Fire Performance of Insulated RC Beams Shear-Strengthened with CFRP Sheets

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Abstract. In the literature, there is a lack of research on the fire performance of RC beams shear-strengthened with FRP laminates. This paper for the first time presents the fire endurance tests of insulated FRP shear-strengthened RC beams. A total of seven rectangular RC beams were constructed: three were tested at ambient temperature to determine their load-bearing capacity while the remaining four were first exposed to ISO 834 standard fire for 2.5 hours. Fire endurance tests indicated that the RC beam without insulation was characterized by shear failure due to the propagation of diagonal cracks. In contrast, the insulated FRP shear-strengthened RC beams could achieve a satisfactory fire resistance of 2.5 hours with small deflection responses under fire exposure. Because the additional fire protection layer provided adequate protection, the temperature responses recorded at the FRP-concrete interface were less than 250 °C, while the temperatures of the steel stirrups were around 120 °C during the entire fire exposure.

1. Introduction

Externally bonded (EB) fiber-reinforced polymer (FRP) composites are increasingly used for repair of reinforced concrete (RC) structures, mainly owing to the superior material properties of FRP composites including high strength, light weight, tailorable performance characteristics, and minimal alterations to the size of the strengthened member. However, a typical ambient-cure epoxy adhesive used for the EB FRP strengthening system has a low glass transition temperature of approximately 45 °C–80 °C [1]. When the epoxy adhesive is subjected to an elevated temperature approaching to this characteristic temperature, it will change from a glassy to a viscous state, and its strength and stiffness will be significantly reduced [2]. The EB FRP laminates may also burn in the fire unless additional insulation is provided to separate them from the fire. Therefore, the fire performance of FRP-strengthened RC members is an important issue, which should be appropriately considered to meet the requirements of fire-safety design for indoor applications (e.g., buildings) [3].

Shear strengthening of an RC beam with EB FRP laminates is challenging and should be designed appropriately. This is because the brittle characteristic of concrete under shear loading may cause catastrophic failure, especially when the EB FRP laminates are used to enhance the load-bearing capacity of an RC beam with insufficient shear resistance (i.e., shear-deficient RC beam). However,
almost all fire endurance tests and numerical studies in the literature were conducted on flexurally FRP-strengthened RC beams [4-12]. There is a lack of research on the fire performance of RC beams shear-strengthened with FRP laminates. This paper presents the first-ever fire endurance tests on insulated RC beams strengthened in shear with carbon FRP (CFRP) sheets.

2. Preparation of Specimens
A total of seven rectangular RC beams were constructed: three were tested at ambient temperature to find out the load capacity, while the remaining four were designed to be exposed to ISO 834 standard fire for 2.5 hours. Of the four beams, B2-0 was exposed to fire without insulation and served as a reference, while the others were all protected by an additional insulation layer. The design parameters varied in the experimental study included the layer of CFRP U-wraps used for the shear strengthening system and the shear span-to-depth ratio of the beams (see table 1 for more details). Figure 1 illustrates the details of the geometric dimensions and the steel reinforcements of the beam specimens. All the beam had the same size with a cross-sectional area of 200 mm (width) × 400 mm (depth) and a total length of 2,885 mm. Six 20-mm steel bars were served as the tensile reinforcement, while two 12-mm steel bars were adopted as the compressive reinforcement. The shear stirrups consisted of ϕ 6 steel bars with a spacing of 200 mm. It is worth mentioning that the flexural strength of the beams was over-designed, while the shear strength resistance of the beams was deficient, so that a typical shear failure would be obtained under the two-point loading. The flexural strength of the beams was estimated as approximately twice of that corresponding to the shear resistance according to the design provisions specified in the Chinese Design Code (GB 50010-2010).

![Figure 1. Details of geometry and steel rebars (unit: mm).](image)

All the beams were cast with ready-mixed concrete, which was delivered by a local material company and designed to obtain a target compressive strength of 25 MPa. After curing for 28 days under laboratory conditions, the measured average values of cubic compressive strength and elastic modulus of the concrete were 28.6 MPa and 24.9 GPa, respectively. The EB shear strengthening system consisted of one or two layers of 0.167-mm thick CFRP U-wraps, which were 80 mm wide with a clear spacing of 100 mm between two adjacent U-wraps. Five flat coupons were prepared and tested to measure the mechanical properties of the EB CFRP U-wraps as per ASTM D3039 [13]. The tensile strength, modulus of elasticity and tensile rupture strain of the CFRP sheets were measured as 3721 MPa, 2.43×10^5 MPa, and 1.74%, respectively. Such tensile properties were calculated by the net area of the CFRP sheets (i.e., the fibers) while excluding that of the adhesive, as suggested by previous studies [14-15]. The average tensile strength, elastic modulus and elongation of the epoxy adhesive used in the experimental study were measured as 41.5 MPa, 3.30 GPa and 1.60%, according to ASTM D638 test standard.

For the insulated FRP shear-strengthened RC beams, the fire protections adopted were all the same, which was applied to the bottom and two sides of each beam with a 20-mm insulation layer (see table 1). The insulation material (with a commercial designation of SJ-2) supplied by a local material company is a lightweight, fire-resistant cementitious plaster that can be manually applied (troweled) to the surface of the specimen. According to the brochure provided by the manufacturer, it has the
thermal properties at ambient temperature as follows: dry density is 500 kg/m$^3$, specific heat capacity is 1000 J/(kg·K) and thermal conductivity is 0.12 W/(m·K).

### Table 1. Details of the specimens.

| Beam | Purpose        | Shear strengthening (U-wraps) | Shear span-to-depth ratio | Fire insulation       |
|------|----------------|-------------------------------|---------------------------|-----------------------|
| B1-0 | Room temperature tests | —                            | 2.4                        | —                     |
| B1-1 | One- ply       | 2.4                           | —                          | 20 mm SJ-2 layer      |
| B1-2 | Two- ply       | 2.4                           | —                          |                       |
| B2-0 | Fire endurance tests | —                            | 2.4                        | —                     |
| B2-1 | One- ply       | 2.4                           | —                          |                       |
| B2-2 | One- ply       | 1.6                           | —                          |                       |
| B2-3 | Two- ply       | 2.4                           | —                          |                       |

3. Results and Discussion

3.1. Results from Room Temperature Tests

Figure 2 shows the setup for the room temperature tests. During the loading process of B1-0, vertical cracks initially appeared at the bottom of the beam within the critical shear span. As the load increased, new vertical cracks continued to occur, and the cracks propagated obliquely to the loading point. When the ultimate load was reached, the crack width increased rapidly, and eventually, the concrete below the loading point was crushed. After the loading test, the maximum measured width of the major shear crack was larger than 1.5 mm. The failure of B1-0 was characterized as a typical shear failure due to the propagation and widening of the diagonal shear cracks. For the two strengthened beams (i.e., B1-1 and B1-2), the occurrence and development of concrete cracks are similar to those of the unstrengthened RC beam (i.e., B1-0) in the early loading stage. With increasing load, the propagation of diagonal cracks in the webs of the two strengthened beams is relatively slower than B1-0. This was due to the contribution of the CFRP U-wraps, which led to the restriction of shear cracks. That is, the CFRP U-wraps sustained part of the shear force. Finally, the two strengthened beams failed because of the debonding of the CFRP U-wraps.

Figure 3 compares the load versus midspan deflection curves of the three beams tested at ambient temperature. When the load reached the ultimate load, the measured deflections of B1-0, B1-1, and B1-2 were 6.07 mm, 5.80 mm, and 7.06 mm, respectively. It can be seen from the load-displacement curves that before the concrete cracking, the elastic stiffnesses of the beams are almost the same,
mainly due to the negligible stiffness contribution of the CFRP U-wraps. However, the ultimate loads of B1-1 and B1-2 are much higher than that of B1-0. Compared with B1-0, the gains in ultimate loads are 24% and 30% for B1-1 and B1-2, respectively. In addition, the ultimate load of B1-2 strengthened with two layers of CFRP U-wraps is only slightly higher than that of B1-1, possibly due to the debonding failure of the shear strengthening system which further leads to the insufficient utilization of the high strength of the CFRP composite material.

3.2. Results from Fire Endurance Tests

Fire endurance tests were conducted on four beams, of which an RC beam without fire protection was tested as a reference, while the remaining FRP-strengthened RC beams were all protected with a 20-mm SJ-2 layer, as mentioned previously. During the fire tests, several thermocouples were installed over the beam cross-section of the midspan to record the temperature responses of concrete (TC2 & TC3), steel stirrups (TC6 & TC7), and the CFRP-to-concrete interface (TC1, TC4 & TC5). Taking the beam B2-3 as an example, figure 4 depicts the temperatures measured at various locations during the fire test. The temperatures recorded by the thermocouples in the beam cross-section are less than 320 °C, which indicates that the fire insulation layer has an excellent protection effect on the strengthened beam under fire exposure. The recorded temperatures of steel stirrups and concrete are below 150 °C, which means that most of the mechanical properties of steel and concrete are retained. However, the interface temperature between the CFRP U-wraps and the concrete at the middle height exceeds 200 °C during fire exposure, indicating that most of the bond strength of the interface is lost during the fire. The above test results have confirmed the three-level design approach proposed by Gao et al. [16]. In their study, the fire insulation of Level-II design with a relatively thin insulation layer is considered to protect the RC beam (i.e., concrete and steel stirrups) rather than the EB FRP strengthening system. Therefore, an excellent fire resistance rating is expected to be achieved based on the assumption that most of the mechanical properties of concrete and steel reinforcement are preserved during a fire, even though the contribution of the FRP strengthening system is assumed to be totally lost. Therefore, the insulated CFRP-strengthened beams do not fail for 150 min under fire and consider to be well protected in the present study.

![Figure 4](image-url)

**Figure 4.** Measured temperatures at various locations.

Figure 5 shows the photographs of two typical beams after the fire tests. The RC beam without fire insulation is characterized by shear failure due to the propagation of diagonal cracks, while the insulated CFRP-strengthened beams are well protected with small deflection responses during fire exposure. After the fire tests, only some cracks were observed on the surfaces of the insulation layer. It should be mentioned that the brittle shear failure model on structural components should be avoided
in the event of a fire, because it will cause catastrophic damage without sufficient warning and may further harm the lives of firefighters and residents.

Figure 6 shows the midspan deflection responses of B2-0 and B2-1 during fire exposure. The unprotected beam B2-0 achieved a fire endurance less than 90 min because of the shear failure under fire exposure, while the protected beam B2-1 obtained a satisfactory fire endurance of 2.5 h. The midspan deflection responses of B2-2 and B2-3 were similar to that of B2-1 and thus were not reported herein. From the comparison of the midspan deflection responses, it is clearly seen that the measured deflections of the insulated CFRP shear-strengthened RC beam are about 10 mm after 2.5 h fire exposure, mainly due to the well protection of the supplied insulation layer. However, the unprotected beam B2-0 experienced an abrupt deflection response, and eventually failed due to the formation of shear cracks during fire exposure.

![Figure 5. Photographs of the beams after fire tests.](image)

![Figure 6. Midspan deflection versus time curves.](image)

4. Conclusions
This paper for the first time presents the fire endurance tests on insulated RC beams shear-strengthened with CFRP sheets. The following conclusions can be generated from the test results:

(1) The load-bearing capacities of the FRP shear-strengthened RC beams were significantly enhanced, while the stiffness enhancements due to the presence of FRP U-wraps were negligible, when compared with the measured results of the reference RC beam.

(2) The fire endurance tests indicated that the RC beam without insulation was characterized by shear failure due to the appearance of diagonal cracks while the FRP shear-strengthened RC beams if properly insulated had achieved a satisfactory fire resistance of 2.5 h with small deflection responses under fire exposure.

(3) The applied fire insulation layer could provide excellent protection for the specimens, and therefore, the temperature responses of steel rebars and concrete were lower than 150 °C during 2.5 h fire exposure. The insulated RC beams shear-strengthened with CFRP sheets had excellent fire resistance due to the retention of the residual mechanical properties of concrete and steel rebars.
However, the bond strength between the CFRP U-wraps and the substrate concrete were lost under fire exposure.

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