Experimental investigations of timber beams strengthened by CFRP and Rebars under bending

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Abstract. Wooden structure houses deteriorate over time due to environmental aging, fatigue, and other reasons. In order to solve this problem, composite timber beams strengthened by extra steel bars (rebar) and carbon fiber-reinforced plastic (CFRP) are studied experimentally in this paper. Specimens with various strengthening, ie., rebars only, CFRP only, and a combination of the two, were considered under four-point flexural tests. Failure, displacement and strain response and ductility capacity were evaluated for the present tested models. Dramatic enhancement of the capacity in addition to improved deflection and ductility were gained for the strengthened beams relative to the plain specimens, indicating the effectiveness of the reinforcement on the flexural strength of such composite beams.

1. Introduction
The Chinese have a long history of building wood houses, many excellent ancient architectures are wood structure. However, lots of wooden structure houses deteriorate over time due to environmental aging, fatigue, and other reasons. Traditional wood structure repair and reinforcement methods often require extensive repair site, easy to destroy the original appearance of the structure or bring other secondary effects.

Because of high geometrical plasticity, easy to cut and shape, high strength, light weight and easy construction, CFRP has become the common reinforcement material in the field of building engineering including wood structure [1-6]. In this paper, a new reinforcement method for timber beam by rebar and CFRP is introduced. The method is that the rebar is embedded and bonded in the timber beam by grooving at the bottom of the beam, and the groove is covered and by the CFRP cloth bonding. In other words, the timber beam was reinforced by two different materials, CFRP and steel bar. The synergy of timber, rebar and CFRP will determine reinforcement effects.

2. Experimental program

2.1. Test specimens and material properties
The timber used for the test beam is loblolly pine, an important tree species for afforestation and industrial timber species growing in southern China [7]. The main physical and mechanical properties of wood is shown in Table 1.

Carbon fiber cloth were made by Japanese carbon fiber silk, mainly for structural components of the tensile, shear and seismic strengthening. They had a net thickness of 0.111mm and the width of 200mm. Its mechanical properties were tested, and the results is shown in Table 1.
The rebar of Grade HRB335 is used in this test, and it is widespread used in building construction as reinforcement, with good strength and plasticity. Because the tensile strength of steel is much higher than the timber, wood failure will not be pulled off the steel bar, or even yield, so the selection of a smaller diameter Φ10 screw steel, and the smaller diameter with a lower cost of steel. The steel bars used in the program were tested in the laboratory, giving average yield strengths of 380 MPa. The reinforcement is arranged in the tensile zone to be primarily subjected to tensile stresses. In this experiment, the steel bar and wood were bonded by anchorage glue. It is an important aspect of this study to observe the adhesive performance, and the researcher hope that the timber beams can work together with the rebar by the anchorage glue. This experiment uses XK-360 anchorage glue. XK-360 anchorage glue has the advantages of acid and alkali resistance, low temperature resistance, aging resistance, good heat resistance, no creep at room temperature, water logging resistance, long-term load stability in wet environment, resistance to welding, good flame resistance, seismic performance good and so on.

### Table 1. properties of timber and strengthen materials

| species     | Compressive strength /Mpa | Flexural strength /Mpa | Flexural modulus of elasticity /Mpa | Thickness /(mm) | tensile strength /MPa | Elastic Modulus /GPa | Bendin g strength /MPa | Elongation |
|-------------|---------------------------|------------------------|-------------------------------------|-----------------|-----------------------|-----------------------|------------------------|------------|
| loblolly pine | 28.05                      | 64.16                  | 6.24                                |                 |                       |                       |                        |            |
| CFRP glue   | 0.111                      | 3426                   | 265                                 | - 50            | -                     | 85.5                  | 2.5%                   |            |
| rebar       |                           |                        |                                     |                 |                       |                       |                        |            |

2.2. Specimen design

Twenty-one timber beams were constructed for four-point bending. Table 2 summarizes the specimens program. The cross-sectional dimension of all specimens was 80 mm(width)×150 mm(depth)×2000 mm(length), as shown in fig.1(a). These beams were categorized into eight different groups. The variations from one group to another and beam designations are given in Table 1 and Figs.1. Seven beams in case 1 acted as control specimen. Two beams in case 2-3 were strengthened with 10-mm-diameter deformed bars. Two beams in case 4-5 were strengthened with steel bars and carbon wrap. Two beams in case 6-8 were wrapped with different longitudinal or transverse configurations or varying depths of wrapping, using carbon fabrics.

![Figure 1. Strengthening scheme used in cases 2-8](image-url)
Table 2. Beam designations

| Group | Case | No. of beams tested | Designation                                      |
|-------|------|---------------------|--------------------------------------------------|
| 1     | 1    | 7                   | L-1, L-2...L-7 (beams not strengthened)          |
| 2     | 2    | 2                   | 1S-1, 1S-2 (The beam with one rebar)              |
|       | 3    | 2                   | 2S-1, 2S-2 (The beam with two rebars)             |
| 4     | 2    | 2                   | 1S-1C-1, 1S-1C-2 (The beam with one rebar and carbon wrap) |
| 3     | 2    | 2                   | 2S-1C-1, 2S-1C-2 (The beam with two rebars and carbon wrap) |
| 6     | 2    | 2                   | (The beam with carbon wrap, width 80mm and length 1000mm) |
| 4     | 7    | 2                   | (The beam with carbon wrap, Two layers CFRP with width 80mm and length 1000mm, 1200mm) |
| 8     | 2    | 2                   | (The beam with carbon wrap, Three layers CFRP with width 80mm and length 1000mm, 1200mm, 1400mm) |

2.3. Instrumentation, test set-up, and test procedure

The whole experiment was carried through on the electro-hydraulic servo controlled loading system in Nanjing Forestry University, as shown in Fig. 2.

![Figure 2. Experimental set up and measurement](image)

WYJ - Displacement meter; YBP - Strain gauges

3. Test results and discussions

3.1. Failure modes and analysis of observed mechanisms

The typical failure modes were identified as shown in Fig. 3.

The failure in the plain timber specimens were quite abrupt with a sudden tensile rupture in the most time. The failure was initiated in different areas in various plain specimens, which is believed to be
generally the result of the existence of knots. Most of the specimens split at the bottom or the scar near the middle of beam, however, a few of beams exhibit a large plastic deformation without fracture phenomenon, as shown in fig. 3a, 3b, 3c.

![Typical failure modes of tested beams](image)

**Figure 3.** Typical failure modes of tested beams: (a)L-7; (b)L-3; (c)L-2; (d)1S-2; (e)1S-2(midspan); (f)2S-2; (g)2S-2; (h)1S-1C-2; (i)1S-1C-2; (j)2S-1C-1; (k)2S-1C-2; (l)1C-2; (m)2C-1; (n)3C-2

In case 2, the failure mode of the strengthening beam is brittle bending failure. Several cracks are found at the bottom of the beam with the load increasing, and one was developed into a main fracture. The wooden beam could restore original state again soon after load released, however, the bending deformation of rebar can not be restored into a straight line. A little steel slip observed in the beam
groove at the end of the bar, and the central steel was protruding, as shown in fig.3d, fig.3e.

The reinforcement beam (In case 3) were damaged at shear bending region. Large deformation occurred during the later period of the test. In the end, beams were broken and Compression deformation is very obvious in the top region. The rebar, however, there is no obvious deformation, and the side slip at both end is smaller, as shown in fig3f, fig 3g.

In case 4, the failure phenomena of two beams was differentiated. One of the specimens was cracked from the scar in the middle of the beam, and the carbon cloth broke suddenly and debonding from the bottom. The crack of the other specimen beam is generated in the tension zone of the timber beam, and the crack continues to develop with load increasing. When the beam damaged, the steel bar at the bottom of the slip occurred, and the carbon cloth along the length of the groove cut into three stripe, as shown in Fig. 3h and Fig. 3i.

In case 5, the failure mode of the strengthening beam is the compression deformation of the wood in the compression area. The whole beam has a large bending deformation and no obvious cracks in the tension end. The carbon fiber cloth is basically intact, as shown in Fig.3j and Fig. 3k.

In case 6-8, the failure mode of the beams wrapped with carbon fabric were characterized by the stripping of CFRP and the fracture at the scarring of beams, as shown in Fig.3l and Fig.3m.

3.2. Ultimat load and elastic modulus
Table 3 and 4 presents the values of ultimate load and elastic modulus obtained in the test. As compared with plain beams, most of all the strengthened specimens were significantly enhanced in flexural strength. The ultimat load of beams in bars-strengthened increased by 28%. The combination-strengthened (in case 4,5) possessed flexural strength 26%-32% larger than plain beams(in case 1).

| Species code | Ultimate load /kN | elastic modulus /Mpa | Average ultimate load | Average elastic modulus |
|--------------|-------------------|----------------------|-----------------------|------------------------|
| L-1          | 25.35             | 6109                 |                       |                        |
| L-2          | 32.55             | 7275                 |                       |                        |
| L-3          | 24.86             | 6545                 |                       |                        |
| L4           | 30.66             | 5531                 | 27.84                 | 6107                   |
| L-5          | 22.87             | 6035                 |                       |                        |
| L-6          | 34.71             | 6426                 |                       |                        |
| L-7          | 23.90             | 4826                 |                       |                        |
| Standard deviation | 4.70           | 778                  |                       |                        |
| Coefficient of variation | 0.17       | 0.13                 |                       |                        |

3.3. Displacement vs load relationship
Fig. 4 shows the load versus deflection curves of all specimens. It can be seen from Fig.4a that the strength and ductility of 7 contrast beams are quite different, which indicates that the mechanical properties of the material itself are more discrete. Compared with the plain beams, the strength and rigidity of the strengthened beams are generally higher, as shown in Fig. 4b and Fig. 4c, they exhibit large plastic deformation at the later stage of loading, and the beams in the combination reinforcement program show a stable high strength and a higher stiffness and large plastic deformation of the mechanical characteristics, and the ductility phase strength remained unchanged, or even increased slightly.
Table 4. Ultimate load and elastic modulus of reinforced timber beam

| Species code | Ultimate load /kN | elastic modulus /kN |
|--------------|-------------------|---------------------|
|              | Test Data | Average | Enhancing ratio (%) | Test Data | Average | Enhancing ratio (%) |
| 1S-1         | 30.40     | 27.67   | -0.6               | 6162      | 5478    | -10                |
| 1S-2         | 24.94     |         |                    | 4794      |         |                    |
| 2S-1         | 40.58     | 35.79   | 28                 | 9945      | 9315    | 53                 |
| 2S-2         | 31.01     |         |                    | 8686      |         |                    |
| 1C-1         | 32.68     | 34.98   | 25.6               | 5974      | 6986    | 14                 |
| 1C-2         | 37.28     | 34.98   | 25.6               | 7997      | 9315    | 53                 |
| 2C-1         | 35.85     |         |                    | 6186      |         |                    |
| 2C-2         | 39.27     | 37.56   | 34.9               | 9146      | 7675    | 26                 |
| 3C-1         | 28.43     | 30.08   | 8.04               | 4839      |         |                    |
| 3C-2         | 31.73     |         |                    | 4812      | 4825    | 21                 |
| 1S-1C-1      | 37.50     | 34.97   | 26                 | 6627      | 6943    | 14                 |
| 1S-1C-2      | 32.44     |         |                    | 7259      |         |                    |
| 2S-1C-1      | 35.44     | 36.91   | 32                 | 7870      | 9679    | 58                 |
| 2S-1C-2      | 38.39     |         |                    | 11488     |         |                    |

Figure 4. Load versus deflection curve in four-point bending test
3.4. Analysis of strain response in beam span

The five typical strain values of the strain measuring points at the midspan cross section of various types of wood beams are shown in Fig. 5 which illustrates the strain distribution along the depth of the cross section. Figs. 5 show the following conclusions.

During the linear loading process, the longitudinal strain at the midspan cross section showed a linear distribution along the cross-sectional depth, indicating that the strain at the midspan cross section approximately agreed with the plane section assumption. As the load increased, the strain curve was not a straight line. The reason was that the glued connection, as one of the structural connections, was damaged and/or the material was damage, accompanied by structural rigidity changes.

The beam with rebar has an initial neutral axis of 15 mm below the center of the beam section, which indicates that the steel bar starts to exert its effect to bear the large load from the initial stage of the loading, which plays the role of reinforcement, as shown in fig. 5(b).

Both wrapped beams and unwrapped beams has its initial central axis in the center of the beam section, which indicated that the bottom of the carbon fiber cloth can not significantly improve the strength of the bottom of the beam. The tensile strain is relatively small at the later stage of loading, and the strain of the strengthened carbon beam is smaller than that of the carbon cloth, which indicates that the carbon cloth is not as good as the reinforcing bar. The initial neutral axis of the beam strengthened by two-layer steel bar and carbon fiber sheet is about 18mm below the center of the section and slightly decreased at the later stage, which indicates that the two type of strengthen material play important role during loading. The strain response at all levels of load is small, indicating that the overall stiffness was significantly improved.

![Figure 5. Typical strain changes of six beams at the midspan cross section](image)

4. Conclusion

Wooden structure houses are widely used in our country. Aiming at the characteristics of large discreteness and low seismic performance of timber beams, a kind of new reinforcement technology with embedded rebars and CFRP is put forward. By using 21 test beams, the flexural capacity test is carried out, the experimental results show that.

(1) The timber beams with carbon or rebars are significantly better than the contrast beam. The rebar and carbon fiber sheets can improve the flexural rigidity and flexural capacity of the timber beams. The reinforced beams have certain signs before the failure. With the bending of the steel bars, the whole member can still provide a certain bending capacity. The two rebars and a layer of carbon
cloth can significantly improve the rigidity and strength of wood, and ductility better.

(2) In the linear loading process, the strain distribution all of beams were in accordance with the assumption of plane section. Rebars can improve the stiffness of the bottom of the beam, causing the initial neutral axis decreases, and improve rigidity greatly. However, the carbon sheet can do less.

(3) The results showed the interracial bonding was a decisive cause to influence the mechanical properties. For the gule is not dedicated glue for rebar and CFRP, some CFRP cloths was separated from timber beam, in the later stage of test, so as steel bar. So the effect of timber beam reinforcement should be further enhanced through improving the bonding performance.

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