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Experimental Study on the Fire Resistance of RC Beams Strengthened with Near-Surface-Mounted High-$T_g$ BFRP bars

Hong Zhu\textsuperscript{a}; Gang Wu\textsuperscript{a}; Lei Zhang\textsuperscript{a}; Jianfeng Zhang\textsuperscript{a}; David Hui\textsuperscript{b}

Abstract: A lack of knowledge regarding the fire resistance of fiber reinforced polymer (FRP) reinforced/strengthened concrete structures has impeded the wide acceptance and use of these materials. This paper presents the results of both mechanical property tests performed on basalt FRP (BFRP) bars during and after exposure to high temperatures and the fire resistance of reinforced concrete (RC) beams strengthened with near-surface-mounted (NSM) high-$T_g$ BFRP bars. Experiments were conducted on 108 effective tensile test specimens and 7 four-point bending beam specimens. The results indicate that a resin matrix with a higher $T_g$ value and good compatibility after pultrusion curing process with fiber were very useful for improving the heat resistance of FRP bars, meaning that NSM FRP strengthened RC beams could exhibit improved fire resistance. The FRP bars maintained sufficient anchorage if only two ends of the NSM FRP bar were protected against fire by stretching them into supporting components or wrapping them with U-shaped fire protection boards. The NSM high-$T_g$ FRP strengthened RC beams could potentially exhibit the same level of fire resistance as the RC beams. These preliminary conclusions improve the prospects of using FRP materials in engineering applications.

Key words: A. Polymer-matrix composites (PMCs); A. Resins; B. High-temperature properties; B. Mechanical properties; Fire resistance

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1. **Introduction**

Fiber reinforced polymers (FRPs) have been demonstrated to be effective and have been commonly used to strengthen structures since the Hanshin earthquake. In addition to the commonly used FRP sheets and FRP plates, round FRP bars, rectangular FRP strips and strand FRP tendons are also readily available products on the market. However, there is some uncertainty or doubt regarding the use of FRPs in elevated and fire temperatures [1-2]. Because of the softening and decomposition of resin in FRPs and the degradation of the bond between an FRP and a structure at high temperatures, their use is primarily restricted to bridge structures in which fire resistance is not a primary design consideration [3]. Guidelines for designing FRP strengthened structures [4-5] specify that the strengthening effect of a material at elevated temperatures or under fire conditions should be ignored unless a fire protection system is used to maintain the temperature of the composite strengthening component below the lower glass transition temperature ($T_g$) of the resin and adhesive. Many studies of fire protection systems consider the insulation type, insulation thickness, flat insulation layer or U-shaped insulation layer to be primary parameters and conclude that satisfactory fire performance can be achieved in FRP strengthened RC members, provided they are appropriately designed and adequately insulated [6]. One study demonstrated the feasibility of providing 2 h of fire resistance in FRP strengthened beams if they are well insulated [7].

Numerous studies [8-13] have reported that strengthening reinforced concrete (RC) beams with near-surface-mounted (NSM) FRP bars or strips is an effective strengthening method at ambient temperature. Additionally, laboratory experiments [14] and real fire tests [15] have demonstrated that NSM strengthening systems exhibit better performance than external bonding (EB) strengthening systems at elevated temperatures or during fires, and their performance can be considerably better than what is commonly believed [14]. This increased performance is reasonable because the NSM method can enhance the bond between the FRP and the concrete and can provide better anchoring capacity in the FRP bars or strips. NSM FRPs also provide better fire protection because the FRP is embedded in the concrete cover.
Nevertheless, it is commonly agreed that NSM FRP strengthened RC beams should be protected by a fire protection system if the NSM technique is used in buildings. A thicker insulation layer results in an increased level of fire resistance. However, the addition of a fire protection system increases engineering costs and the complexity of the construction. Therefore, engineers should understand the degree of difference in fire resistance between NSM FRP strengthened RC beams and common RC beams and how to reduce this difference with or without the use of a fire protection system. The goal of this paper is to compensate for this lack of knowledge in the literature.

This study involved both the experimental investigation of the mechanical properties of BFRP bars during and after exposure to high temperatures and an experimental study on the fire resistance of RC beams strengthened with NSM BFRP bars. According to the results of the mechanical property tests conducted on 108 BFRP bar specimens, the best of the three BFRP bar types was selected as the strengthening bar that was used in the beam specimens. The level of fire resistance was compared between the RC beams and NSM high-T<sub>g</sub> FRP strengthened RC beams, both with and without entire protection.

2. Mechanical property testing of BFRP bars during and after exposure to high temperatures

The temperature resistance of FRP bars depends not only on the temperature resistance of the fiber and resin but also on the cohesion between the two materials. Although many experiments have been conducted with structural specimens that were reinforced or strengthened with FRP bars and some research has been performed on the long-term mechanical properties at elevated temperature less than 100°C [16-17], only a few experiments have been conducted on the mechanical properties of these bars at high temperatures [2, 18-19]. Based on existing literature data, Saafi [20] proposed a series of simplified formulas to calculate the reduction factor of FRP bars at high temperatures. Wang [2] tested GFRP bars with diameters of 9.5 mm and 12.7 mm and CFRP bars with a diameter of 9.5-mm. Because the room-temperature cured thermoset polymer matrices used in the FRP strengthening of concrete structures commonly exhibit T<sub>g</sub> values in the range of 60–85°C [3], the potential for changes in the T<sub>g</sub> of the resin matrix has not been
considered. Since the low $T_g$ of resin is the greatest shortcoming of the bars, an improved resin with a higher $T_g$ was tested in this study. Basalt fibers are significantly cheaper than carbon fibers and exhibit excellent temperature resistance because they are produced by a drawing process from molten rock at 1400-1500°C. Therefore, three different BFRP bars composed of basalt fibers and one of three resin types were manufactured and provided for this study.

The mechanical properties of the FRP bars during and after exposure to high temperatures were required for a comprehensive evaluation of their temperature resistance. However, data provided in the literature only report the mechanical properties of the bars during exposure to high temperatures. Therefore, most of the specimens were prepared for testing after exposure to high temperatures so that the specimens could be used in a comparison.

2.1 Specimen details and material characteristics

Generally vinyl resin and epoxy resin are most commonly used resins in FRP composites. The bond between the fiber and the epoxy resin is better under ambient temperature conditions, whereas the vinyl resin has better impregnation ability during the pultrusion process of FRP bars. To investigate the effect of $T_g$ on the mechanical properties of BFRP bars during and after exposure to high temperatures, the three types of resin used in this study were termed normal vinyl resin (V), heat-resistant vinyl resin (HV) and heat-resistant epoxy resin (HE), and their $T_g$ values were 127°C, 174°C and 210°C, respectively. The heat-resistant resins were not the special resins used in the aerospace field, but instead were modified resins with a cost increase of less than 40%. This cost increase was deemed acceptable by the market because it increases the total cost of the BFRP bars by no more than 5%. The compositions of the three types of ribbed BFRP bars and the parameters for the fibers, resin matrices and FRP bar are listed in Table 1. The manufacturer of resin V and resin HV was Shanghai Fuchen Chemicals Co, Ltd China, and the manufacturer of resin HE was Changsu Jiahua Chemicals Co, Ltd, China.

The BFRP bars used in the tension test (which was performed after exposure to high temperatures) were first placed in a high-temperature oven after both ends of the bars had been protected by rock wool, as shown in Fig. 1. This protection
effectively avoided high-temperature damage to the anchorage and ensured that the rupture was restricted to the test region. The oven temperature was increased linearly from ambient temperature to a test temperature of 100, 200, 250, 300, 350 or 400°C over a period of 30 min and then maintained at the test temperature for another 90 min. Next, the BFRP bars were taken out of the oven, and the rock wool was then removed. The bars were anchored in accordance with the test method recommended by ACI 440.3R-04, as shown in Fig. 2. When the bonding adhesive in the anchors reached its final strength, the bars were then placed in a tensile test machine and tensioned to rupture. The BFRP bars used in the tension test (which was performed during exposure to high temperatures) were directly anchored, as shown in Fig. 2, and then placed in a creep tensile test machine with a high-temperature chamber in which the test portion of each bar could be heated from ambient temperature to a test temperature of 100°C or 200°C. These bars were tensioned until rupture after a 30-min heating process, which is the same heating time that was used in the tests by Wang [2]. At least 5 effective specimens were tested during each high temperature exposure, and 3 effective specimens were tested after each high temperature exposure. Totally 108 specimens were tested.

2.2 Tensile test results

Table 2 shows the tensile strength and modulus of each specimen and their calculated averages and deviations. The rupture of each specimen occurred within the test region. Most of the deviations were below 5.0%, and the largest tensile strength and modulus deviations were 5.6% and 7.6%, respectively. The scatter of the tensile strength and modulus after exposure to high temperatures was smaller than the scatter during exposure to high temperatures reported in literature [2]. In Fig. 3, the normalized average strength and modulus of all of the BFRP bars are compared to experimental curves reported by Wang [2] and prediction curves developed by Saffi [20].

The three BFRP bar curves (during exposure), which were stopped at a temperature of 200°C due to heating capacity limitations of the chamber, exhibited the same trend as tests that were conducted by Wang, as shown in Fig. 3. A comparison between the curves of the BFRP bars during and after exposure indicated that the strength and modulus
degradation of the BFRP bars that were tensioned after exposure to high temperatures was slower than those tensioned
during exposure to high temperatures (up to approximately 300°C), after which they accelerated quickly. Due to the
softness and decomposition of the resin and the combustion of fiber, the FRP bars without protection lost most of their
strength and modulus when the environment temperature reached or was maintained at 400°C. The variability after
400°C in the tests by Wang was high; therefore, these data are not shown in Fig. 3. Additionally, data at temperatures
above 400°C were not a focus of this paper because the authors believe that the unprotected FRP bars suffered greater
damage than the mounted FRP bars, even if the latter were mounted only in bonding adhesive. This hypothesis was
proven in the subsequent beam experiments.

In these tests, the T_g values of the resins used in the BFRP bars were 127, 174 and 210°C. The T_g value of the common
resin in Wang’s test was less than 100°C. On one hand, no obvious changes occurred in any of the test curves shown in
Fig. 3 when the temperature was close to T_g. This phenomenon is different in FRP bars compared to FRP sheets. In
Cao’s test [21], the tensile strengths of the CFRP sheets were significantly reduced along with increasing temperatures
below T_g, and the tensile strength of the CFRP sheets remained at a stable ultimate value after the temperature exceeded
T_g. On the other hand, HV-BFRP bars have higher temperature resistance than V-BFRP bars because the T_g of the resin
used in the former is higher, but the temperature resistance of HE-BFRP bars is not better than HV-BFRP bars, even
though the former has a higher resin T_g. Tables 1 and 2 clearly indicate that although BFRP bars with epoxy resin matrix
exhibit the best mechanical properties at ambient temperature, they lose their superiority when heated. The surface
configurations of three types of BFRP bars after being exposed to temperatures of 350°C and 400°C are shown in Fig. 4.

From Fig. 4, the HE-BFRP bars had more configuration change than the V-BFRP bars and HV-BFRP bars. Pitting of the
resin, outer fiber rupture, uneven expansion and local bending occurred in the HE-BFRP bars and caused more
degradation in the mechanical properties. After the extension test, the HV-BFRP bars had the same fracture mode as in
ambient temperature, but the fracture of fibers in HE-BFRP bars mostly occurred on the same section, which was
different from the cases in ambient temperatures. In this study, uneven expansion of the HE should be the primary
adverse reason for the further decrease of the mechanical properties of the HE-BFRP bars. A decrease in tensile strength and modulus by approximately 20% during exposure to 200°C (Fig. 3) was most likely because of the uneven expansion that also occurred below the \( T_g \) temperature. Additional experimental data from different researchers with products from different manufacturers are needed. Therefore, regarding these two aspects, the \( T_g \) of resin is not the only factor that determines the temperature resistance of FRP bars. The compatibility after pultrusion curing process between the fiber and resin is also important at high temperatures. In this test, basalt fiber and heat-resistant vinyl resin (HV) were suitable, and thus the HV-BFRP bars exhibited better temperature resistance. For this reason, the HV-BFRP bar (BFRP bar impregnated in heat-resistant vinyl resin) was selected as the strengthening bar in the beam specimen experiment.

3. **Fire resistance of strengthened beams**

Most researchers have focused on investigating the installation of an extra fire protection system to protect the entire length of FRP strengthened structures [6-7]. However, extra fire protection systems increase engineering cost and the complexity of construction, and the doubts associated with using FRP as a structural material have not been completely eliminated. Improvements to the fire resistance of FRP strengthened RC structures without protection require further investigation. Advantageously, the NSM method is considered to be better than the EB method for fire resistance, and Bruke [14] recently reported that the heat resistance time significantly increases if approximately 50 mm of the NSM bond length is left unheated while the other region is heated to 200°C. This opinion has also been proposed by Blontrock [22]. Following this line of reasoning, two beams were designed to demonstrate that only a short unheated length on two ends would be required under fire conditions.

The three primary goals for conducting the beam experiments are described as follows. The first goal was to confirm whether the NSM strengthened RC beam with FRP bars impregnated in a resin with a higher \( T_g \) value could exhibit the same fire resistance as common RC beams without entire fire protection. The second goal was to demonstrate the
importance of maintaining unheated conditions at the bonding ends of the FRP bars, and the third goal was to test the minimum thickness of an entire fire protection board if 2 h of fire resistance is required.

3.1 Beam experimental program

Table 3 provides an overview of the beam specimens and experimental program. The abbreviation ‘NSM’ refers to an RC beam strengthened with near-surface-mounted BFRP bars. Each strengthened specimen had the same parameters as an RC beam specimen before strengthening. The seven beams were 4.1 m long and had identical cross-sectional geometries (200×450 mm), as shown in Fig. 5. The beams had internal reinforcement that consisted of three 18-mm-diameter steel bars with a steel reinforcement ratio $\rho_s$ of 0.92%. Two steel bars with diameters of 12 mm were placed on the top portion of the beams as hanger bars. The yield strengths $y_s$ of these two steel bars were 430 MPa and 425 MPa respectively. The yield strength $y_{sv}$ of the stirrup was 235 MPa and the strength $f'_c$ of the concrete was 37.2 MPa. The thickness of the concrete cover from the stirrup surface was 20 mm, and two slots measuring 20 mm wide and 20 mm deep were cut into the concrete cover, after which two HV-BFRP bars were inserted into the slots. The BFRP bars were mounted with bonding adhesive, and a 5-mm-thick hump was formed at the bonding adhesive surface, according to a recommendation by Wu [12] to obtain better bonding performance. The bonding adhesive was a common adhesive that is typically used in ambient temperature conditions. Details of the loading, supporting and displacement measuring points with information on the section before and after strengthening are shown in Fig. 5.

Two reference specimens, ‘RC’ and ‘NSM’, were tested to failure at room temperature to obtain the ambient ultimate load. Specimens ‘F-RC’, ‘F-NSM-long/0’, ‘F-NSM-short/0’, ‘F-NSM-entire/thick’ and ‘F-NSM-entire/thin’ were prepared for the fire test. ‘F’ denotes fire, and ‘long’, ‘short’ and ‘entire’ refers to different lengths of fire protection. ‘long/0’ indicates that only longer local protection was used on the two ends of the FRP bars (an 850-mm-long fire protection board with 30 mm of rock-wool board and 25 mm of calcium silicate board were wrapped around the specimen in a U-shape from the bottom without stretching the FRP to the supporting parts, as shown in Fig. 6a).
‘short/0’ indicates that only a short amount of local protection was used on the two ends of the FRP bars (225-mm-long sections on the two ends of the BFRP bars were stretched out of the fire furnace with no other protection, as shown in Fig. 6b). ‘entire/thick’ indicates that the specimens were protected in the furnace with 30 mm of rock-wool board and 25 mm of calcium silicate board in a U-shape from the bottom (Fig. 6c), and ‘entire/thin’ indicates that the specimens were protected in the furnace with only 25 mm of calcium silicate board (Fig. 6c). The thermal properties were defined in accordance with the material data sheet provided by the manufacturer. The average thermal conductivity of the calcium silicate board and rock-wool board was 0.2 W/m.K and 0.039 W/m.K, respectively.

3.2 Test setup

The ambient ultimate loads of the RC beam and NSM strengthened beam, 260 kN and 310 kN, respectively, were obtained from the experimental beams ‘RC’ and ‘NSM’. The specimens used for the fire test were placed on the top of the fire furnace such that the bottom surface and two side surfaces of the beams were exposed to fire temperatures and flames inside of the furnace, as shown in Fig. 7. The ratio of the sustaining load during fire to the ambient ultimate load was 0.6, which is more severe than the actual conditions encountered during the service phase of a building. The temperature of the furnace was controlled to follow the standard time-temperature curve in ISO 834, and the actual temperature was monitored by thermocouples that matched the standard curve (Fig. 7).

3.3 Experimental results

3.3.1 Failure mode

Each beam reached its bending failure mode when the displacement was 1/20 of the clear span. In the later heating stage, water vapor emitted from the concrete and the odor from the resin became more widespread. Local damage to the concrete and BFRP bars was observed after the beams were removed from the furnace and the protection boards were removed. Fig. 8 shows that concrete spalling occurred in beams both with and without protection. Many fine cracks and several major cracks occurred in the concrete, and these cracks resulted in the exposure of the BFRP bars and some of
the steel bars to the fire. The bonding adhesive completely converted into powder, and most of it fell off. The BFRP bars were more severely damaged in beams F-NSM-long/0 and F-NSM-short/0 where the powder fell off because there was no protection, which indicated that the bonding adhesive was still providing some protective function, even after it converted into powder. In beams F-NSM-entire/thick and F-NSM-entire/thin, the concrete, bonding adhesive and FRP bars were still tough and their morphology was better than the beams without fire protection board. Numerous studies have been conducted at the micro scale on improving the fire retardancy of composites [23-27], such that it will become much easier to obtain more cost-effective bonding adhesive with improved fire retardancy. Meanwhile, from the results of recent studies on fire retardant coatings [28-29], the application of fire retardant coatings onto the heat-exposed surfaces of bonding adhesive could also provide increased fire resistance to the FRP bars if more strict requirements are imposed.

3.3.2 Fire resistance time and deflection-time relationship

The fire resistance times of the five beams are listed in Table 3, and the displacements of all of the beams are compared in Fig. 9. Each beam had a final displacement of 190 mm. The two beams that were strengthened with NSM FRP bars and did not have fire protection in their middle portions achieved 101-min and 99-min fire resistance, which were very similar and were 14% higher than that of the RC beam. This result indicates that the NSM FRP strengthened RC beams could exhibit the same level of fire resistance as RC beams if the fire resistance of the FRP bar is better than the FRP bars that are commonly used. This preliminary conclusion favors the future use of FRP materials. If the bonding adhesive in the slot could provide better protection for FRP bars, then damage in the FRP bars could be reduced, and the beam could achieve better performance. Nevertheless, further experiments are required to study beams subjected to a sustaining load ratio greater than or less than 0.6 and a greater strengthening ratio. Studies on the residual performance of materials and structural specimen after being subjected to fire are also needed.
The data and curves for beams F-NSM-long/0 and F-NSM-short/0 shown in Table 3 and Fig. 9 indicate that their performances were nearly the same. The 225-mm-long ends of the FRP bars were sufficiently shielded from the fire to protect the NSM FRP bar anchorages. The other 850-mm-long, U-shaped fire protection board was redundant. These results indicate that the two ends of NSM FRP bars are stretched into a supporting concrete column or concrete wall in engineering applications, then the FRP bars can potentially maintain enough anchorage if a sustained fire occurs in a building.

If the U-shaped fire protection board covered all of the side and bottom surfaces of a beam, it contributed to the fire resistance of the beam. A thicker insulation layer resulted in an increased level of fire resistance. The effect of this fire protection board has been demonstrated in previous experiments with RC beams, HRC beams and some EB strengthened beams or NSM strengthened beams [6-7]. In this experiment, the beams F-NSM-entire/thick and F-NSM-entire/thin exhibited more than 2 h of fire resistance. 25-mm-thick calcium silicate board was sufficient for attaining 2 h of fire resistance, and it was much thinner than that in Palmieri's test [6]. This result further supports the conclusion that NSM FRP-strengthened RC beams can exhibit improved fire resistance if the fire resistance of the FRP bar is improved compared to the FRP bars that are currently used.

4. Conclusion

This paper investigated the fire resistance of RC beams strengthened with NSM BFRP bars, which were composed of basalt fiber and heat-resistant vinyl resin. These BFRP bars were selected from three types of bars impregnated in different resin matrices according to the results of mechanical property tests performed on bars during and after exposure to high temperatures. The RC beams strengthened with NSM BFRP bars and with different lengths and thicknesses of fire protection were tested to compare their fire resistance to the RC beams. The following conclusions are based on the results presented in this paper.

1. BFRP bars impregnated in heat-resistant vinyl resin exhibited better temperature resistance than the other two bar
types impregnated in common vinyl resin or heat-resistant epoxy resin. After improving the $T_g$ of the vinyl resin matrix used in the FRP bar (174°C in this paper), the NSM FRP-strengthened RC beam exhibited the same level of fire resistance as the RC beams. This preliminary conclusion favors the future use of FRP materials in engineering applications.

(2) There was no obvious change in the strength-temperature curves and modulus-temperature curves of the FRP bars when the temperature were close to their $T_g$ values, which was different than the behavior that was observed when FRP sheets were used. The $T_g$ value of the resin matrix was not the only factor that determined the temperature resistance of the FRP bars. The compatibility between the fiber and resin after pultrusion curing process and then at high temperatures was also an important factor that affected the fire performance of the FRP bars. The high temperature, combined with strain function, had a greater impact on the tensile performance of the bars.

(3) The FRP bars maintained sufficient anchorage with the concrete if only the two ends of the NSM FRP bars were protected against fire. This protection was achieved by stretching the ends of bars into the supporting components or wrapping it with U-shaped fire protection board. Only a short length (225 mm in this paper) of protection board was required.

(4) The fire resistance of the beam increased along with an increase in the thickness of the protection board along the beam. The fire protection board thickness required to achieve adequate fire resistance in the structural component could be reduced if the NSM material, which exhibited better fire resistance, was used in the FRP bars. Only 25-mm-thick calcium silicate board was required to obtain 2 h of fire resistance, and this thin board was easy to install and exhibited better deformation compatibility with the structural component being protected.

Acknowledgments

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Foundation of Jiangsu Province of China (No. BK20100015) and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

References


<table>
<thead>
<tr>
<th>Name</th>
<th>Diameter (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Density (tex)</th>
<th>Diameter (μm)</th>
<th>Bunches</th>
<th>Weight ratio</th>
<th>Style</th>
<th>Product marking</th>
<th>$T_s$ (°C)</th>
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<tbody>
<tr>
<td>V-BFRP bar</td>
<td>1293</td>
<td>48.9</td>
<td></td>
<td>4800</td>
<td>13</td>
<td>28</td>
<td>80%</td>
<td>normal vinyl resin</td>
<td>854 Bis-A</td>
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<td>HV-BFRP bar</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>heat-resistant vinyl resin</td>
<td>898HT</td>
<td>174</td>
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<td></td>
<td></td>
<td>heat-resistant epoxy resin</td>
<td>CP01-A/B</td>
<td>210</td>
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Table 2. Tensile strength and modulus of each BFRP bar

<table>
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<tr>
<th>BFRP bar name</th>
<th>During/after temp. (°C)</th>
<th>Strength (MPa)</th>
<th>Modulus (GPa)</th>
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<tr>
<td>V-BFRP</td>
<td>after 100</td>
<td>1193.0(5)</td>
<td>1163.7(5)</td>
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<td>during 200</td>
<td>1048.8(3)</td>
<td>1111.8(3)</td>
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<td></td>
<td>after 300</td>
<td>1074.5(3)</td>
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<td></td>
<td>after 350</td>
<td>489.5(1)</td>
<td>493.9(1)</td>
</tr>
<tr>
<td></td>
<td>after 400</td>
<td>121.4(1)</td>
<td>117.3(1)</td>
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<td></td>
<td>during 100</td>
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<td>1177.4(1)</td>
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<tr>
<td></td>
<td>during 200</td>
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<td></td>
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<td></td>
<td>after 250</td>
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<td>after 300</td>
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<td></td>
<td>after 400</td>
<td>72.4(1)</td>
<td>73.8(1)</td>
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### Table 3. Program details and experimental results for beam specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Environmental temperature</th>
<th>Strengthening scheme</th>
<th>Ambient ultimate load / sustaining load during fire P (kN)</th>
<th>Fire resistance (min)</th>
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<tbody>
<tr>
<td>RC</td>
<td>Ambient</td>
<td>No strengthening</td>
<td>260 / -</td>
<td>—</td>
</tr>
<tr>
<td>NSM</td>
<td>Ambient</td>
<td>NSM (near-surface-mounted) FRP bars</td>
<td>310 / -</td>
<td>—</td>
</tr>
<tr>
<td>F-RC</td>
<td>Fire</td>
<td>No strengthening</td>
<td>- / 156 (=0.6×260)</td>
<td>88</td>
</tr>
<tr>
<td>F-NSM-long/0</td>
<td>Fire</td>
<td>NSM, fire protection only at ends (longer)</td>
<td>- / 186 (=0.6×310)</td>
<td>101</td>
</tr>
<tr>
<td>F-NSM-short/0</td>
<td>Fire</td>
<td>NSM, fire protection only at ends (short)</td>
<td>- / 186 (=0.6×310)</td>
<td>99</td>
</tr>
<tr>
<td>F-NSM-entire/thick</td>
<td>Fire</td>
<td>NSM, thicker fire protection along entire length</td>
<td>- / 186 (=0.6×310)</td>
<td>147</td>
</tr>
<tr>
<td>F-NSM-entire/thin</td>
<td>Fire</td>
<td>NSM, thinner fire protection along entire length</td>
<td>- / 186 (=0.6×310)</td>
<td>128</td>
</tr>
</tbody>
</table>
Fig. 1. Protection of bar anchorages
Fig. 2. Schematic of tension test specimen (all units in mm)
Fig. 3. Comparison of the tensile strength and modulus of the FRP bars in this study to experimental results from Wang and predictions from Saafi: (a) normalized tensile strength with increasing temperature and (b) normalized tensile modulus with increasing temperature.
Fig. 4. Surface configuration of BFRP bars after high-temperature exposure

(a) HV-BFRP after exposure to 350°C before tension

(b) V-BFRP after exposure to 400°C after tension

(c) HE-BFRP after exposure to 350°C before tension
Fig. 5. Specimen details: (a) beam size, critical points and the assignment of steel and BFRP bars, (b) cross section before strengthening and (c) bottom of cross section after strengthening
Fig. 6. Schematic of the local or entire fire protection of four beams:
(a) F-NSM-long/0, (b) F-NSM-short/0 and (c) F-NSM-entire/thick and F-NSM-entire/thin
Fig. 7. Schematic of beam fire test setup
Fig. 8. Bottom surface morphology of strengthened beams after loading and exposure to fire temperatures:
(a) F-NSM-long/0, (b) F-NSM-short/0, (c) F-NSM-entire/thick and (d) F-NSM-entire/thin
Fig. 9. Deflection-time curves of the beams