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A Newly Developed Sandwich BRFP Composite Beam at Elevated Temperatures

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Abstract

The mechanical behaviour of composite materials at high temperatures has always been a hot topic for scientists to research. This paper studies the behavior of a new reinforced concrete composite beam at elevated temperatures. The fire condition experiments were carried out using the experimental method of heating and reloading in the high-temperature furnace, as well as the method of finite element analysis. The experimental results show that wrapping fireproof basalt mat can effectively help the structure bearing 30% more load by slowing the heating speed; while FEM presented that simple wrapping is not enough to withstand high temperatures exceeding 600 ℃, the thermal insulation performance of fireproof materials may have adverse effects on the structure itself. Combining the results of the FEM heating simulations with those of the laboratory heating, the FEM heating simulations were capable of revealing the realistic situation, which provided a positive contribution to the accuracy of the results of the subsequent thermal loading experiments. This research offers a perspective prediction in fireproof buildings.

Keywords: BFRP, composite beam, sandwich beam, elevated temperatures, experiment, numerical modelling.

1 Introduction

Over the years, global warming has become a severe issue and reducing energy consumption in buildings is necessary. For e.g., sandwich wall panel (SWP) was developed to provide thermal insulation to building enclosures to minimise energy consumption while heating and cooling the inner building space [1]. The sandwich structure consists of thin skin layers that are stiff enough to bear compressive and tensile loads, and the core part of the sandwich is thick enough to take the shear force [2, 4]. Besides its remarkable mechanical properties, the SWP has the merits of sound isolation and being highly temperature resistant. Fiber-reinforced polymer composite deck systems have emerged as a “new” material that is lightweight and corrosion-resistant. However, it is still challenging to maintain the lightweight, temperature resistance, and good mechanical properties performance in SWP [5]; the stuffed core and the thin skins are thick. In addition, the cohesive method and manufacture need additional consideration [4].

For the eco-environment aspect, organic and vegetable fibers in nature present prominent qualities in multidimensional aspects [1, 3, 5, 6, 9-11]. Fibers are the target material this article selected as the staffed core and reinforced material in SWP. Fabric-reinforced cementitious matrix (FRCM) composite is a lightweight solution but has high performance, a better strength-to-weight ratio than steel, and natural fiber degradation in the environment [9]. In addition, adding fiber could significantly reduce early shrinkage and improve crack resistance and flexibility during service [12, 13]. Basalt fiber exhibits good at high temperatures. The melting point of basalt fiber is approximately 1400 degrees; due to the higher fire resistance, basalt fibers are currently used in fire-protection devices [11]; Basalt fiber has long-term durability, high acid and solvent resistance, low water absorption, remarkable heat, and sound insulation characters [6]. Because of their excellent mechanical properties such as high energy absorption ability [5] and their efficient thermal cladding solution [9]. More suitable and economical than synthetic composite materials [1].

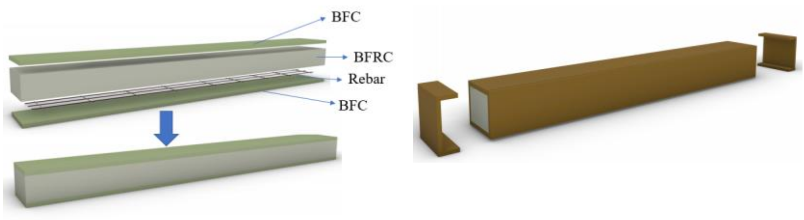
In this research, the SWP consisted of BF mat as its skin layers, and BF reinforcement concrete with steel rebar to verify the layer's laminated sequence and numbers. A set of four-point bending tests in elevated temperatures was carried out to investigate the mechanical properties of SWP and its fire resistance. Abaqus FEM was used to simulate the corresponding experiments and to reveal the internal stresses of the composite.

2 Methods

2.1 Experiment

2.1.1 Specimen preparation

The sandwich panel assembly with one rebar layer consists of a mortar-soaked basalt fiber mat (BFC) and basalt-fiber-reinforced concrete (BFRC). Concrete reinforced panels (all casted with basalt fiber) were sandwiched by mortar-soaked basalt mat. In order to keep the panels from being affected by temperature in high temperatures, half of the samples were fully wrapped with basalt fiber (BF) mats (Figure 1), the fire isolation property could be well performed [11]. The mortar-soaked basalt mats are made to enhance the soft and weak characteristics of the original BF mat by soaking it in mortar to allow the mortar liquid to be fully immersed in the pores of the BF mats.

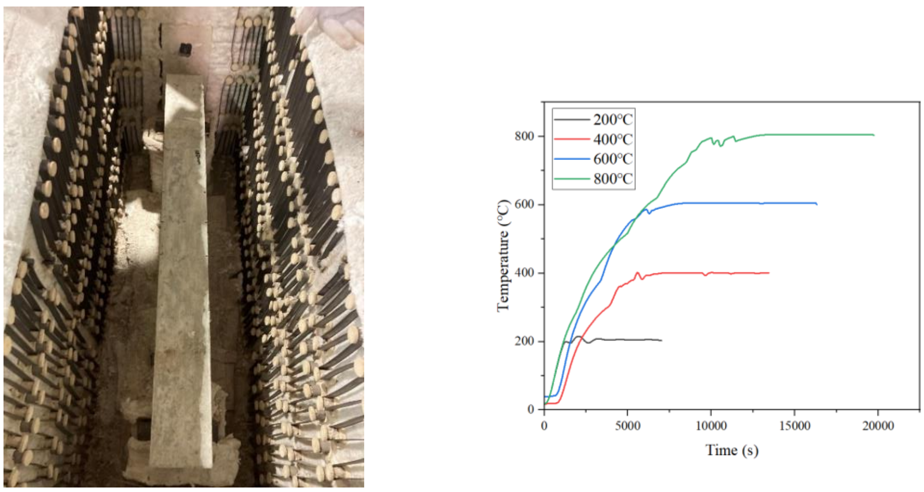


(a) (b)

Figure 1: The composition of the sandwich panel: (a) one-layer beam (b) the wrapping scheme.

2.1.1 Four-point-Bending test in elevated temperature setup

The failure mechanism of the constructed sandwich structure under bending was investigated using a quasi-static bending test. In this article, the quasi-static bending test was performed in a heating furnace to simulate the loading situation. According to the Chinese standard GB/T 9987.1, the time required for a fire-resistance rating was 1.5 hours. The test procedure for this facility involves preheating the furnace to a target temperature before beginning to load the beam evenly until it completely fails. The heating rise curve displayed on the controller screen allows us to see the slope of the heating rate for each time (Figure 2).



(a) (b)

Figure 1: (a) Furnace four-point bending apparatus; (b) The furnace temperature.

2.1 Numerical

2.1.1 Materials properties

Because BFC is a composite material obtained by soaking basalt fiber mat in mortar liquid, its essence can be understood as a mortar with weak strength. After the pressure test, it was found that the strength of BFC was very weak, so the strength of mortar was used in the simulation, and the maximum strength of the experimental value was used as $f_{cm,BFC}$.

For most metals, the post-yield behavior is defined by Abaqus's conventional metal plasticity model. Abaqus connects the provided data points with a series of straight lines to simulate the material's smooth stress-strain behavior. It is possible to employ a highly accurate approximation of the actual material behavior since any number of points can be utilized to simulate the actual material behavior.

2.1.2 Thermal Behavior

To model the structure in fire, the material and geometric non-linearity, time, and temperature vary, and the strength needs to be complete. In this demonstration, every component that assembled the sandwich beams was tested for the relative strength in the corresponding temperature. The furnace time-temperature curves were also recorded to fill into the “Amplitude” set.

3 Results and Discussion

3.1 Experimental

From the results of experiments, it is believed that the basalt fiber could positively retain the strength of the beam in high temperatures. The displacement of wrapped beams was twice larger than the unwrapped beam, claiming that the basalt fiber could keep the beam in strength and shape for longer. The experiment at 400 degrees, the core part BFC’s tensile and compressive are affected by the temperature; compared with the #BFM group, which has the fiber wrapped, the flexural displacement under high temperature is greater than the specimen without wrapping.

The 600-degree specimen was wrapped with fiber, and the experimental data reduced the effect of high temperature on the strength of the specimen by 70%. While the curve is very flat, the value of displacement is significantly larger than any of the previous group of data. It can be said that high temperature decreases the specimen’s elastic modulus significantly, and then the deflection will blast due to the rigidity increasing.

$$\delta_{max} = \frac{Pa}{48EI}(3{L_o}^3 - 4a^2) \tag{1}$$

In both wrapped and unwrapped specimens, compared with the control group, the number and length of cracks at the bottom were larger than those at the top when bent at a temperature of 200℃. Thus, it can be judged that the tensile capacity of BFC is greatly affected at 200℃, but the compressive capacity does not change much. Above 200 ℃, both the top and bottom show a larger number of cracks, and the compressive and tensile capacities of BFC are significantly weakened under high temperatures. Figure 3 shows all the load-displacement plots for the different conditions. The damage caused by the high temperatures and its effect on the beam post-failure can be observed in Figure 4.

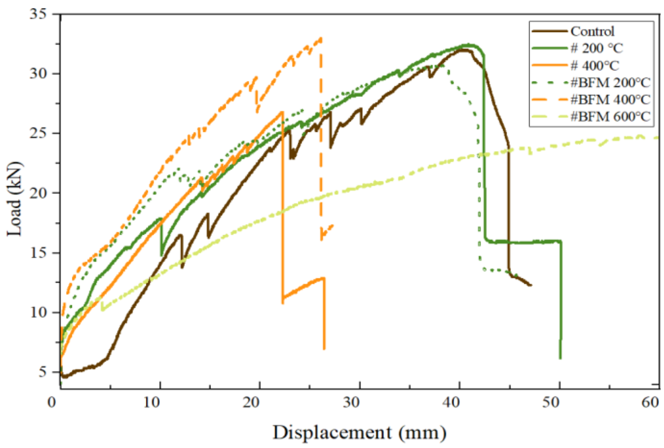


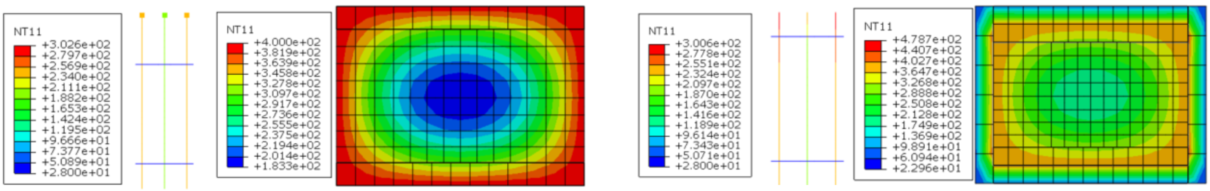
Figure 2: The P-L curve of one-layer beams in Four-point bending.

Figure 3: The failure patterns of layered beams.

3.2 Numerical

3.2.1 Heating Analysis

In the case of the beams wrapped with fiber mat, the rate of heat penetration into the beams was much slower from the beginning of the heating process, and the heat energy was absorbed by the fiber cloth, so that the temperature of the beams did not rise as much as the group without the wrapping, and the rate was slower. It is worth noting that in the later stage of heating, the temperature of the fiber cloth in the outermost layer is the lowest due to heat insulation, radiation absorption, and the characteristics of its own thermal conductivity. An example of the simulated heat conduction is shown in Figure 5. For the 600 °C group, the temperature dramatically reduces the performance of the reinforcement and leads to a decrease in strength. The loading curve of the FEM rised slowly, and the beam cannot be broken because the strength is too low.



(a) (b)

Figure 4: Heated simulation for (a) Unwrapped one layer beam at 400 °C; (b) Wrapped one layer beam at 400 °C.

3.2.2 P-D curve analysis

The P-D curve of FEM of 200 °C group, with or without wrapping, has almost no effect on the trend of the curve, but the wrapped beam can achieve higher loading force at the same maximum displacement; the two curves are almost coincident in the initial linear loading phase, but the elastic displacement of the wrapped beam is longer than the unwrapped beam, which leads to the rise of the wrapped beam than that of the unwrapped beam displacement is larger than that of the unwrapped beam. The stress distribution of the model is shown in Figure 6.

The displacement of the beam heated at 600 °C is the largest of all experiments, and the force that can be carried is also the smallest. In the results of the heating simulation, only the wrapped fiber cloth was less than 100 °C, and the rest of the components were heated to about 600 °C. The BFRC at this temperature also loses most of its strength, and the whole beam is not subjected to huge breakage. It can be continuously and slowly bent because its strength is too low, resulting in a large maximum displacement (Figure 7).

3.3 Comparison between Experiment and FE results

In the FEM beams with one layer of reinforcement, the BFC in the region of loading was subjected to larger forces, a phenomenon that coincided with the experimental results, where almost all specimens had more significant damage in the region near the loading. From the comparison of the FEM and experimental results, the slope of the curves and the trend is approximately the same. Figure 8 shows the comparison of the experiment and numerical comparison at different temperatures.

However, the accuracy of the FEM simulation on temperature is still relatively high. Although this experiment did not use a thermocouple as an accurate instrument to measure the temperature to visually detect the internal temperature of the beam, through each group of different heating results and loading results, it can be inferred that the situation simulated by FEM: (1) the heat insulation and thermal insulation effect of basalt fiber is very good; (2) the BFC board is not as good as BF fiber mat in insulation, in the process of heating because in the BFC contact surface of the BFRC produced a thermal bridge, there is a gradient change of temperature which will damage in loading, this concludes that when choosing composite materials, the thermal conductivity should not vary too much.

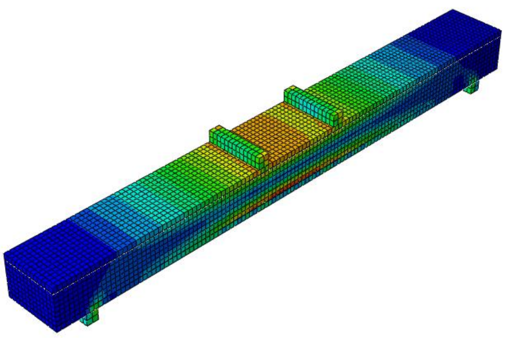


Figure 5: Stress distribution of 1-layer beam.

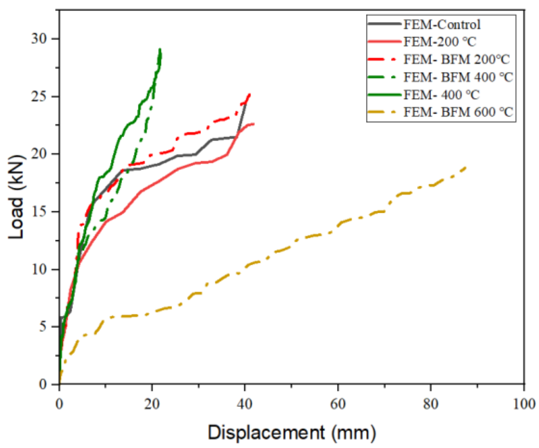


Figure 7: P-L curve in FEM of 1-layer beams in elevated temperature.

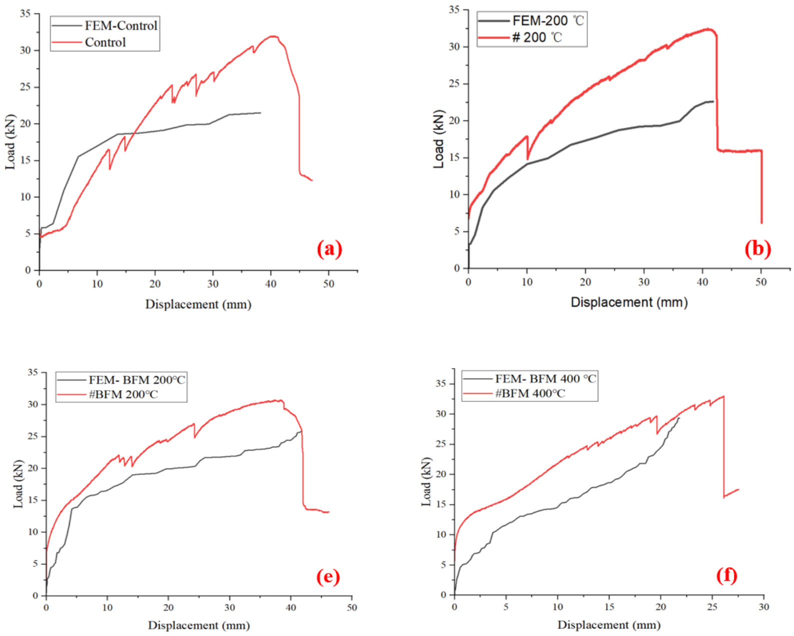


Figure 8: FEM result vs Experiment results in one-layer beam.

4 Conclusions and Contributions

In the high-temperature loading experiment, it can be concluded that the wrapped beam can withstand greater stress and greater displacement at the same temperature. The maximum bearing capacity of #BFM in the 400 °C data is 2.4 times that of the unwrapped beam, and 400 °C is the maximum temperature that the unwrapped beam can withstand in this experiment.

The heating of the beam wrapped with basalt fiber can be concluded intuitively through the FEM simulation: 1. The internal temperature rise rate of the wrapped beam is relatively slow, which is conducive to extending the linear loading of the material by about 1/3; 2. The wrapped fiber can not only slow down the temperature rise rate but also help to keep the internal temperature uniform so that the temperature difference of the whole beam is 20-50 degrees smaller than that of the unwrapped beam. Compared with the measurement results of the laboratory, the overall trend of the FEM calculation curve is reasonable, but the FEM cannot predict the moment of beam damage. The curve has been on an upward trend until the set displacement is reached. Since the properties of basalt fibers at high temperatures are obtained from literature reading, which cannot fit the real situation of the experiment very well, for instance, the simulated heating results are somewhat different from the real situation, resulting in loading-displacement are understandable.

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