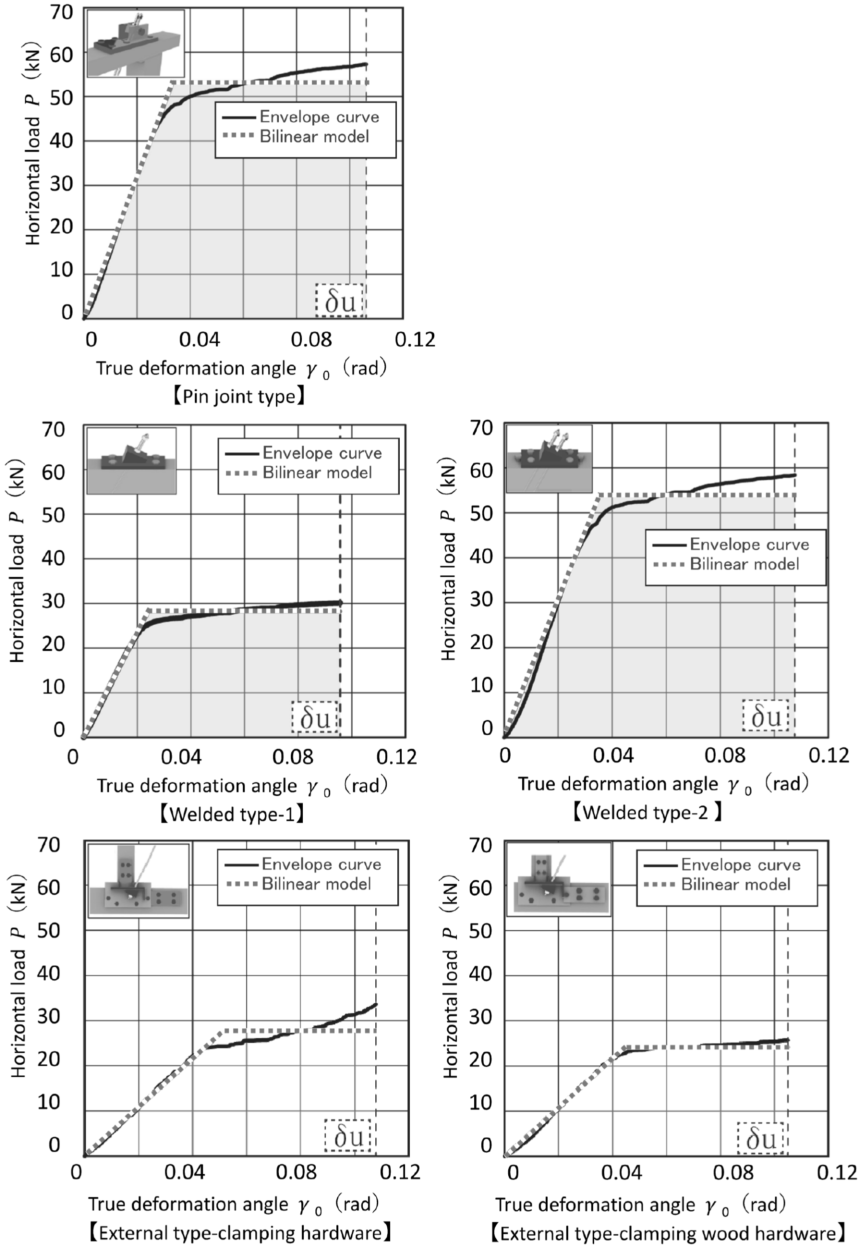

Fig.13 Bilinear model and substitution results

Table 4 Calculation of characteristic values

	【Pin joint type】			【Welded type】		【External type】	
	First unit	Second unit	Third unit	1 wire	2 wires	Clamping hardware	Clamping wood hardware
Initial stiffness K (kN/mm)	0.547	0.549	0.539	0.415	0.529	0.190	0.190
Yield strength Py (kN)	42.15	39.68	40.60	22.81	39.43	23.08	19.17
Yield displacement δy (rad)	0.027	0.025	0.026	0.020	0.026	0.043	0.036
Ultimate strength Pu (kN)	53.20	53.58	53.54	28.23	53.97	27.73	24.19
Ultimate displacement δu (rad)	0.106	0.098	0.104	0.096	0.108	0.108	0.105
Plasticity ratio μ	3.163	2.914	3.040	3.924	3.050	2.099	2.340
Structural characteristic coefficient Ds	0.433	0.455	0.444	0.382	0.443	0.559	0.521
Short-term standard shear strength P_0(kN)	8.613			7.699	6.697	3.138	2.723

＊The gray shading indicates the test of a single steel wire.

Fig.14 Exterior of Kobuntei

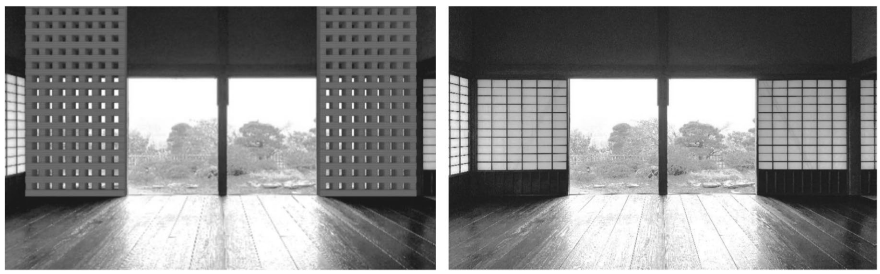

Fig.15 Potential and actual reinforcement methods at Kobuntei
left: Lattice window (conceptual image) right: ϕ7 stealth brace (installation photo)

5. Summary of findings

In the research for this paper, we performed horizontal load testing on three types of reinforcement methods. The results confirm that all methods exhibit excellent structural characteristics in terms of initial stiffness, yield behavior, and ductility, indicating that these methods constitute effective new options for the seismic retrofitting of historic buildings.

Common seismic retrofitting methods include sacrificing the openness of a space by installing load-bearing walls, or using lattice walls or steel columns to provide reinforcement in a way that maintains natural light and airflow. These methods nearly always compromise the architectural design. Our development exploits the characteristics of shoji, which maintain full-width openings and have two panels that overlap when slid aside for opening. Specifically, by installing reinforcement members in the gap between the two panels, our technique improves seismic performance without compromising traditional aesthetic. Seismic retrofitting using ϕ7 Stealth Braces made it possible to preserve the original appearance of Kobuntei.

Conclusions

The positive results detailed in this paper have driven us to pursue several related initiatives. First, to expand the product's scope of application, we will conduct further validation tests regarding differing angles resulting from changes in beam span. In conjunction, we will establish standards based on our results and create a brochure that clearly summarizes the product's characteristics. Finally, we will educate architectural firms and cultural heritage preservation organizations to raise awareness of the ϕ7 Stealth Brace and promote its use.

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