Experimental study of the performance of CFRP strengthened small scale beams after heating to high temperatures

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HIGHLIGHTS

- CFRP strengthened small beams were heated uniformly to elevated temperatures up to 300 °C and then cooled to 20 °C.
- The deformations and behaviour of the CFRP strengthened small beams after the heating and cooling are presented.
- The effect of heating and cooling on the initial delamination load and residual capacity are analysed.

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ABSTRACT

The behaviour of FRP strengthened flexural elements is a subject of this experimental study on the effect of elevated temperatures after heating and cooling. Six groups of CFRP strengthened simply supported small scale beams were loaded prior to the heating with a point load of 1 kN and heated uniformly in loaded condition to a specified temperature of 50 °C, 100 °C, 150 °C, 200 °C, 250 °C or 300 °C. Once a uniform temperature was established the samples were left to cool to room temperature and tested in four point bending. Results from the deflection of the small beams, development of strain in the laminate and failure modes are presented and discussed.

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1. Introduction

In recent years fibre reinforced polymer (FRP) materials have been widely used to strengthen structures due to their high strength, low weight, ease of installation and lack of corrosion. The effect of elevated temperatures on the resistance of FRP strengthened reinforced concrete (RC) members has been found to have a significant influence on the performance of the strengthened systems. Existing investigations of the effect of elevated and high temperatures and fire have been limited in most cases to fire studies based on standard fire curves [1–6]. Relatively little is known about the residual properties of FRP strengthened systems after heating to high temperatures and cooling. More research in this area could be used to assess strengthened systems after heating to high temperatures and fire and to contribute to the knowledge about structural behaviour of such systems at different levels of heating. The behaviour of FRP strengthened flexural elements has been a subject of various investigations but the information on the effect of elevated temperatures after heating and cooling is still relatively limited.

The testing and prediction of the different properties FRP have been reported by Karadeniz and Kumlutas [7] who investigated different equations for determining the coefficient of thermal expansion (CTE) of fibre reinforced polymers in longitudinal and transverse directions. The best agreement with experimental results was obtained from values expressed by the elastic moduli, the Poisson's ratios and volume fractions of the fibres and the matrix.

Twenty-four RC beams strengthened with 100 mm wide CFRP plates were tested by Barnes and Fidell [8]. The plates were bolted to the concrete after the curing of the adhesive with some of the samples insulated with a cementitious fire protection applied in a layer of 15–20 mm. The beams were subjected to 1 h fire loading without additional static load. During the heating of the unprotected beams the temperature at the CFRP–concrete interface reached 580 °C and the fire exposure resulted in the adhesive layer...
being destroyed and the deterioration of the CFRP plate due to the loss of the resin component. During the heating of the insulated beams the temperature at the CFRP–concrete interface reached 140 °C which was above the glass transition temperature (Tg) of the adhesive. The adhesive was not destroyed and the fire protected beams failed at a load similar to the unprotected control unstrengthened beam. Comparison of the unprotected and protected CFRP strengthened beams revealed the latter to be stiffer and fail at higher loads.

Zhou and Tan [9] investigated the performance of glass FRP (GFRP) strengthened beams subjected to temperatures up to 800 °C. The small scale samples were strengthened with GFRP sheets, of those 3 groups had an additional protective layer. The samples were heated following the ASTM E119 standard curve. The exposure of elevated temperatures resulted in a substantial decrease in the stiffness and ultimate strength for samples heated above 600 °C.

Two simply supported CFRP strengthened T-beams loaded with a uniformly distributed load were tested in a study by Williams et al. [10] to ASTM E119 [11] fire test. The beams were insulated on three sides with a sprayed insulation to a thickness of 25 mm and 38 mm and after 4 h of exposure the maximum temperature recorded at the FRP bondline were 434 °C and 200 °C for the 2 different thicknesses. It was concluded that protected RC beams could retain most or all of their unstrengthened capacity if the temperature were kept below 200 and 593 °C for the concrete in compression and reinforcement, respectively [12]. It was also stated that the effect of strengthening may still be retained up to a yet unknown temperature which in this case would be limited by the combustion temperature of the polymer resin between 300 and 400 °C.

Eighteen rectangular beams 127 mm by 254 mm and 1219 mm length were strengthened with two layers of CFRP sheets for flexure and GFRP sheets for shear in the study by Weber and Kachlalek [13]. The samples were heated to 150 °C and then tested under 3-point bending. Above the Tg of the resin the strengthened system had a reduced stiffness and the ultimate capacity of the beam was determined by the behaviour of the internal reinforcement. The strain of the strengthening material was found to decrease with higher temperature which was attributed to relaxation of the concrete–FRP interface. The ultimate capacity of the samples was reduced by 46% at 150 °C temperature.

Klamer et al. [14] presented results from four different types of CFRP strengthening of RC beams. The beams were designed to fail due to high shear stresses, a shear crack, at the end-plate and concrete cover rip-off and tested at 20, 50 and 70 °C. The beams designed to fail due to high shear stresses were not affected by the temperature in terms of failure load except that at 70 °C less concrete remained attached to the adhesive layer. Beams designed for shear failure reached their highest load at 50 °C, whilst at 70 °C the failure occurred at an earlier stage attributed to lower bond strength. Beams designed for a plate end debonding exhibited a similar behaviour at 20 and 50 °C; at 70 °C the failure occurred as soon as yielding of the reinforcement begun. The reduced capacity of the beams at 70 °C was explained by the reduced bond strength and Young’s modulus of the adhesive. The heating to elevated temperatures had a significant effect on the beams designed to fail due to a concrete rip-off where at 50 and 70 °C they experienced reduced failure load of 5% and 10% respectively. Thermally induced stresses would have significant effect in this case as they will concentrate at the end of the plate but the reduced Young’s modulus of the adhesive would reduce the stress concentration.

Four CFRP-strengthened beams 254 × 406 × 3960 were tested in the study of Ahmed and Kodur [15]. The beams were strengthened with 2 CFRP sheets with length of 3680 mm and 2440 mm and epoxy resin with Tg of 82 °C. The beams were insulated with 2 types of insulation consisting of vermiculite-gypsum layer and a top layer of intumescent coating. The simply supported and axially restrained beams were subjected to 4 point bending and tested under design fire exposure and under ASTM E119 standard fire. The FRP-strengthened beams failure was found to depend on the temperature at the level of the reinforcement; the heating above the Tg did not lead to immediate failure. The cool anchorage of the FRP strengthening contributed to the performance of the beam by providing a cable mechanism.

Three 120 × 180 × 1500 mm RC beams were strengthened with CFRP fabric and textile with bonding provided by a cementitious mortar or epoxy and tested under constant service load by Hashemi and Al-Mahaidi [16]. The beams were subjected to a temperature of 900 °C which led to the increase in deflection until the beams failed. The epoxy and CFRP strengthened RC beam experienced a sudden increase in deflection at 66 °C which was assumed to be caused by an initial intermediate debonding. Later at 385 °C air temperature in the furnace another significant increase in the deflection was attributed to the debonding of the CFRP. The strengthened RC beams with a cementitious adhesive performed better reaching a failure at 844 °C.

Shier and Green [17] strengthened 250 × 350 × 3200 mm beams with 3 layers of CFRP wrap and cured at 120 °C proved to have a small strength reduction at temperature of 140 °C compared to noncured samples.

Donchev et al. [18] studied the effect of elevated temperatures (up to 300 °C) on CFRP strengthened concrete samples using microscopic analysis. At 250 °C some changes were observed in the specimens compared to the room temperature samples: some minor cracks were observed in the CFRP layer and the thin layer of fibres had melted into the adhesive. Microcracks were observed in the adhesive layer as well as change of the colour from grey at room temperature to brown at elevated temperatures. At 300 °C significant voids were observed in the adhesive together with colour change to dark brown/black and visible cracking in the CFRP layers.

In conclusion the behaviour of FRP strengthened beams has been studied with main focus on the effect of heating during the exposure to high temperatures and fire. However, the effect of temperatures on the performance and failure modes of FRP strengthened flexural members after heating and cooling is relatively limited.

2. Methodology

2.1. Preparation of samples

Twenty one small scale beams with dimensions of 100 mm × 100 mm × 500 mm made of concrete class C25/30 (cylindrical/cubic compressive strength) were tested in the study. The concrete mix proportions for 1 m³ were: cement 405 kg, water 230 kg, fine aggregate 660 kg and Thames valley coarse aggregate (10 mm maximum size) 1080 kg. Six of the 7 groups were subjected to uniform heating and one of the groups was used as control. The samples were reinforced with 4 mild steel rebars of 6 mm diameter in the longitudinal direction and 7 links of 3 mm diameter. The specimens were strengthened with 20 mm wide and 400 mm long CFRP plate with thickness of 1.2 mm and structural adhesive “Epoxy plus” from SBD Weber.

The experimental work was carried out in two phases:

Phase 1: the samples were heated in loaded condition in the temperature range between 20 and 300 °C, cooled to room temperature and unloaded.

Phase 2: The temperature treated samples from phase 1 were loaded till destruction.

2.2. Heating regime (phase 1)

Six groups of simply supported small scale beams were loaded prior to the heating with a midspan point load of 1 kN and heated in loaded condition to the specified temperature. The samples were uniformly heated to a temperature of 50 °C, 100 °C, 150 °C, 200 °C, 250 °C or 300 °C. The air temperature in the oven was mea-