Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Experimental behavior of FRCM-confined concrete under high temperature

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ABSTRACT: The paper investigates the behavior of concrete confined through FRCM (Fiber Reinforced Cementitious Matrix) composites subjected to high temperatures. Small scale cylindrical specimens (150x300 mm) were confined using two types of carbon fiber (dry and resin impregnated). For the sake of comparison two layers of FRCM were applied to all confined specimens. After curing, cylinders were exposed to four ranges of increasing temperatures being 20°C (ambient), 80°C, 100°C and 250°C and then tested under cyclic loading. The experimental results show that thermal stress significantly influences the confinement effectiveness of FRCM composites. Exposure to high temperatures reduces the ultimate confined strength and strain. For specimens confined with resin impregnated fibers, the observed stress-strain trend of confined elements tested after high temperatures exposure significantly differs from specimens tested under standard ambient conditions.

1 INTRODUCTION

Composite materials have been widely used in structural engineering to strengthen and upgrade existing concrete or masonry structures. Among others, fabric reinforced cementitious composites are gradually substituting the use of fiber reinforced polymers (FRPs) in the construction industry. This is mainly due to a better performance of FRCM composites in terms of durability and a higher compatibility with concrete and masonry substrates, because they replace the use of polymeric resins as a binding phase in favor of cementitious matrices, suitably added with substances aimed at improving their interaction with the resistant phase and support (Papanicolaou et al. 2008, Harajli et al. 2010). The cement-based matrix of the composites offers some advantages in comparison with the epoxy-based matrix of FRPs such as: easier application, especially onto rough and irregular surfaces like in old masonry (Mazzotti et al. 2015) or concrete construction, better bond behavior at high temperatures (Tetta & Bournas 2016, Raoof & Bournas 2017) and higher physical and chemical compatibility with the concrete or masonry substrate (Donnini & Corinaldesi 2017).

The beneficial effects from these features compensate the lower effectiveness of cementitious composites than FRPs (Donnini et al. 2019). Confinement of axially loaded concrete columns through FRCM jacketing is one of the main applications of the composite. Bournas et al. (2007) compared the confinement effectiveness of FRP and FRCM composites on small scale concrete specimens. Toska & Faleschini (2021) experimentally investigated the effect of cyclic loading and of different bonding conditions on the confinement effectiveness of FRCM composites (Toska et al. 2023). The ability to enhance seismic performance of FRCM jacketing was also experimentally investigated for undamaged and damaged reinforced concrete columns subject to cyclic horizontal loading (Bournas et al. 2009, Toska et al. 2022).

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However, cementitious composites are relatively recent and further research is still needed to understand their behavior. One of the still little studied aspects concerns the effect of high temperatures on the behavior of composites and the effectiveness of the interventions in which these materials are applied when exposed to high thermal stresses. Some researchers have compared the loss of strength of FRCM or TRM cementitious composites with those of FRP ones by means of tensile tests on specimens conditioned to thermal stress (Donnini et al. 2017, Messori et al. 2019). As expected, the results show a clear better resistance to high temperatures for the FRCM composites although, after a certain temperature, a decreasing trend in the tensile strength of the tested specimens is observed as the temperature increases. Recently, Kapsalis et al. (2021) published an extensive review on experimental investigations dealing with the behavior of textile reinforced concrete subjected to high temperatures. The same authors later on investigated the performance of textile-reinforced concrete after fire exposure (Kapsalis et al. 2022). TRC specimens with various reinforcement (carbon or glass fibers, uncoated or coated textiles) were casted and subjected to temperatures up to 700°C. The residual tensile capacity of the exposed specimens is analyzed and the results showed that the use of uncoated carbon fibers is the most promising solution to maintain a high residual capacity after fire exposure.

Regarding the behavior con FRCM-confined concrete under high temperature, Trapko (2013) investigated the effectiveness of confinement using FRCM composites in comparison to those confined through FRPs when subject to high temperatures. However, the investigated temperature range varies only from 40 °C to 80 °C. Ombres et al. (2021) investigated confinement through PBO-FRCM composites subject to temperatures ranging between 20 °C and 200 °C. The test results evidenced that the thermal conditioning affected both the mechanical properties of the FRCM materials and the effectiveness of the concrete confinement.

In this context, the present study investigates the performance of FRCM confined concrete subject to temperatures varying from ambient to 250 °C. Cylindrical specimens were confined with two types of FRCM jackets that differ from the carbon fabric applied: dry and epoxy resin coated.

2 EXPERIMENTAL PROTOCOL

2.1 *Materials and specimens*

In the presented experimental campaign, small scale specimens with $b \ x \ h$ dimensions 150 x 300 mm were casted using the same concrete batch. For the FRCM composite, the reinforcement consists in two types of carbon fabric: one in dry condition and the other coated using an epoxy-resin solution. The inorganic matrix consists in a premixed fiber reinforced cementitious mortar with a compressive strength of 25 MPa and flexural strength of 4.8 MPa. All materials were provided by the same manufacturer. The properties of the carbon fiber are shown in Table 1. For the sake of comparison and based on the previous experience of the authors, all specimens were confined using two FRCM layers.

Confinement was applied following always the same protocol. First the concrete specimen was damped with water to avoid water absorption from the FRCM composite, a first layer of mortar (3-4 mm thick) was applied around the cylinder and above it the carbon fabric was wrapped gently pushing it into the matrix. Then a second layer of mortar and then fabric was applied repeating the same procedure. The last layer was covered with the last mortar application. Carbon fabric was applied continuously with a final overlapping length of 200 mm.

Table 1. Properties of carbon fibers.

Fiber type	t_f (mm)	E_f (GPa)	f_f (MPa)	ε_f (%)
Carbon	0.047/0.061	240	4900	1.80

Figure 1. Application of the confining FRCM jacketing on the cylindrical specimens.

After FRCM jacketing application specimens were left curing for at least 90 days and then, before axial compression testing, they were exposed to increasing temperature levels being: 20 °C (ambient), 80 °C, 100 °C, 250 °C. Only specimens confined with coated carbon fibers were exposed to the 80 °C temperature. This aimed to investigate if the epoxy coating would undergo any degradation even for temperatures lower than 100 °C, given the poor behavior of organic matrixes at high temperatures. Specimens features are summarized in Table 2.

Table 2. Specimens' features.

Specimen	D (mm)	l_b (mm)	t_f (mm)	Fabric	T (°C)	Layers
REF	150	-	-	-	20	-
C2_Amb_1	150	200	0.047	Dry	20	2
C2_100_1	150	200	0.047	Dry	100	2
C2_250_1	150	200	0.047	Dry	250	2
2CR_Amb_1	150	200	0.061	Coated (Epoxy Resin)	20	2
2CR_80_1	150	200	0.061	Coated (Epoxy Resin)	80	2
2CR_100_1	150	200	0.061	Coated (Epoxy Resin)	100	2
2CR_250_1	150	200	0.061	Coated (Epoxy Resin)	250	2

2.2 *Test setup and loading protocol*

After the temperature exposure, specimens were axially loaded adopting a cyclic loading protocol. The tests were carried out using a universal loading machine under displacement control mode. Single compressive cycles were performed using a displacement rate of 0.6 mm/min was used for both loading and unloading paths. To avoid the complete unloading of the specimens and undesired movement of the specimens itself or of the instrumentation a small axial load of about 0.5 MPa was maintained during the unloading cycles. Before loading, both the upper face of the specimens was capped with high-strength mortar to ensure a proper distribution of the axial loading.

The axial load was acquired continuously during the test, using the 600 kN load cell of the universal testing machine. Axial strains were monitored using three linear voltage displacement transducers (LVDTs), that acquired the displacement between the top and bottom plates. LVDTs were installed equally spaced at 120°. Figure 2 shows a reference specimen and the instrumentation disposition during the testing.

Figure 2. Test setup.

3 RESULTS

3.1 *Failure modes*

Specimens confined with dry and coated carbon fabric showed different crack pattern and failure modes while no significant differences were observed in the crack pattern of the confined specimens when exposed to different temperatures. First, small vertical cracks were observed in the confinement jacket when the axial load was near the initial unconfined strength for all tested specimens. After an initial homogeneous crack distribution, a main crack, generally near the overlapping end, propagates until failure is reached. For specimens confined with epoxy resin coated carbon fabric, the failure was more abrupt and is characterized by wider crack openings and also spalling of the external mortar layer.

3.2 *Axial stress-strain behavior: Dry vs resin impregnated carbon fiber*

All specimens were tested under a cyclic compression loading protocol, however, for the sake of simplicity, only the envelope curves will be considered in this section. The initial concrete strength was evaluated on two specimens and the unconfined axial stress-strain curves together with the failed specimens after testing are shown in Figure 4. The unconfined compressive strength is 20.6 MPa while the axial strain at peak stress was about 0.36%. At ambient temperature, specimens confined with dry carbon fabric displayed a similar behavior to what previously observed by some of the authors in a previous work (Toska & Faleschini, 2021). The first peak, reached at strain values close to those observed for unconfined concrete, is followed be a slight strength decrease which in turn is followed by a new stress increase or by an almost constant strength until failure. On the other hand, for specimens confined with coated carbon fibers the softening phase was not observed and the stress-strain curves were characterized by a hardening trend until failure. Carbon fabric coated in epoxy-resin performed better both in terms of axial strength and axial strain capacity. For normal ambient temperature this

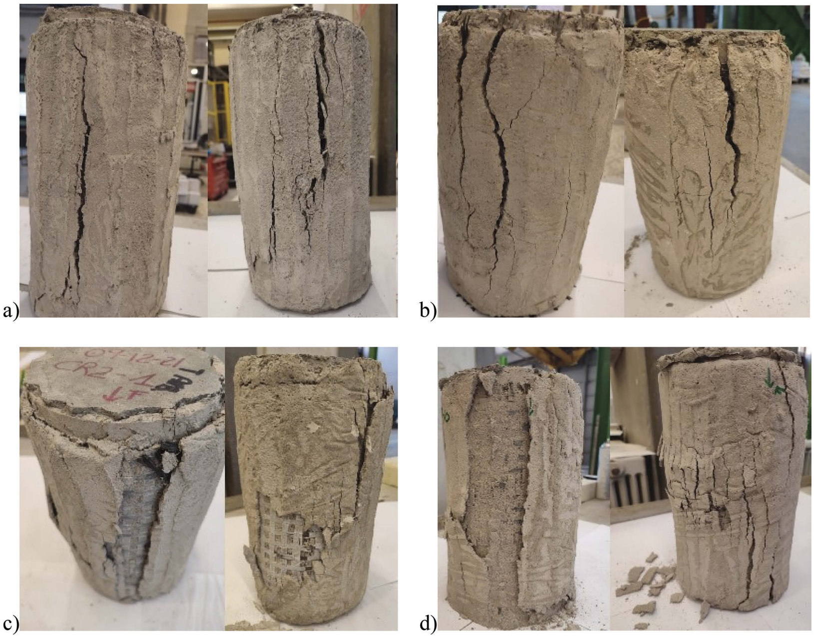

Figure 3. Final crack pattern for a) C_20_2C, b) C_250_2C, c) C_20_2CR and d) C_250_2CR.

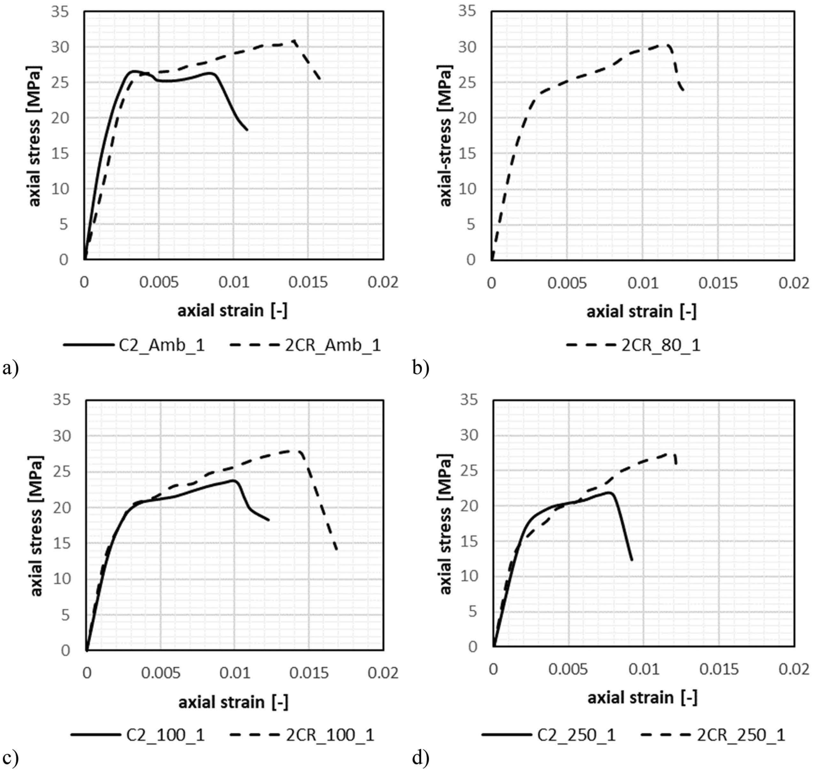

Figure 4. Axial stress-strain curves for specimens confined with dry and pre-impregnated fabrics at different temperature steps: a) ambient, b) 80 °C, c) 100 °C and d) 250 °C.

is in line with what previously observed by some of the authors in (Toska et al. 2023). The better behavior of coated carbon FRCM jacketing, in terms of confined peak strength and strain, surprisingly, was maintained also for the higher temperature steps. Strength enhancement, results about 19%, 17% and 27% more effective for coated cases respectively for ambient, 100 °C and 250 °C. Since specimens are tested after cooling down, investigating their residual capacity, the better performance of jackets with coated fabrics is believed to be due to melting and re-hardening of the polymeric coating of the fabric that results in a better fiber-matrix bond. Similar behavior was observed also on pullout test by de Andrade Silva et al. (2014) for temperatures up to 200 °C.

3.3 *Influence of high temperature*

Figure 5 Compares axial stress-strain curves for confined concrete through FRCM composite with dry carbon fabric. Both curves, for specimens exposed at 100 °C and 250 °C, result significantly different from the one for ambient temperature. The effect of high temperature is significant already at 100 °C. Strength enhancement at the first peak (at axial strain near to that of unconfined concrete), that is very clear and significant for specimens at ambient temperature, is not present after high temperature exposure. Confined strength results 26.4 MPa for ambient temperature specimens, 23.5 MPa after 100 °C exposure and 21.4 MPa after 250 °C exposure. Ultimate axial strain at 100 °C is about 1%, resulting slightly higher than at ambient temperature (about 0.9%) and at 250 °C (about 0.8%).

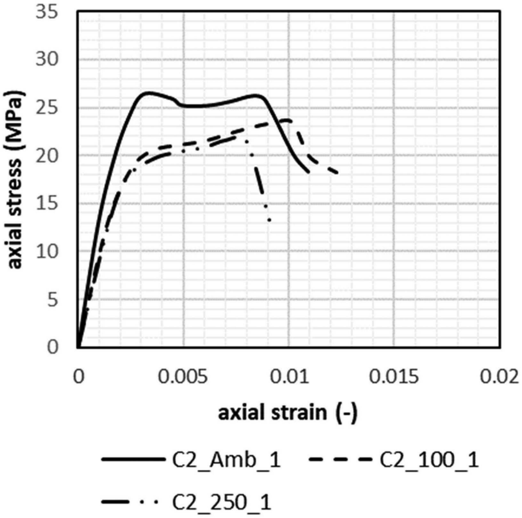

Figure 5. Axial stress-strain curves for specimens confined with dry carbon fabric.

Specimens confined with coated carbon fabric also experienced a significant performance reduction when exposed to high temperatures. Confined peak strength decreased from 30.7 MPa at ambient temperature to 27.5 MPa after 250 °C exposure. At 80 °C, strength remained similar to the unconditioned one (about 30 MPa), while at 100 °C peak strength was almost the same as the one recorded at 250 °C (about 28 MPa). The ultimate axial strain capacity remained relatively high, varying between 1.2% and 1.4%. Even though peak strength degradation was low (about 10%), axial stress-strain curves (Figure 6) differ significantly for the different temperature steps. As observed for the dry-fabric cases, strength enhancement at the first peak (following the first branch of the stress-strain curve) is gradually reduced as temperature gets higher, moving the inflection point of the hardening branch lower for each step.

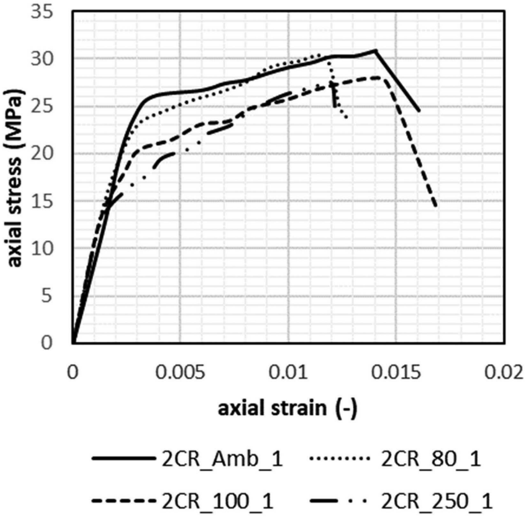

Figure 6. Axial stress-strain curves for specimens confined with coated carbon fabric.

4 CONCLUSIONS

The present work investigates the behavior of FRCM confined concrete when exposed to high temperatures. Small scale cylindrical concrete specimens were casted and confined using two types of carbon FRCM composites, that differ on the initial treatment of the fabric: dry and epoxy resin coated were tested. After 90 days of curing from the jacketing application, specimens were exposed to increasing temperature steps: 20 °C (ambient), 80 °C, 100 °C and 250 °C. After cooling down, the specimens were tested under compressive cyclic behavior to investigate their residual strength and strain capacity. Results show a significant change in the axial stress-strain behavior after high temperature exposure. Epoxy coated FRCM jackets performed better than dry ones at all temperature steps, both in terms of strength enhancement and axial strain capacity. Between ambient and maximum considered temperature (i.e. 250 °C), 19% strength reduction was observed for dry carbon FRCM while only 10% for coated ones.

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