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FUNDAMENTAL STUDY ON REPAIR BY EPOXY RESIN MIXED WITH CELLULOSE FIBER TO RECOVER BENDING PERFORMANCE OF WOODEN PARTS

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ABSTRACT: This study conducts basic research on the reinforcement effect achieved by mixing epoxy resin and cellulose fiber to gauge the bending performance. Flowability tests indicated that increasing the amount of cellulose fiber relative to epoxy resin decreases flowability, and resins containing approximately 5% cellulose fiber are easier to apply. The compression test results indicated that the compressive strength of the material decreased upon mixing epoxy resin with cellulose fiber. However, the test piece containing cellulose fiber showed higher compressive strength than Cedar and Douglas fir. Compression test results confirmed that when the wood was filled with epoxy, the reinforcing effect achieved was greater than that of sound wood; it was sufficiently effective as a compression repair material. Furthermore, bending test results showed repair work utilising epoxy resin helped recover the bending performance of the test pieces with a 35% defect. Thus, the composite resin of cellulose fiber and epoxy resin is effective as a repair material for the bending material.

KEYWORDS: Cellulose fiber, Epoxy resin, Termite, Repair method

1 INTRODUCTION

1.1 BACKGROUND

Several historical and cultural properties constructed out of wood still exist in Japan. However, the strength of the wood of these buildings has decreased over time due to decay, insect damage, and deterioration. Therefore, appropriate repairs and restoration should be carried out to preserve the original timber used. Wood deteriorates in several ways; termite damage deteriorates the wood from the inside while fungal decay begins on the surface.

Current methods of repairing degraded areas include traditional techniques, such as root joints, and scientific techniques using synthetic resins and carbon fiber [1]. While each repair method has its advantages, cosmetic surface, workability, construction period, and cost can be concerns. Yamada et al. [2] examined the compressive strength of simulated deteriorated pieces to confirm the reinforcing effect of synthetic resins and the compressive and bending strength of wood exposed outdoors like pine wood, which deteriorates in a short period by Formosan subterranean termites. Their examination confirmed that the repair method using epoxy resin had a stronger reinforcing effect on the compressed material than on sound material; however, no reinforcing effect was confirmed on the bent material.

1.2 PURPOSE OF STUDY

This study aims to focus on the recovery of bending performance of wooden structures and propose a more appropriate and effective repair method. We conducted a basic study on the reinforcing effect achieved by mixing cellulose fiber with epoxy resin. The bending performance of the repair structures was confirmed after evaluating the material performance of the resin mixed with the cellulose fiber by conducting compression tests.

1.3 RESEARCH CONTENT

In this report, the material performance of the resin is evaluated by compression and fluidity tests, and the bending performance of the repaired member is confirmed by ultrasonic propagation velocity measurement and bending test, especially to examine the repair method using synthetic resin.

2 CONSIDERING REPAIR METHODS

Based on the literature survey [1]-[10], the characteristics of repair methods used in the past for cultural property buildings are shown in ***Table 1***. Carbon fiber repair methods are mainly classified as bonding, filling, or strengthening methods. Epoxy resins are often used for bonding and filling, and synthetic resins, such as isocyanate-based prepolymers, are often used for strengthening. The latter penetrate the interior of wood by application or impregnation and react with moisture and cellulose to strengthen the interior of the resin, thereby restoring the strength of the degraded wood [6, 7]. Sekino et al. [6, 7], stated concerns that the excessively high hardness of the resin and the fact that when impregnated,

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if the surface is not finished again, the texture of the resin may not match with the weathered surface.

Table 1: *Results of bending strength tests*

Method	Strength Recovery	Construction	Design
Carbon Fiber	○	◎	×
Sheet Roll	○	◎	×
Plate Embedding	○	×	◎
Auxiliary	—	○	×
Oblique Scarf Joint	◎	△	×
+Reinforced plastic	△	○	×
Synthetic Resin	○	○	○
Epoxy	△	○	△
Isocyanate prepolymer	—	○	—
Acrylic	○	◎	×

Recent research has examined carbon fiber repairs for cultural properties constructed out of wood [8, 9]. There are two types of repair methods using carbon fiber: the external adhesive type of carbon fiber board and the embedded type into the member, and the rolled type and auxiliary type of carbon fiber sheet [8]. Externally bonded molds and sheet-wound molds of carbon fiber board can be used to attach to damaged members. The external adhesive type of carbon fiber board is made by impregnating carbon fiber with epoxy resin, hardening it, and then affixing it with an adhesive. This makes it easy to install. However, since it is plate-shaped, the use of external adhesive type carbon fiber board is limited to smooth areas. v but they are thin, flexible, and can handle complex shapes. Auxiliary types include the use of carbon fiber rods as anchors or braces. Moreover, except in the case of embedding, the carbon fibers are exposed to the surface, which may prove to be an unsuitable design from design perspective.

Filling termite damage with synthetic resin can be done to prevent wood degradation caused by decay, and insect damage. Yamada et al. [2, 10] investigated the compressive and flexural strengths of pine wood exposed outdoors to Formosan subterranean termites, and that of small pieces subjected to simulated deterioration to confirm the reinforcing effects of synthetic resins. Results revealed that the repair method using epoxy resin was more effective for compressive materials than for sound materials, but not for flexural materials.

3 CELLULOSE FIBER

Cellulose fiber is biomass material derived from plants. Attention to plant biomass materials such as cellulose fiber was sparked by the depletion of oil resources. Consequently, biomass became much discussed whenever crude oil prices soared, leading to calls for the development of technologies to replace petroleum-derived plastics with renewable biomass resources as fuel and raw materials for chemical products [11].

This study also investigated the reinforcing effect of adding cellulose fiber to epoxy resin. Additionally, the cellulose fiber used in this study was extracted from rice straw produced at the University of Tokyo. The materials used in the production process have extremely low environmental impact.

The process of cellulose extraction is as follows:

(1) After adding distilled water into the rice straw and letting it stand, the process of pulverizing the rice straw with a mass collider is repeated to remove lignin and hemicellulose from the cellulose surface in the cell wall. This exposes the cellulose to the surface. The material input is shown in ***Photo 1***.

Photo 1: *Separation work*

(2) Using a vacuum and a flask, only the crushed rice straw is removed from the liquid in the rice straw and distilled water. ***Photo 2*** shows the separation process.

Photo 2: *How the ingredients were added*

(3) Dry in a drying oven (60 °C).

The cellulose condenses and hardens when the cellulose fiber is dried. They are broken up after drying to finish the process. ***Photo 3*** shows how it looks after drying.

Photo 3: *Cellulose fiber after drying*

4 MATERIAL PERFORMANCE OF RESIN

4.1 EPOXY RESIN

4.1.1 Outline of compression tests

To confirm the reinforcing effect of blending epoxy resin with cellulose fiber, test pieces containing a blend of epoxy resin with cellulose fiber by 2%, 5%, and 10% were prepared and subjected to compression tests. The size of each test piece was 20 × 20 × 40 mm compared with the previous studies [2, 10]. ***Photo 4*** shows the state of fabrication. We used formwork plywood wrapped with silicone resin-treated glassine paper to prepare the pieces. The curing period was 23°Cfor four days plus 60°Cfor three days. Additionally, the cellulose fiber B was mixed with the main agent and hardener. We made three pieces for each repair method.

We used a two-liquid mixture (main curing agent) resin. The component of the main agent was an epoxy resin, and that of the curing agent was a polyamine. To confirm the original performance of the epoxy resin used this time, a test piece N without compounding cellulose fiber was prepared, and the compression test was performed.

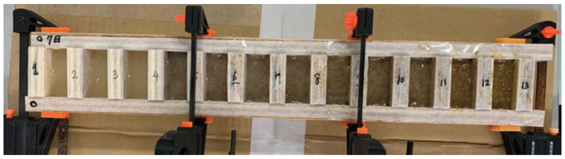

Photo 4: *The state of fabrication of test pieces*

4.1.2 Compression test results

Figure 1 shows the compression test results**.** Adding cellulose fiber to epoxy resin increased the strength of resin containing 2% cellulose fiber. Contrarily, the resin containing 5% or 10% cellulose fiber decreased compressive strength. However, it acts as an effective repair material for compression in this study because it has a higher value than the design basis quasi-compressive strength of Douglas fir (27.0 N/mm^2). Its compressive strength was about 40 to 50 N/mm^2, which was confirmed to be similar to the experimental results of past studies in which wood was filled in with epoxy resin. [2].

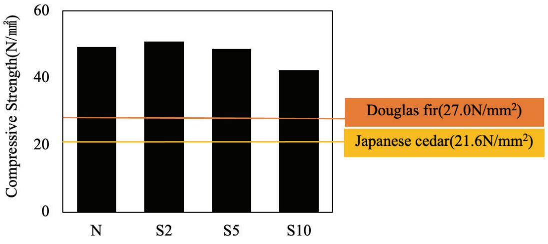

Figure 1: *Results of compressive strength tests*

4.2 WORKABILITY

Viscosity measurements were performed using a B-type viscometer. The B-type viscometer is shown in ***Photo 5***. To measure the viscosity, a sample liquid was placed in a container such as a beaker and the spindle was immersed in the liquid. When the motor was rotated, the spring and spindle also rotated; however, the spring is twisted by the flow resistance of the measured sample. This twist is detected by a torque sensor and obtained as a torque value. The viscosity is calculated from the constant determined by the combination of this torque value and the spindle speed.

Photo 5: *B-type viscometer [13]*

The viscosity values of each resin obtained from the flowability test results are shown in ***Figure 2***. The change in resin fluidity was confirmed by mixing different percentages of cellulose fiber with epoxy resin. The results showed that the more cellulose fiber was added, the higher the viscosity and the lower the fluidity.

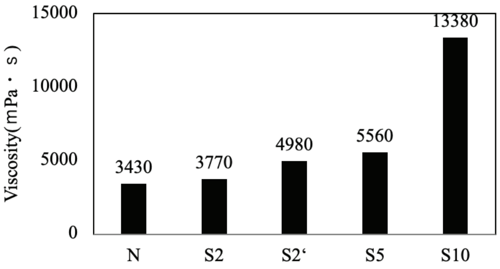

Figure 2: *Viscosity values of epoxy resin and cellulose blends*

As shown in ***Figure3***, it can be confirmed that the fluidity of the pieces with 10% cellulose fiber added to epoxy resin was greatly reduced compared to the pieces with 2% or 5% cellulose fiber added.

It is considered that a highly flowable repair material, which is easy to fill to the back against deterioration of termite paths, is more effective as a repair material at the time of resin filling in deteriorated materials. Contrarily, a less flowable repair material is more effective at the time of curing until the filled resin hardens.

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The general liquid viscosity [14] is comparable to a resin containing 10% of the thickest cellulose fiber. It is considered difficult to fill wood materials with this viscosity value. Contrarily, epoxy resin with 2% or 5% cellulose fiber shows the same viscosity value as strawberry jam, and with this viscosity, the resin can be filled deep into the termite path against deteriorated components. Thus, this viscosity is suitable for filling.

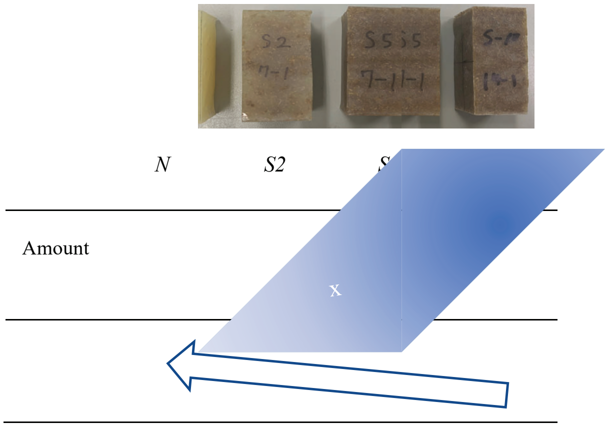

Figure 3: *Relationship between the amount of cellulose fiber and liquidity*

5 VERIFICATION OF BENDING PERFORMANCE FOR SIMULATED DETERIORATED PIECES

5.1 OUTLINE OF BENDING TESTS

A simulated deterioration test piece similar to termite damage deterioration was produced, and a bending test was performed. The bending test was carried out according to JIS Z 2101. ***Figure 4*** shows the parameters of the flexural pieces. To reproduce the wood degradation from termite damage, the simulated degradation test piece was produced. The shape of the test piece was a column of square cross-section with side length a = 20 mm, a total length L = 320 mm, and load span l = 280 mm.

Table 2: *Pieces for bending strength tests*

Piece		Defect (%)	Number
B-0		0	3
	None		
		20	3
BS2-20		20	3
		20	3

A longitudinal slit was inserted symmetrically as shown in ***Figure 4***. The defect ratios to the volume of each piece and the wood opening area were about 20%, 30%, and 35%. Pieces were prepared by mixing 2% and 5% cellulose fibers with epoxy resin as shown in ***Photo 5***.

Additionally, to confirm the bending performance recovery before and after each repair method, bending tests were also conducted on sound materials without repair and at each defect rate. The first and second parts of the test piece names in ***Table 2*** indicate the repair method and defect rate, respectively. B is unfilled, BN is filled only with epoxy resin, and BS2 and BS5 are filled with epoxy resin containing 2% or 5% of cellulose fiber, respectively. In this study, Douglas fir was used as the tree

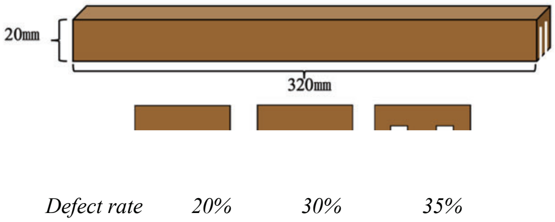

Figure 4: *Shape of the piece*

Photo 5: *Pieces for bending strength tests*

Photo 6: *Conducting bending strength tests*

5.2 BENDING TEST RESULTS

Figure 5 shows the bending test results at each defect rate for each repair method. The results were compared with B-0 (the sound). The bending strength decreased with increasing defect rate. Considering the unrepaired test pieces (B), the bending strength of B-20 (the 20% defect) is decreased by 11% compared to B-0, B-30 (the 30% defect) is decreased by 18%, and B-35 (the 35% defect) is decreased by 20%. The average repair effect at 20% defect across resin-filled pieces(BN, BS2 and BS5) changed compared to the unrepaired piece little.

As for the resin-filled test pieces (BN, BS2, and BS5) with 20% defect, no repair effect was confirmed compared to the unrepaired material (B) regardless of the repair method. On the other hand, in the resin-filled test pieces with 35% defect, strength recovery was observed in all test pieces compared to the unrepaired test piece (B-35) with the same failure rate. Additionally, with a 35% defect, the test pieces that mixed the cellulose fiber (BS2 and BS5) showed a higher reinforcing effect than the one containing only epoxy resin (BN). It was indicated that the reinforcing effect was higher as the mixing quantity of the cellulose fiber became larger from 2% in BS2 to 5% in BS5. From these results, it is considered that resin mixed with cellulose fiber is an effective repair material for recovering the bending performance in material with a 30% and 35% defect rate. However, there is a dispersion in the obtained strength, and further examination is necessary.

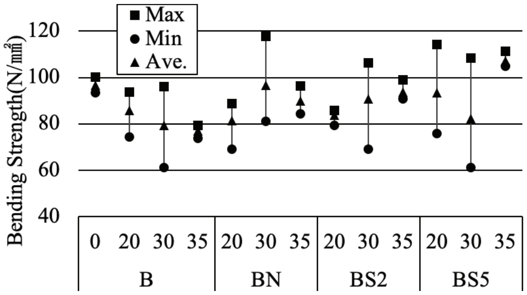

Figure 5: *Results of bending strength tests for repair methods*

To confirm whether the filling was sufficient, ultrasonic propagation velocity measurement, which is a non-destructive diagnosis, was performed before and after filling, and sufficient filling was confirmed from the change in velocity. The height of the terminal was placed at the center of the piece (20 mm each in the short-side direction), and an ultrasonic propagation velocity measuring instrument was used.

The ratio of the ultrasonic propagation velocity measurement results performed after epoxy resin filling of the simulated deteriorated piece to the ultrasonic propagation velocity of the sound piece is shown in ***Figure 6***. The experimental results showed that the rate of change in velocity is comparable or higher for sound pieces. This suggests that the simulated deteriorated pieces were sufficiently filled with epoxy resin.

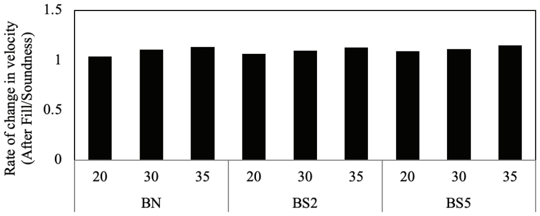

Figure 6: The ratio of ultrasonic propagation velocity after epoxy resin filling to that of the sound piece

The rate of change in ultrasonic propagation velocity before and after resin filling is shown in ***Figure 7.*** In the pieces with a defect rate of 30% and 35%, an increase in the ultrasonic propagation velocity due to resin filling was confirmed. This suggests that ultrasonic propagation measurement may be an effective method for confirming whether defects are sufficiently filled. Contrarily, no significant change was observed in the rate of change in velocity before and after resin filling in the 20% defect piece. It is inferred that the depth and width of the defect at the measurement position affected this as shown in ***Figure 8***.

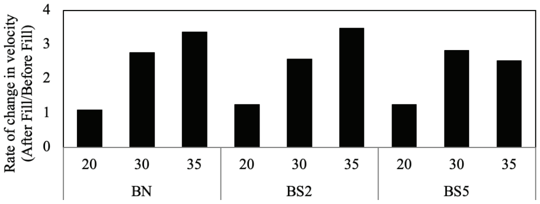

Figure 7: The rate of change in ultrasonic propagation velocity before and after resin filling

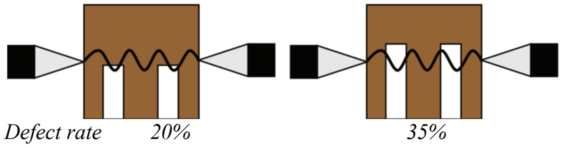

Figure 8: *Results of bending strength tests by defect rate*

6 CONCLUSION

This study mainly focused on the bending performance and carried out basic research on the reinforcing effect of mixing plant-derived cellulose fiber into epoxy resin for the proposal of more appropriate and effective repair.

A literature search revealed that although the winding form of carbon fiber sheets is effective in improving bending performance, design problems remain in cosmetic materials, and no reinforcement effect has been confirmed for bending materials in repair methods using epoxy resins.

From the results of compression tests on resins, it was found that compounding cellulose fibers with epoxy resin tends to reduce the compressive strength. However, the test pieces with cellulose fibers were found to have high compressive strength compared with the standard compressive strength of Cedar and Douglas Fir. Furthermore, the results of ten compression tests conducted when wood members were filled with epoxy resin with a compressive strength of ~40-50 N/mm^2 have confirmed that these materials are more effective than sound materials in reinforcing wood.

Flowability tests showed that with the increase in the amount of cellulose fiber relative to epoxy resin, the flowability decreased. When deteriorated materials are filled with resin, it is considered that highly flowable repair materials, which are easy to fill deep against deterioration of termite, are more effective as repair materials. Less flowable repair materials are more effective when considering the curing time until the filled

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resin hardens. Therefore, resins containing about 5% cellulose fiber are the easiest to apply.

Ultrasonic propagation velocity measurements showed a large rate of change before and after filling, suggesting the effectiveness of resin filling in pieces with a defect rate of 30% and 35%.

The results of the bending tests showed that the repair with epoxy resin had a higher reinforcing effect on the members with larger defect rates. Additionally, the recovery of bending performance was confirmed by combining epoxy resin with cellulose fiber for 35% deficient pieces. The composite resin of cellulose fiber to epoxy resin is an effective repair material for bending materials.

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