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Research of Seismic Brace Using Aramid Fiber Rope to Retrofit Building

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Abstract

The purpose of this study is to develop aramid fiber rope for structural reinforcement of existing building with a good workability. During this study a seismic brace using an aramid fiber rope for the timber houses is developed to achieve the purpose. In order to introduce the fiber-rope to the base material, 2 types of joint, wedge joint and joint by hand-tie are proposed. To perform the best of fiber's strength, the wedge type of joint is optimized to avoid stress concentration on the fiber rope. Moreover, the workability for assembling the fiber rope to the joint at the construction site, which includes the unraveled fiber degree and the deviation of the fiber density at the rope end, are investigated. On the other hand, hand-tie method is proposed assuming situation under no subsidy and needs in first-aid solution for structural reinforcement. The knots of hand-tie are optimized by a tensile test. Finally, the developed seismic brace is attached to a wooden frame and load bearing wall tests are carried out. Through experimental results, the effect of the seismic brace using the aramid fiber rope is confirmed. Also, points to be noted when assembling the fiber rope at the construction site become clear.

Key words: Seismic brace, Fiber rope, Aseismic reinforcement, Aramid Fiber, Timber structure

1. Introduction

Demands of high-performance fibers have been risen due to energy and resource saving.[1] In the previous research, new materials such as chemical fibers, polymeric materials, etc. have been used as structural materials for buildings [2][3]. However, high-performance fibers are not fully utilized as structural materials yet.

The previous research has been studied the high-performance fibers for structural reinforcement of the existing steel structure factory [4] [5]. However, as long as there are not-confirmed timber houses increased in Japan, demands of reinforcement method are risen to reduce serious

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damages on the structure after the earthquake strike. This paper research to develop a seismic brace using an aramid fiber rope aiming good workability with low in cost.

The purpose of this study is to develop aramid fiber rope for structural reinforcement of existing timber house with a good workability. During this study a seismic brace using an aramid fiber rope for the timber houses is developed to achieve the purpose. In order to introduce the fiber-rope to the base material, 2 types of joint, wedge joint and joint by hand-tie are proposed and carried out the experimental study. To perform the best of fiber's tensile strength, the wedge type of joint is optimized to avoid stress concentration on the fiber rope. Moreover, the workability for assembling the fiber rope to the joint at the construction site, which includes the unraveled fiber degree and the deviation of the fiber density at the rope end, are investigated by the tensile test. On the other hand, hand-tie method is proposed assuming situation under no subsidy and needs in first-aid solution for structural reinforcement. The knots of hand-tie are optimized by a tensile test. Finally, the developed seismic brace is attached to a wooden frame and load bearing wall tests are carried out. Through experimental results, the effect of the seismic brace using the aramid fiber rope is confirmed. Also, points to be noted when assembling the fiber rope at the construction site become clear.

2. Connection Fitting

2.1. Aramid fiber rope

The aramid fiber is an aromatic polyamide fiber produced by organic chemical synthesis. The aramid fiber has higher tensile strength than natural and general synthetic fibers. For this research, a para-aramid fiber (in detail, a co-poly-paraphenylene/3,4' -oxydiphenylene terephthalamide, hereafter is called 'Technora') is used [6]. Technora is made from copolymers and developed by Teijin Limited. It has high tensile strength and resistance against heat and chemicals, especially acids and alkalis. So far, it is used in rubber reinforcement, ropes, protective goods, cement and plastic reinforcement and many industrial applications.

Table 1 shows mechanical properties of Technora and steel. Technora has high resistance against acids, alkalis and organic solvents. It also shows good hydraulic resistance. Thus, this fiber can be used outside and/or in combination with concrete. Due to high tensile strength and chemical resistance, a rope made of this high-performance fiber can be applied for the seismic brace to reinforce the building. Figure 1 shows a configuration of the fiber rope, which is formed by knitting many bundles of the twisted fiber yarns.

Table 1. Mechanical properties

	Density (g/cm^3)	Tensile strength (N/mm^2)	Rupture elongation (%)	Tensile elasticity (N/mm^2)
Technora	1.30	1760	3.7	5290
Steel	7.85	2750	1.9	21500

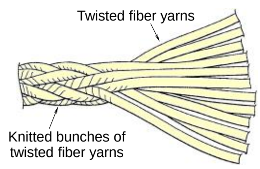


Figure 1. Configuration of high-performance fiber rope

2.2. Wedge type joint

Compression fitting is usually used for steel wire for joint. However, the repulsive force of aramid fiber is small when it is compressed and the sufficient frictional force cannot be obtained by a compression fitting. Also, it is hard to plastically deform. Therefore, a wedge type joint is proposed. The fiber rope can securely be gripped and does not slip out of the joint. Figure 2 shows an outline of the wedge type joint. The wedge joint is composed of a wedge member, a sleeve member, and a clevis bracket. For this joint, the fiber rope is inserted between the sleeve and wedge members, and is gripped without slipping due to the wedge effect.

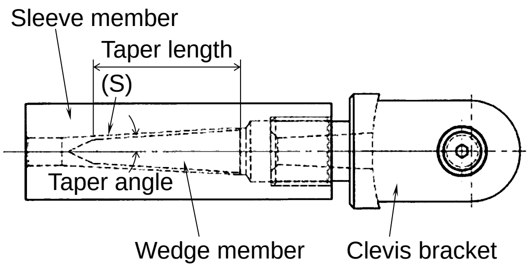


Figure 2. Wedge type joint

2.3. Optimization of wedge shape

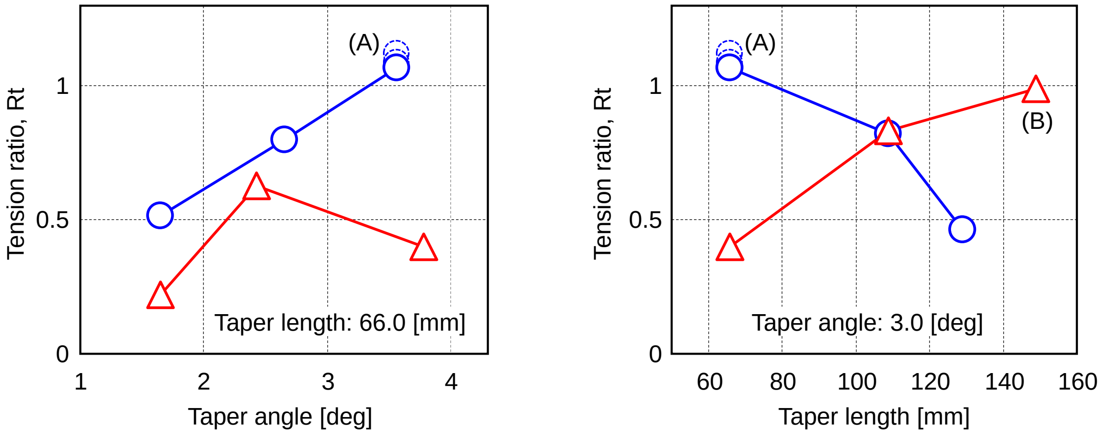
In this chapter, shape of wedge is optimized. If stress concentration occurs at a certain portion of the fiber rope, the fiber rope may be broken at that portion at lower than its original strength. Therefore, it is necessary that the stress on the fiber rope should be equally distributed in the sleeve member. A taper angle of the wedge member is slightly larger than the outer sleeve member, so that the wedge effect is reliably obtained. The stress concentration occurs around the tip of the wedge member, which is shown by the portion (S) in figure 2. The wedge shape is optimized based on the experiments to generate its original strength. For the shape of wedge, the taper angle and length are designed as parameters. Figure 3(a) shows experimental results for varying the taper angle under the taper length of 66.0 mm. Figure 3(b) is results for varying the taper length under the taper angle of 3.0 degree. The fiber ropes which nominal loads are 50 kN and 100 kN, are used for these experiments.

The tension ratio ‘Rt’ on the vertical axis of graphs indicates a ratio between the breaking load (i.e., the breaking load while the fiber rope is assembled with the connection fitting) and the strength of the fiber rope itself. In other words, ‘Rt = 1’ means that the breaking load is equal to the original strength of fiber rope.

Within the designed parameters, the fiber ropes of nominal loads of 50 kN and 100 kN show different tendency. For example, Rt increases with increasing taper length for the 100 kN rope. On the other hand, Rt decreases with increasing taper length for 50 kN rope. This fact indicates that there are different optimized shapes in each fiber rope.

For the 50 kN rope, the Rt is close to 1 at point (A) in the Figure 3 . Two additional experiments are conducted under the same condition to eliminate the influence of error and ensure the results. Here, the results are indicated by dot lines. The fiber ropes break outside the connection fitting during all experiment. It is confirmed that the condition (A) is the optimized shape for the 50 kN rope to avoid the stress concentration.

For the 100 kN rope, Rt is close to 1 under the condition shown in (B). However, the fiber rope breaks inside the sleeve at the condition (B). Therefore, the optimized shape of the 100 kN rope seems to be close to the condition (B).



(a) Varying taper angle (b) Varying taper length

Figure 3. Tensile strengths based on wedge shape

3. Investigation of Workability

3.1. Assembling process

Even though the fiber rope has high tensile strength, it is lightweight and flexible. The fiber rope is easy to wind in rings. The rope and the wedge joint are carried separately to the construction site. Then, they are assembled there. Figure 4 shows a process in which the fiber rope is joined with the wedge joint. For the fiber rope, the knitted fiber bundles are covered with a polyester jacket. Assembling the joint and the fiber is performed following procedure:

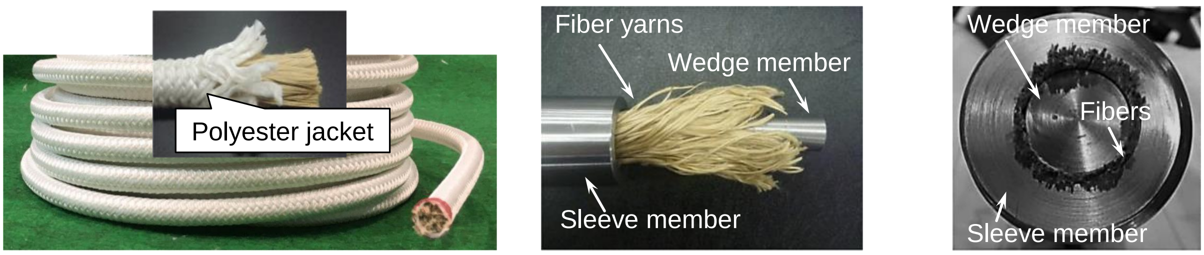
(1) The fiber rope is cut to the necessary length for the seismic brace at the construction site (see figure 4(a)).

(2) The outer polyester jacket at the rope end is peeled off and the fiber yarns are loosened.

(3) The loosened fiber yarns are inserted into the sleeve member.

(4) The fiber yarns are arranged uniformly around the hole of the sleeve member. Then, the wedge member is driven into the hole (see figure 4(b)).

(5) Extra fibers at the rope end are eliminated (see figure 4(c)).



(a) Wound fiber rope to carry (b) Inserting unraveled fiber yarns (c) Elimination of extra fibers

Figure 4. Assembling process of fiber rope

3.2. Fiber treatment at rope end

As described an above chapter, after the fiber yarns are twisted as bundles, most of the bundles are knitted. It is investigated that how the treatment of the rope's end affect on the tensile strength with the fitting. (i.e., the degree of loosened fiber yarns). As shown in figure 5, the following three loosened states are compared:

(a) This is a state which the fibers are still knitted and twisted. Hereinafter, it is referred as the 'knitted state'.

(b) This is a state which the fibers are still twisted, but they are unknitted. Hereinafter, it is referred as the 'twisted state'.

(c) This is a state which the fibers are completely unraveled. Hereinafter, it is referred as the 'unraveled state'.

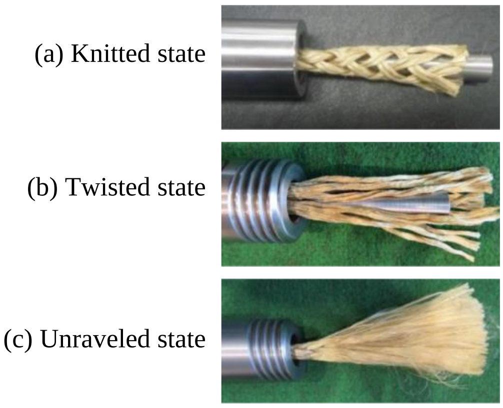


Figure 5. Degree of loosed fiber yarns

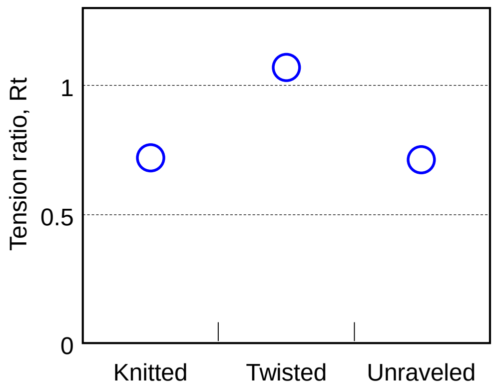


Figure 6. Tensile strengths based on fiber treatment

Tensile tests are carried out using the maximum strength of 50 kN rope. For the tests, the wedge shape of the connection fitting is the combination of shape (A) in Figure 3. Figure 6 shows the results of three different states of the fiber treatment. The tensile strength of the twisted state is higher than that of the unraveled state. In conclusion, high tensile strength can be secured by leaving the twists of the fiber yarns.

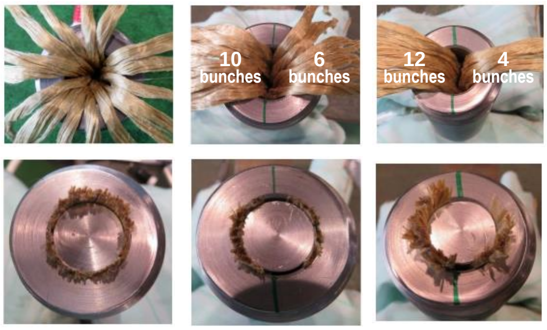
3.3.Deviation of fiber density distribution

A distribution of the fiber density should be uniform inside the sleeve of the wedge joint. However, uneven distribution of fiber density may occur when the fiber rope is assembled with the joint. It is investigated how the deviation of the fiber density distribution affects the tensile strength. The fiber rope used in this investigation consists of 16 twisted fiber bundles. Experiments are conducted in the following three steps. As shown in Figure 7, the 16 twisted fiber bundles are arranged uniformly or non-uniformly.

(a) The 16 fiber bundles are evenly arranged. Hereinafter, it is called the 'even state'.

(b) The 10 fiber bundles on one side and the 6 bundles on the other side. Hereinafter, it is called the ‘bias 10:6’.

(c) The 12 bundles are on one side and the 4 bundles on the other side. Hereafter it is called the ‘bias 12:4’.



(a) Even state (b) Bias 10:6 (c) Bias 12:4

Figure 7. Deviation of fiber density distribution

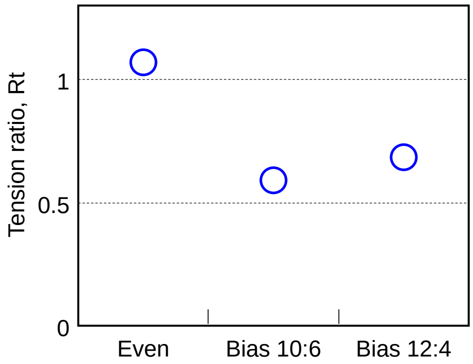


Figure 8. Tensile strengths based on deviation of fiber density distribution

Figure 8 indicates experimental results on the deviation of the fiber density distribution. The joint used in here was same shape as the condition (A) in Figure 3. If there is a bias in the fiber density distribution, the tensile strength extremely decreases. Therefore, it is necessary to arrange the twisted fiber bundles uniformly around the sleeve hole and the wedge member is accurately driven into its center when assembling the fiber rope to the joint.

4. Load-Bearing Wall Tests

4.1. Test conditions

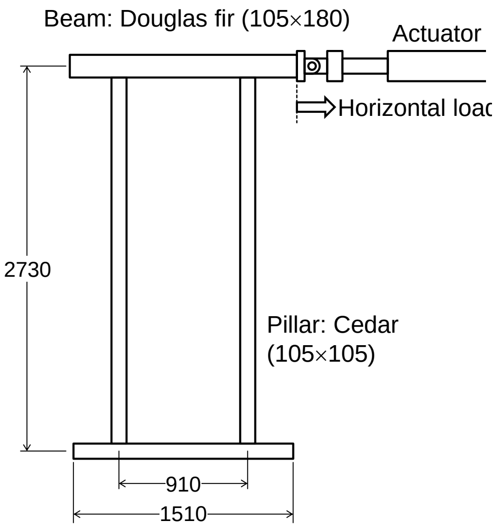


Figure 9. Configuration of load-bearing wall tests

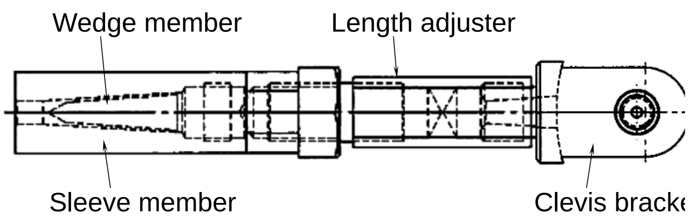


Figure 10. Connection fitting with length adjuster

Load-bearing wall tests are carried out to confirm the effectiveness of the developed seismic brace using the fiber rope. As shown in figure 9, pillars are made of cedar and beams are made of douglas fir. A horizontal load is repeatedly applied in one direction to the wooden frame by the actuator. Experimental methods are based on ‘Allowable Stress Design of Wooden Shaft Construction Housing, Chapter 2: Experiment Method and Evaluation Method of Each Part of Wooden Shaft Construction Housing, Section 1.2: Method of In-Plane Shear Experiment [7]’. The horizontal load is gradually increased in the multiple steps. When the load falls below 80% of its maximum value, or when the interlayer deformation angle becomes larger than 1/15 rad., an occurrence of breaking is judged based on the reference [7]. Here, the interlayer deformation angle is obtained from dividing the interlayer displacement by the frame height.

The 50 kN rope is used for the experiments. An initial extension of 2 to 3 % is given to the fiber rope, so that a tension is immediately generated right after the frame deformation occurrence. The connection fitting with length adjuster, which is shown in figure 10, is used for adding the initial extension.

4.2. Test results and consideration

Figure 11 shows experimental results between the horizontal loads and interlayer deformation angles. For the wooden frame with the seismic brace, the break occurs at the pillar (see figure 12). In parallel with the experiment, simulation analysis is performed using the ‘midas iGen (general analysis software)’. For the simulation analysis, it is assumed that the lower portion of the wood frame is rigidly supported and a horizontal load of 5.2 kN is applied to the upper beam of the wooden frame. The applied horizontal load is the maximum load for the wooden frame without the seismic brace, which is obtained through the experiments. Figure 13 shows the analytical results. Comparing the experimental and simulation results of the load-bearing wall tests with and without the seismic brace, it is indicated that the seismic brace can greatly decrease the deformation of the wooden frame. The effectiveness of reinforcement by the fiber rope is confirmed.

The wall magnification is calculated from the experimental results. The wall magnification is 0.5 in the case of only frame and 1.0 when the seismic brace is applied. The wall magnification with the seismic brace is higher than that without the seismic brace. However, the wall magnification 1.0 is equivalent to the case where a wooden brace of 10 mm×90 mm is used for the load-bearing wall by the wooden shaft assembly method. In other words, although the fiber rope is excellent in terms of construction workability, there is no special advantage in performance comparing to the conventional brace. As a cause for the performance, it may be conceivable that the displacement of the fiber rope becomes longer than necessity against the horizontal load. For the further studies, detailed analysis and improvement will be done.

5. Hand-tie fitting

5.1.Outline of hand-tie joint

This chapter assuming demands on structural reinforcement method for low cost and first-aid solution. Therefore, hand-tie as a joint method is developed.

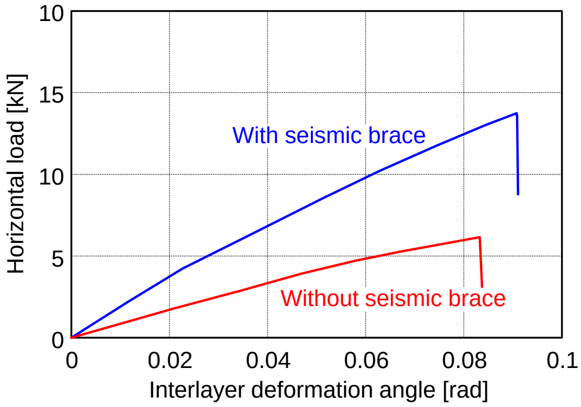


Figure 11. Experimental results between horizontal load and interlayer deformation angle

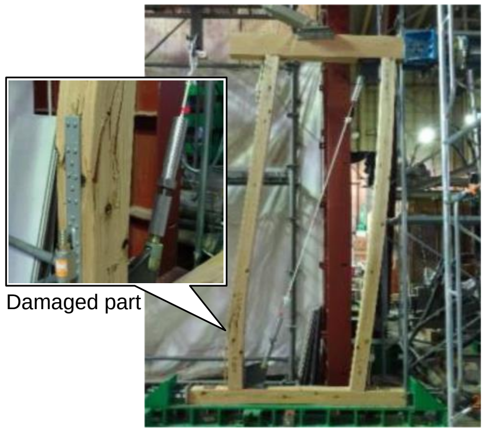
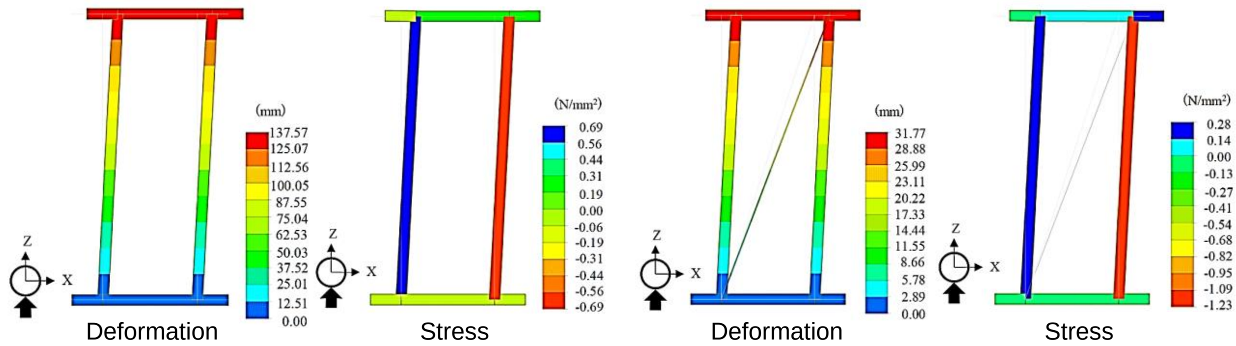


Figure 12. Wooden frame with seismic brace after destruction occurs



(a) Without seismic brace (b) With seismic brace

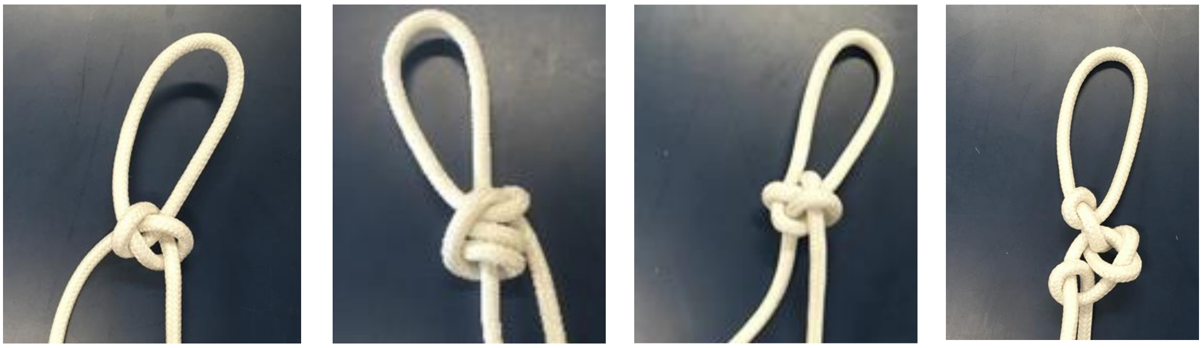
Figure 13. Simulation analyses of load-bearing wall tests

5.2.Optimization of knot

In order to optimize knot, knot refers to the method of tying the fishing line. Then, easiness of hand-tie and behavior during the tensile test is confirmed.

In this chapter, 4 types of knot are suggested. Figure 14 shows each knot. Figure 15 shows the outline and detail of the steel plate (SS400) that ties the rope. The properties of the fiber rope used in this rest are shown in the Table 2. 10 kN rope was used for Bowline and Improved clinch knot, and 50kN rope was used for all knots.

For the test specimens, both ends of rope are tied to the hole of the 2 steel plates and the plates are grabbed in the chuck of the Amsler tester. The elongation of the rope was measured by a winding displacement gauge. In addition, a monotonic tensile test was conducted until the yield strength of the rope deceased.



(a)Bowline (b)Improved clinch knot (c) Reef knot (d)Taut-line hitch

Figure14. Outline of knot for the investigation

5.3. Result of the tensile test

The results for 10kN and 50kN are shown in Table 3, and the load-displacement curves are shown in Figure 16. From the table and figure below, it is considered that Bowline could be tied more easily than other knots and relatively stable results was obtained. On the other hand, Improved clinch knot, Reef knot and Taut-line have a large number of knots and have complicated knots. Therefore, it is considered that the knots gradually moved and tightened during the tensile test and showed unstable behavior. In conclusion, Bowline with the maximum yield strength of the 10kN rope showed 70% of its nominal strength, and for 50kN rope showed about 40% of its nominal strength.

Table 2. Mechanical properties of rope for hand-tie

Fiber	Twaron	
Density(g/cm^3)	1.44	
Tensile strength (kg/mm^2)	300	
Diameter (mm)	7	11
Maximum Tensile strength (kN)	10kN	50kN

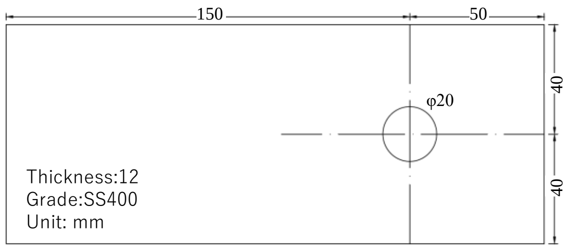


Figure 15. Outline of metal plates

In addition, the Bowline is more practical than other knots because it has greater yield strength against elongation, stable behavior and is easier to tie.

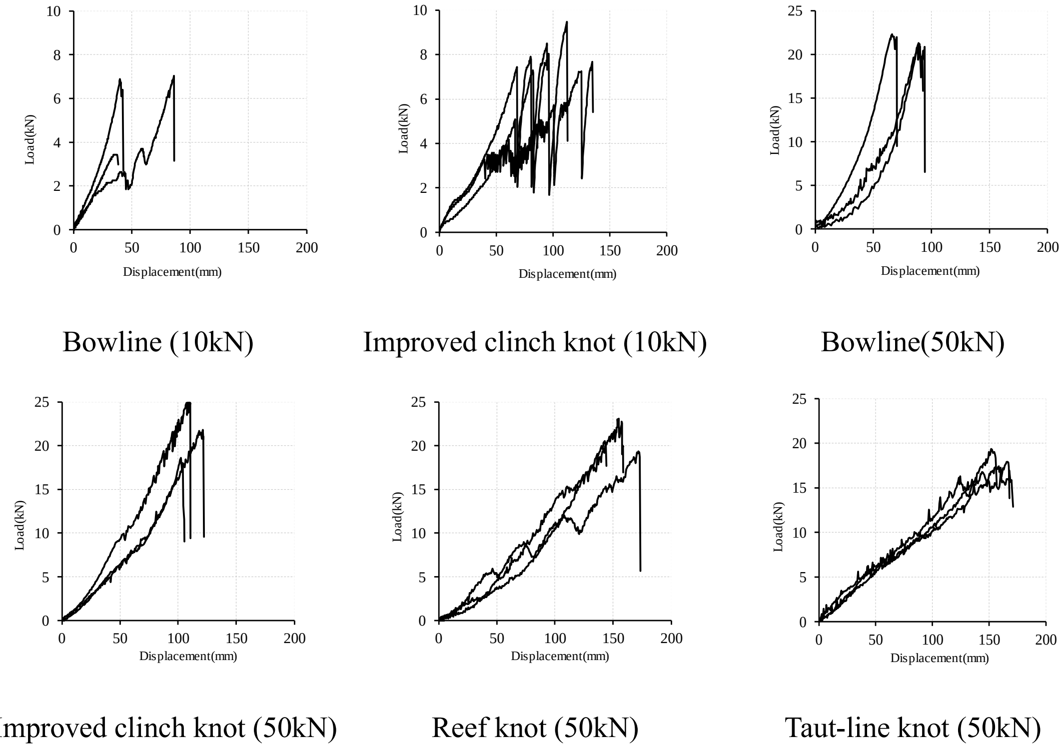


Figure 16. Load-displacement curve

Table 3. Experimental result

Specimen	Knot	Max strength of the rope	Elongation rate (ε) *	Maximum strength (kN)	Elongation (mm)
No.1	Bowline	10kN	0.04	3.42	34.7
No.2			0.32	7.03	86.0
No.3			0.09	6.88	39.9
No.4	Improved clinch knot		0.10	8.51	94.6
No.5			0.27	7.67	134.5
No.6			0.11	9.49	112.3
No.1	Bowline	50kN	0.54	21.30	88.9
No.2			0.30	22.29	66.0
No.3			0.30	21.18	89.2
No.4	Improved clinch knot		0.33	18.60	102.2
No.5			0.21	24.99	109.8
No.6			0.39	21.80	121.6
No.7	Reef knot		0.51	19.35	172.5
No.8			0.34	20.53	142.55
No.9			0.41	23.07	154.8
No.10	Taut-line hitch		0.29	16.6	160.2
No.11			0.32	17.9	166.2
No.12			0.33	19.3	151.8

＊Elongation rate(ε) is calculated by measuring the distance from the knot on both ends before and after the tensile test.

5.Outline of experiment on Aramid fiber with knotting joint

The usage of turnbuckle for introducing an initial tension of seismic brace is investigated. In this chapter, the effect of using turnbuckle is investigated. Basic properties such as maximum strength and behavior during tensile tests were confirmed by monotonic tensile test under connecting fiber ropes to steel plates. The fiber rope used in this experiment had a nominal diameter of 6mm and tensile strength of 19.6 kN. As a representative test specimen, Specimen (a) was with bowline knot with additional treatment called, Secure bowline knot. For the Specimen (b) was with turnbuckle installing between fiber rope to introduce initial tension. Figure 17 and Figure 18 show overview of secure knot applied in the specimen and turnbuckle used in the specimen.

Figure 17. Secure bowline knot

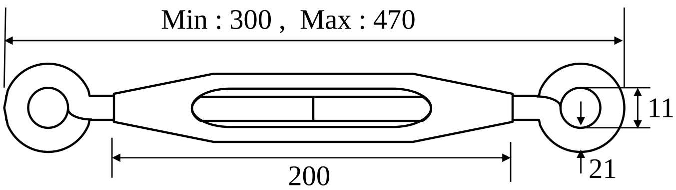


Figure 18. Turnbuckle installed in specimen (b)

The tensile test was carried out under the same condition mentioned in chapter 5. Fig.19 shows the relationship between the load and deformation in the specimen(a) and (b). In this graph, elongation rate was calculated by measuring the distance from the knot at both ends before and after the tensile test. In addition, the load-deformation relationship in the specimen(b) shows the strength by one fiber rope. Specimen(b), the fiber rope was tied with a steel plate, wrapped around 2 times at the end of the turn buckle, and turn it back and tied again with the steel plate. The strength indicated during the test was about 30% to 40% of the nominal strength. The specimen (a), without turnbuckle shows large increase in strength against elongation and it is stable. The specimen (b), with turnbuckle, initial tension was given as rope's 15% to 20% length and the initial rigidity was improved. This result suggests that using turnbuckles are an effective method to introduce initial tension.

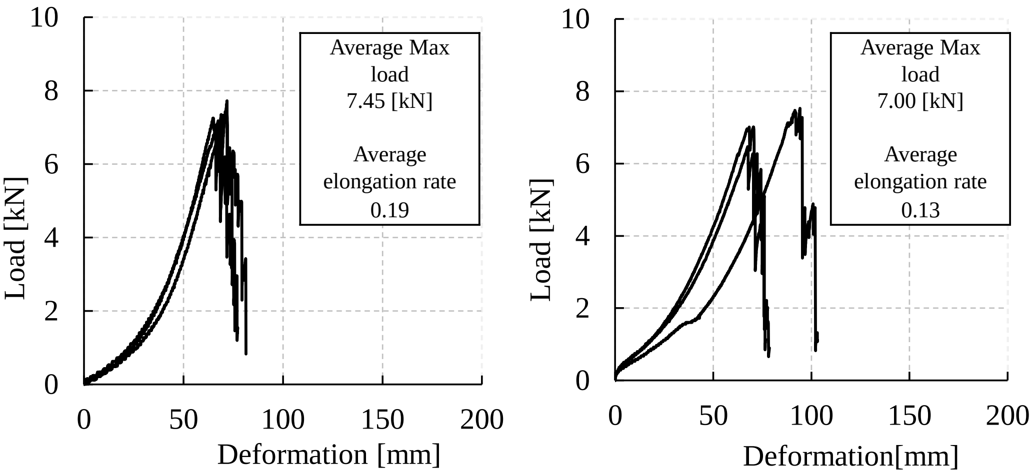


Figure 19. Deformation-Load relationship in specimen(a) and (b)

6. In-plane shear test of seismic reinforced brace using aramid fiber

6.1.The outline of the experiment

In the practical work, hardware shown in Figure 20 was attached to the four corners of the wooden frame, and the fiber ropes are tied to the looped portion by hand. Figure 20 shows the hardware used on the specimen. The construction procedure will follow; one side of the fiber rope was directly tied to the round steel shaft, the other was tied to eyebolt, and initial tension is introduced by tightening the eyebolt. By carrying out in-plane shear test, mechanical properties, rigidity, strength and deformation performance of seismic brace with hand-tie joint were confirmed.

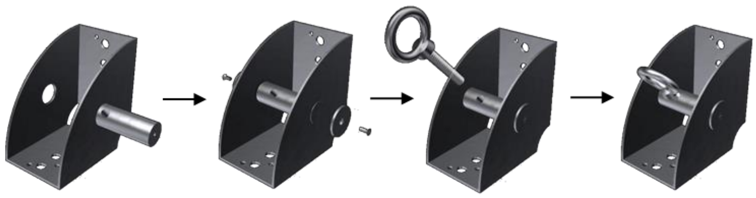


Figure 20. The outline of hardware for fiber rope

6.2. The outline of specimens

Figure 21 shows the outline of specimen. In this experiment, three models were designed to confirm each elements. A specimen No.1 was with only hardware, a specimen No.2 was with the hardware and fiber rope and a specimen No.3 was with turnbuckle instead of the eyebolt to introduce initial tension.

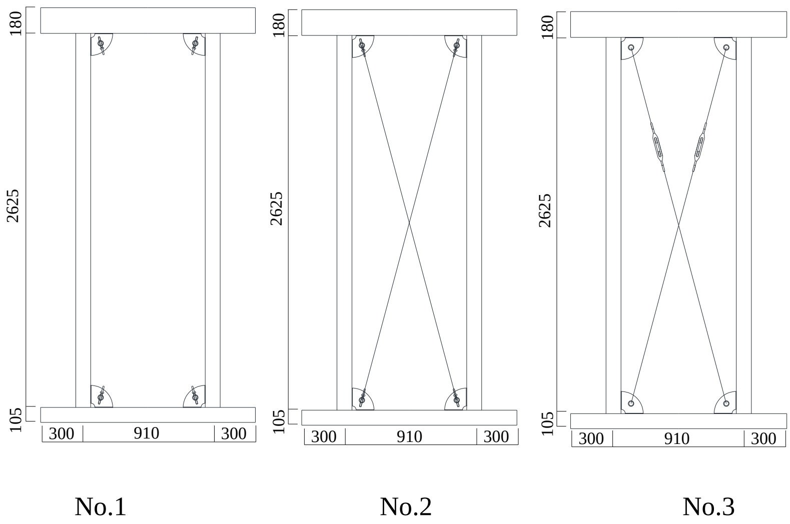


Figure 21. The outline of specimen No.1 to No.3

6.3.The outline of experimental method

In-plane shear test was carried out based on the ‘Allowable Stress Design of Wooden Shaft Construction Housing, Chapter 2: Experiment Method and Evaluation Method of Each Part of Wooden Shaft Construction Housing, Section 1.2: Method of In-Plane Shear Experiment [4]’ A monotonic load was applied to the specimen up to the ultimate deformation of the actuator of 300 mm.

6.4. The results and Analysis

Figure 22 shows the observation of specimen after the experiment. When the load was applied to the maximum deformation, the hardware was deformed, but the damages on the fiber rope was not observed. Moreover, a reduction in the strength was not observed. Figure 23 shows the load - deformation relationship of each specimen. Table 4 shows the characteristic values calculated from the load-deformation angle curve obtained from the experiment. The effect of the applied fiber rope can be observed by comparing the specimen with the fiber rope (specimen No.2 and No.3) and the specimen with only hardware (No.1). For specimen No.3, with turnbuckles and construction is easier. In addition, the initial tension is introduced more comparing to No.2. Thus, the higher strength is indicated. Aiming to further improve in the initial stiffness, it is necessary to increase the number of turnbuckles and make a brace by connecting shorter ropes.

Figure 24 shows the four indices and the wall magnification used to calculate the short-term standard shear strength of each specimen following the reference [7]. All specimens show high strength and yield strength, but the initial deflection is large. The wall magnification is a quantitative value to evaluate the strength of timber wall. It is calculated by following procedure: at first deciding short-term shear strength P_0, P_0 takes the smallest value of (a) Yield strength P_y ,(b)Final yield strength Pu×(0.2/Ds), (c) Max strength P_{max} × 2/3, (d)Strength at 1/120 rad. Then, short-term allowable shear strength P_a is calculated by P_0 × 0.8. Finally, the wall magnification is decided by P_a/1.96L (L=length of the wall). For the specimens, the wall magnification gets smaller due to low rigidity, small plasticity rate and Pu×(0.2/Ds). Figure 25 shows a comparison with conventional timber braces of 5×90,30×90,45×90 in tensile direction. The aseismic reinforcement method suggested in this paper shows low stiffness than general brace, but maximum strength can be expected higher because of its high deformation performance. Therefore, it is considered that this method is inferior to conventional timber bracing during small and medium deformation, but can withstand against large deformation range.

Specimen	No.1	No.2	No.3
Notes	Screws are broken and the side of hardware is deformed.	Screws are broken and the side of hardware is deformed. No damages on the fiber rope.	Screws are broken and the side of hardware is deformed and no damages on the turnbuckle. No damages on the fiber rope.

Figure 22. Observation of the experiment

7. Conclusions

In this paper, a seismic brace using an aramid fiber rope is developed and 2 types of joint are suggested. The key advantage of this seismic brace is to retrofit a building in a short period of time because it can easily be carried and handled.

The results obtained in this research are summarized below:

(1) The wedge type connection joint to assembly the fiber rope with structural members is developed so that the fiber rope does not slip out. The wedge shape of the connection joint is optimized to prevent the stress concentration on the fiber rope.

(2) Procedure of assemble the joint and fiber rope become clear. The twists of the fiber yarns should be remained to maintain the tensile strength high. It is necessary that the twisted fiber bundles are uniformly arranged around the sleeve hole.

(3) The effectiveness of this seismic brace is confirmed through simulation and experimental results of the load-bearing wall tests.

(4) The hand-tie joint is suggested for first-aid solution in low cost. In addition, the bowline is effective knot to use as a tension member.

(5) It is effective that using turnbuckle to introduce an initial tension.

(6) The metal device is designed to attach a seismic brace with hand-tie to the timber frame. The effectiveness of using the seismic brace is confirmed during the in-plane sheer test.

For the future research, this seismic brace will be applied for actual buildings to improve the seismic resistant strength.

Table 4. Characteristic values

Specimen	Max strength P_{max} [kN]	Yield strength P_y [kN]	Deformation angle at P_y [rad]	Initial stiffness K [kN/rad]	Final yield strength P_u [kN]	Angle at yielding point θ_v [rad]	Plasticity rate μ	Structural characteristic factor D_s	Short-term standard shear strength P_0 [kN]	Short-term allowable shear strength P_a [kN]
No.1	7.27	3.96	0.026	140.68	6.42	0.043	1.56	0.69	1.40	1.12
No.2	8.38	4.25	0.024	176.54	7.15	0.041	1.65	0.66	1.55	1.24
No.3	8.78	4.84	0.026	187.13	7.55	0.040	1.65	0.66	1.72	1.37

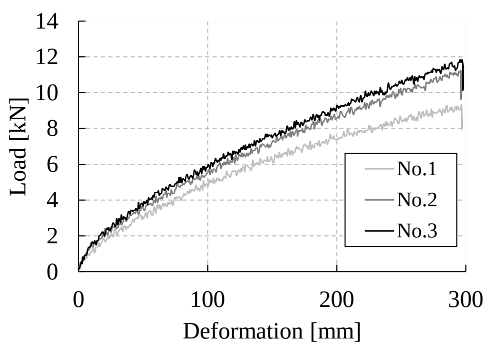


Figure 23. Load-deformation relationship

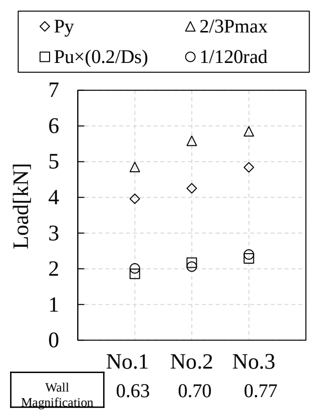


Figure 24. Indices and the wall magnification

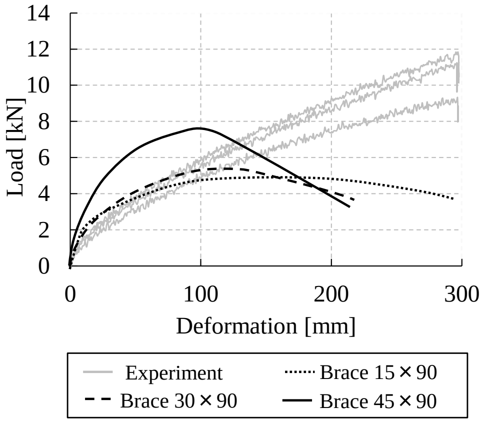


Figure 25. Comparison between general timber brace in tensile direction

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