An experimental study about structural behavior of CFRP Bar embedded into wood surface

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ABSTRACT

Recently there has been an increase in people’s interest in friendly-environment wooden-structure buildings due to changes in the diversified housing environment. Resulting from such increased interest, there is also growth in the amount of consumed and imported woods required for various designs of wooden buildings. However, due to lack of experience in designing such buildings, many problems have arisen, including excessive dependence on traditional wooden architectures. This study considers the construction method of inserting a CFRP Bar into the wooden surface. From a comparison of maximum internal force, the experimental specimen group reinforcing the lateral side and the bottom side of wood showed an increased maximum internal force over 50% more than the non-reinforced specimen group, so it is known that if the load reduction rate, \( \Delta P_{\text{max}} \), is increased, the transformation rate of CFRP Bar is increased. From this result, it is also known that the CFRP Bar properly distributes the external force being exercised from outside, and this proposed construction method is effective.

1. Introduction

1.1. Background and objectives

According to a recent survey by Korea Forest Service on prospective customers of detached houses on the preference of housing structure, 70 to 80% of the participants preferred wooden construction. Since 2005, regulations have been revised so that buildings whose roof height is 18 m or lower, eaves height is 15 m or lower, and total floor area is 3,000 m² or less can be constructed solely with timber.

Accordingly, it is expected that the domestic demand on wood will continue to grow due to the interest in timber, an eco-friendly material, and the expansion of Hanok construction, and already domestic timber production rate is on the rise (Korea Forest Service 2013).

And yet, because of the high dependency on imported timber, it has been analysed that the increase in foreign hardwood prices and the aftermath of the recovery from the 2016 Fukushima earthquake would slow down the increasing rate of timber imports. Therefore, it is urgently required to research and develop eco-friendly repair and reinforcement methods for aged wooden structures as well as an innovative technology that would reduce timber consumption and prevent the exterior deformation of structure. Repair and reinforcement methods include a method that improves ductility and another that improves stiffness, and because timber already has excellent ductile capacity, it would be more effective to improve stiffness.

The existing repair and reinforcement method using metal poses problems like heavy weight and corrosiveness. However, CFRP Bar (Carbon Fiber Reinforced Polymer Bar), developed in the latter half of the twentieth century, offers many advantages, such as light weight, workability, non-corrosiveness, durability, and high tensile strength among others. The poor economic performance, which had been highlighted as its weakness, is being overcome as its price is falling thanks to technological improvement and the increase in acceptance (Park 2009, 2010).

Therefore, this study aims to propose a method of embedding CFRP bar into wood surface and evaluate the structural performance of the reinforced timber.

1.2. Scope and methodology

While there have been many studies on concrete strength related to the bonding strength between rebar and concrete, bonding length, reinforcement types and gap, little research has been done on the bonding strength between wood and reinforcement, and there is need to study such factors.

Therefore, the study aims to propose a method of embedding CFRP bar into wood surface and examine the bonding performance and structural properties between CFRP bar and timber. Through the bonding test between CFRP bar embedded into wood surface...
and timber, the study noted the optimal surface thickness, and after reinforcing wood members consistent with the test results, it evaluated the structural performance. Finally, the study examined the strength performance, ductility, and differences in stiffness based on the number and reinforcement types of CFRP bar.

### 2. Observation

#### 2.1. Reinforcement method

Shown in Figure 1 is the surface embedding method with CFRP bar. The procedure followed from (a) surface planing → (b) wood fluting → (c) epoxy resin coating → (d) CFRP Bar embedding→ (e) adhesion of CFRP Bar using epoxy resin on wood. To improve the bonding force between the base material and the reinforcement, epoxy was coated on the groove, and CFRP bar was embedded, and finally, to produce the targeted coating thickness, the epoxy adhesive was injected.

Shown in Figure 2 is the shape of the CFRP bar. The used CFRP bar is a spiral steel rod based on a circular steel bar to which a 1 mm high strength polyester line is applied via a 6 mm gap, and 0.2 mm silica is compressed on the surface of the CFRP bar to improve the bonding force with the base material. To examine the dynamic properties of CFRP bar, the study conducted a tensile test by injecting epoxy resin on both ends of CFRB bar and fixing it with steel pipes based on ACI 440.3R-04 (American Concrete Institute).

Table 1 shows the dynamic properties of the used CFRP bar. Figure 3 shows the material test conditions of the used timber. The study used Douglas fir wood for the test timber, and before creating the

![Figure 1. Procedure of specimen construction.](image1)

![Figure 2. Shape of CFRP bar.](image2)
specimens, the non-destructive compressive strength was measured and only timber of which the standard error is within 10% was used for the test. The measurement of compressive strength and moisture content was based on KSF 2206 (Korean Industrial Standards 2004) and KSF 2199 (Korean Industrial Standards 2001). The epoxy resin used in this study was polyvinyl acetate (Park and Hong 2008).

Table 1. Mechanical properties of CFRP bar.

| Item      | CFRP diameter (mm) | Tensile strength (MPa) | Modulus of elasticity (GPa) |
|-----------|--------------------|------------------------|-----------------------------|
| CFRP-Bar  | 10                 | 2,800                  | 165                         |
|           | 12                 | 2,951                  | 169                         |

Table 2. Mechanics of the used material.

| Item                  | Compressive strength (MPa) | Tensile strength (MPa) | Moisture content (%) |
|-----------------------|----------------------------|------------------------|----------------------|
| Wood (Douglas fir wood)| 10                         | -                      | 15                   |
| Epoxy (Polyvinyl acetate) | 100                      | 30                     | -                    |

Table 3. List of bonding test specimens.

| NO | B × D (mm) | CFRP diameter (mm) | Coating thickness (mm) | Bonding length (25db: mm) |
|----|------------|--------------------|------------------------|----------------------------|
| 1  | 250 × 250  | 10                 | 10                     | 250                        |
| 2  | 250 × 250  | 10                 | 15                     | 250                        |
| 3  | 250 × 250  | 10                 | 20                     | 250                        |
| 4  | 250 × 250  | 10                 | 30                     | 250                        |
| 5  | 250 × 250  | 10                 | 40                     | 250                        |

3. Experiments

3.1. Bonding experiment

Table 3 shows a list of the specimens. The section of the specimens was 250 × 250 mm, the bonding length was 25 db, and the diameter of CFRP bar was 10 mm. The main parameter of the bonding test was the coating thickness of CFRP bar, and, considering the coating thickness of RC structure (Construction Standard Specification, MOLIT, 2006 (Construction Standard Specification 2006)), four specimens of each of the five different coating thicknesses of CFRP bar, 10, 15, 20, 30, and 40 mm, were produced. Based on Equation (1), the bonding strength τ₀ was evaluated.

$$\tau_0 = \frac{P_{\text{max}}}{\Phi \cdot L}$$  \hspace{1cm} (1)

Here, τ₀ is bonding strength, Pₘₐₓ is maximum load of load cell, Φ is perimeter of the main rebar, L is bonding length.

3.2. Bonding experiment method

To determine the bonding properties between wood and the CFRP bar embedded into the wood, the study conducted a simple pull-out test based on ACI 440 3R-04. To examine whether CFRP bar reaches the yield point during the test, a wire strain gage (WSG) was attached to the CFRP bar to check for any deformation. As shown in Figure 4, a universal testing machine (U.T.M) with the capacity of 2,000 kN was used for the pull-out test.

3.3. Flexural compressive strength test plan

Table 4 shows the list of specimens for the flexural compressive strength evaluation, and Figure 5 shows the shape of the specimens. All specimens were measured at 160 × 240 × 2,200 mm, and the coating thickness was identical at 30 mm. With the method of surface-embedding CFRP bar into wood as the main parameter, a total of 13 specimens were planned.

Figure 3. Timber material test.
The surface-embedding method was divided into three types: the bottom surface reinforcement, the lateral reinforcement, and bottom-lateral reinforcement, based on which number of CFRP bar and its diameter were varied to create the specimens.

The used material was CFRP bar of 10 mm and 12 mm diameter, and polyvinyl acetate epoxy resin was used for surface-embedding. After the surface-embedding of the CFRP bar, the surface was coated with polyvinyl acetate epoxy resin for precision construction of the coating thickness.

### 3.4. Flexural compressive strength testing method

As shown in Figure 6 a UTM with the capacity of 2,000 kN was used to apply one-point loading on top of the specimen.

### 4. Test results

#### 4.1. Bonding test result

Shown in Figure 7 and Table 5 are the bonding test results between wood and the CFRP bar embedded into the wood.

| Specimens | Reinforcement Shape | CFRP bar diameter (mm) | CFRP bar Number | CFRP bar Reinforcement ratio |
|-----------|---------------------|------------------------|-----------------|------------------------------|
| NONE      | Non                 | -                      | -               | -                            |
| I-CF10-1 | B                   | 10                     | 1               | 0.00204                      |
| I-CF10-2 | B                   | 10                     | 2               | 0.00409                      |
| I-CF12-1 | B                   | 12                     | 1               | 0.00294                      |
| I-CF12-2 | B                   | 12                     | 2               | 0.00589                      |
| S-CF10-2 | S                   | 10                     | 2               | 0.00409                      |
| S-CF10-4 | S                   | 10                     | 4               | 0.00818                      |
| S-CF12-2 | S                   | 12                     | 2               | 0.00589                      |
| S-CF12-4 | S                   | 12                     | 4               | 0.001178                     |
| U-CF10-3 | B + S               | 10                     | 3               | 0.00613                      |
| U-CF10-6 | B + S               | 10                     | 6               | 0.01227                      |
| U-CF12-3 | B + S               | 12                     | 3               | 0.00883                      |
| U-CF12-6 | B + S               | 12                     | 6               | 0.01766                      |

Note: In I-CF10-1, I is the reinforcement shape (bottom reinforcement), CF10 is the diameter of CFRP bar (10 mm), and 1 is the number of CFRP bar. B is bottom, S is side.

The surface-embedding method was divided into three types: the bottom surface reinforcement, the lateral reinforcement, and bottom-lateral reinforcement, based on which number of CFRP bar and its diameter were varied to create the specimens.

Figure 4. Loading apparatus (Bonding test).

Table 4. List of flexural test specimens.

Figure 5. Shape of the specimens.

Figure 6. Loading apparatus (Flexural compressive test).

Figure 7. Bonding strength evaluation.
The test results showed that the bonding strength $\tau_b$ increased with the coating thickness up to 30 mm, but it decreased with the coating thickness at 40 mm. Later, further analysis on the test results would be required, but considering constructability, it is believed that 30 mm coating thickness for CFRP bar embedded into wood would offer sufficient strength.

### 4.2. Flexural compressive strength test results

**Figure 8** shows the final failure patterns at the bottom surface of the flexural compressive strength specimens.

In 'None', non-reinforced specimen, a crack starting from the centre of the bottom surface progressed to the side, and at the same time, the wood crush behaviour on top of the specimen was observed, leading to a final flexural failure. It showed a typical flexural failure behaviour with 7.27 mm deflection under a yield load of 91.9 kN. Among the bottom-reinforced specimen groups, the specimen with one CFRP bar showed the final failure pattern similar to the non-reinforced specimen group in which flexural cracks were dominant, but the specimen with two CFRP bars showed a shear crack pattern with a crack that started from the centre of the bottom surface progressing to the side by 45º, leading to final failure. In all specimens reinforced with CFRP bar, the cracks on the surface continued to increase after the maximum load and resulted in a drastic fall of load, and after a constant load reduction, the specimens showed ductile behaviour with consistent plastic deformation, leading to the final failure.

Shown in **Figure 9** are the load-displacement curves of the specimens. **Figure 9** (1), (2), and (3) illustrated the load-displacement relation of the specimen group with the reinforced bottom surface, with the reinforced side, and with both the reinforced bottom surface and the reinforced side, respectively.

The maximum strength of the specimen group with the reinforced bottom surface was 1.21 to 1.40 times higher than that of None, the non-reinforced specimen, and in the case of CFRP bar of 10 mm diameter, the variation of the maximum strength of the specimens based on the number of CFRP bars was not significant. However, in the case of CFRP bar of 12 mm diameter, the maximum strength of I-CF12-2 was higher than I-CF12-1 by 16%. The maximum strength of the specimen group with the reinforced side was 1.23 to 1.30 times higher than that of None, the non-reinforced specimen.

**Figure 10** shows the comparison of the maximum strength of specimens by the reinforcement types and the number of CFRP bars. **Figure 10** (a) illustrates the comparison of ○ specimen group that uses two CFRP bars of 10 mm diameter and × specimen group that uses two CFRP bars of 12 mm diameter based on the reinforcement types of the bottom surface and the reinforcement types of the bottom-side. While ○ specimen group did not show a significant difference in the maximum strength by the reinforcement types, in × specimen group, the specimen with the reinforced bottom surface exhibited higher reinforcing effect than that with the reinforced side.

**Figure 10** (b) shows the specimen group reinforced with both the bottom surface and the side. The maximum strength based on the number of CFRP bars was compared.

Shown in **Table 6** are the test results of flexural compressive strength. Shown in **Figures 11** and **12** are the ductile and stiffness evaluation results.

In all specimens, excluding None, U-CF10-3, and U-CF12-3, the load drastically fell after the maximum load, and after the load reduction, they showed ductile behaviour.

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**Table 5. Test results of bonding test body.**

| NO | Coating thickness (mm) | Bonding strength $\tau_b$ (MPa) | Ratio (%) |
|----|------------------------|---------------------------------|-----------|
| 1  | 10                     | 2.4                             | -         |
| 2  | 15                     | 2.7                             | 1.13      |
| 3  | 20                     | 3.1                             | 1.29      |
| 4  | 30                     | 3.4                             | 1.42      |
| 5  | 40                     | 3.3                             | 1.38      |

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**Figure 8.** Final crack patterns (Bottom of specimens).
Shown in Figure 13 is the relation between the load reduction ratio $\Delta P_{\text{max}}$ and the strain of the CFRP bar. Here, the strain of CFRP bar signifies the maximum strain, and the load reduction ratio is that of the maximum load to the rapidly reduced load.

It shows that the increase of the load reduction ratio $\Delta P_{\text{max}}$ results in the increase of the strain of the CFRP bar. Therefore, it can be determined that the external force is sufficiently distributed by CFRP bars.

5. Conclusions

This study examined the bonding performance between CFRP bar and wood by embedding CFRP bar into the wood, and conducted a structural performance evaluation of the CFRP bar-embedded wood in relation to the flexural compressive behaviour of the wooden members. The study resulted in the following conclusions.
While the bonding strength increased with the coating thickness up to 30 mm, it decreased with the coating thickness at 40 mm. It is believed that 30 mm coating thickness for CFRP bar embedded into wood would offer sufficient strength performance.

In all specimens under flexural compression load, the cracks on the surface continued to increase after the maximum load and resulted in a drastic fall of load, and after a constant load reduction, the specimens showed ductile behaviour with consistent plastic deformation, leading to the final failure. It is thus determined that despite the rapid progress of strength degradation due to the failure of the base material, the CFRP bars are sufficiently distributing external load.

The maximum strength of the specimen group with the reinforced bottom surface was 1.21 to 1.40 times higher than that of the specimen group with the reinforced side was 1.23 to 1.30 times higher than that of None, the non-reinforced specimen. The maximum strength of the specimen group reinforced with both the bottom surface and the side was 1.30 to 1.51 times higher than that of None. It was shown that there was no marked difference in maximum strength, ductility, or stiffness between the specimen group reinforced with the bottom surface and that reinforced with the side.

It was shown that the increase of the load reduction ratio $\Delta P_{\text{max}}$ results in the increase of the strain of the CFRP bar. Therefore, it can be determined that the external force is sufficiently distributed by CFRP bars.

**Disclosure statement**

The authors also conduct research in areas of interest similar to the business interests of entity. The terms of this arrangement have been reviewed and approved by

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**Table 6. Test results of flexural compressive strength.**

| Specimens | $P_{\text{max}}$ (MPa) | $\delta_{\text{max}}$ (mm) | $P_u$ (MPa) | Ductility | Stiffness |
|-----------|------------------------|-----------------------------|-------------|-----------|-----------|
| NONE      | 104.7                  | 15.63                       | 91.8        | 2.15      | 12.64     |
| I-CF10-1  | 126.7                  | 8.55                        | 112.0       | 1.20      | 15.73     |
| I-CF10-2  | 130.9                  | 9.70                        | 117.1       | 1.20      | 14.43     |
| I-CF12-1  | 129.9                  | 13.77                       | 113.8       | 1.54      | 12.70     |
| I-CF12-2  | 146.6                  | 13.20                       | 122.5       | 1.66      | 15.44     |
| S-CF10-2  | 128.8                  | 11.80                       | 110.8       | 1.86      | 17.45     |
| S-CF10-4  | 130.2                  | 10.53                       | 121.8       | 1.40      | 16.24     |
| S-CF12-2  | 130.1                  | 14.06                       | 113.1       | 1.50      | 12.03     |
| S-CF12-4  | 136.1                  | 13.94                       | 119.7       | 1.46      | 12.52     |
| U-CF10-3  | 136.8                  | 15.87                       | 109.9       | 1.76      | 12.17     |
| U-CF10-6  | 147.0                  | 12.14                       | 140.6       | 1.17      | 13.57     |
| U-CF12-3  | 141.4                  | 18.71                       | 112.9       | 1.65      | 9.96      |
| U-CF12-6  | 158.1                  | 9.90                        | 141.7       | 1.24      | 17.73     |

Note: In I-CF10-1, I is the reinforcement shape (bottom reinforcement), CF10 is the diameter of CFRP bar (10 mm), and 1 is the number of CFRP bar.

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**Figure 11. Ductility performance evaluation.**

**Figure 12. Stiffness evaluation.**
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**Notes on contributor**

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**References**

American Concrete Institute ACI 440. 3R-04, Guide Test Methods for Fiber-Reinforced Polymers.

Construction Standard Specification. 2006. *Minimum Coating Thickness*. Standards for Structural Design of Building (in Korea).

Korea Forest Service, (2013) Statistical Yearbook of Forestry.

Korean Industrial Standards. 2001. *Determination of Moisture Content of Wood*. Korean Standards Association, KS F 2199 (in Korea).

Korean Industrial Standards. 2004. *Method of Compression Test for Wood*. Korean Standards Association, KS F 2206 (in Korea).

Korean Industrial Standards. 2012. *Testing Methods for Compressive Properties of Carbon Fiber Reinforced Plastics*. Korea Standards Association, KS M IOS 14126 (in Korea).

Park, J.-S., (2010) "Flexural Bond Properties according to the Embedment Length by FFR Rod Type", Master’s Thesis, Hanyang University.

Park, J.-C., (2009) “Strength Properties of Hybrid Fiber-Reinforced-Plastic Reinforced Glulam Beams”, Master’s Thesis, Kangwon National University.

Park, J.-C., and S.-I. Hong. 2008. “Strength Properties of GFRP Reinforced Glulam Beams Bonded with Polyvinyl Acetate-Based Emulsion Adhesive." *Journal of the Korean Wood Science and Technology* 36 (4): 19–25.

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Figure 13. Relation between the load reduction ratio and the strain of CFRP bar.