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EFFECT OF CEMENTITIOUS PROTECTION ON FLEXURAL RESPONSE OF CFRP BEAMS EXPOSED TO ELEVATED TEMPERATURE

Abou Ali, Reem [1,3] and Abou-Zeid, Mohamed N [2].
[1,2] The American University in Cairo, Egypt
[3] reemabuali@aucegypt.edu

Abstract: Carbon Fiber Reinforced Polymers (CFRP) has been used extensively over the past decades to strengthen and retrofit the concrete structures. They are proven to enhance the structure load carrying capacity. The externally bonded CFRP systems improve the flexural strength of the concrete structures. This study aims at achieving better understanding of the effect of cementitious protection on flexural response of CFRP reinforced beams exposed to elevated temperature. Beams were prepared using cementitious protection and were exposed to three different temperatures and four durations. The results of this work reveal that CFRP experienced a significant drop in flexural strength upon exposure to elevated temperature. The strength however, was restored up to 63% upon using ready-to-use mortar. It is recommended to use this protection type as means to alleviate the negative impact of elevated temperature on CFRP system. Keywords: CFRP, Elevated Temperature, Protection, Cementitious

1 INTRODUCTION

The fast growing deterioration of the infrastructure along with the need for economical and feasible techniques for the strengthening and repairing of the systems led to the uprising of the fiber reinforced polymers (FRP) composites. The FRP composites came as replacement to the conventional repairing materials (Täljsten 2003). The FRP composites have superior properties such as the high-strength-to weight ratio, high stiffness, corrosion resistance and light weight. The FRP composite are easily tailored to fit almost any shape and geometry (Sen 2015, Yang et al. 2008). The most commonly used FRP composites are carbon, glass and aramid. The carbon fiber reinforced polymers (CFRP) composite materials have drew the attention of the research recently regarding the strengthening and retrofitting of the concrete structures. This was trailed by publishing of the international design codes for strengthening the concrete structure with the external bonded CFRP strengthened beams (Wang et al. 2011). The desirable benefits of the CFRP composites were the key reasons for their wide spread (Wu and Li 2016). CFRP are highly requested in applications where high strength, stiffness, exceptional fatigue performance and lightweight are required. The CFRP composites are considered the superlative resolution where elevated temperature resistance is highly necessitated. Evaluating the CFRP properties at room temperature when compared to aramid and glass fiber, the CFRP exerts no corrosion stress or “stress rupture failure” (Deng et al. 2015, Dong et al. 2013). The externally bonded FRP material following exposure to elevated temperature is expected to show high lessening in strength, stiffness and bond properties. This usually occurs when the glass transition temperature (Tg) of the polymer matrix or adhesive is lower than the surrounding temperature (ACI 440.2R-02 2002, Foster and Bisby 2005). For each FRP system, there is a distinctive Tg; it usually ranges from 60 to 82 °C depending on the current available commercial FRP systems (ACI 440.2R-02 2002).

The CFRP composites are generally used in environments where they can sustain temperatures up to 2000 °C. However, the epoxy-adhesive used to externally bond the CFRP to the concrete structure face mechanical properties degradation when subjected to temperature exceeding the Tg. In accordance, the epoxy adhesive loses the ability to transfer the load from the concrete structure to the CFRP material. The Tg of the available commercial epoxy adhesive in the construction industry lies in the range from 50 to 90 °C. Remarkably, such temperatures are easily reached by exposure to direct sunlight in warm environments (Wang et al. 2011, Ahmed and Kodur 2011, Hollaway 2010). El Maghraby et al. concluded that as the temperature of the CFRP strengthened beams increase to reach 100 °C up to two hours before applying the load, the failure load will not be significantly influenced (El Maghraby et al. 2010).

Among the few concerns faced by the CFRP strengthened beams come the epoxy adhesive material that is polymer based. The polymer-based adhesive is extremely successful when there are no distresses regarding the elevated temperature or fire scenarios. Following exposure to high temperature, the mechanical properties of the epoxy adhesive suffer substantial degradation. The proper explanation for this could be due to exceeding the Tg of the epoxy in which the state of the material is altered from a solid state to liquid state tailed by a substantial lessening in the mechanical properties (Wu and Li 2016, Lopez et al. 2013).

AbouZeid et al. used conventional mortar to protect CFRR systems. The three sets in the right hand sides in Figure 1 shows some improvement in the flexural load through applying a conventional mortar on top of the CFRP at thicknesses of 10 and 20 mm using fresh water. However, this work was performed at 80 °C in which the conventional mortar showed an ability to protect the beams against this temperature exposure. Yet, this potential protection needs to be investigated at higher temperatures beyond 80 °C (AbouZeid et al. 2013). In this study, the effect of protection provided by a ready-to-use mortar applied over the CFRP strengthened beams is examined.

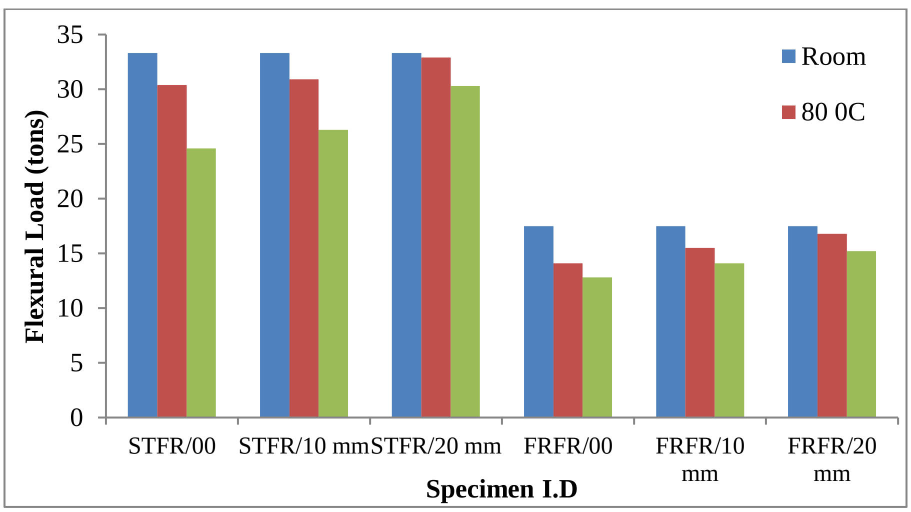

Figure 1: Flexural loads for conventional mortar protected CFRP systems at various temperatures (AbouZeid et al. 2013)

2 MATERIALS AND EXPERIMENTAL WORK

2.1 Materials

A cement-based dry mix fire protection mortar, aggregates with greyish powder, possesses low density of 1.71 kg/liters was used. It was applied over pultruded carbon fiber laminates. The concrete beams were prepared using Ordinary Portland cement type I (ASTM C150). Admixture Type D in ASTM C 494 was used aiming for higher compressive strength by lowering the water-cement ratio. Clean drinkable water was used for the mixing process and for any cleaning purposes during the pouring process. Normal strength concrete mix with compressive strength not less than 30 MPa after 28 days and water-cement ratio of 0.45 is used in this study. Seventy-two beams of dimensions 75 cm x 15 cm x15 cm were prepared in the laboratory of the American University in Cairo (AUC).

2.2 Experimental Work

In this study the two control groups are the unstrengthened unprotected and CFRP strengthened unprotected beams. The protected CFRP strengthened protected group will be measured against the two control groups. Each testing group consists of twenty-four beams. For each reading, there are two replicas. The seventy-two beams are tested against three various temperature values; 70,120 and 180 ° C. The beams are exposed to elevated temperature for four durations of exposure; one hour, two hours, four hours and eight hours. Figure 2 shows the three sets at the various temperatures and durations.

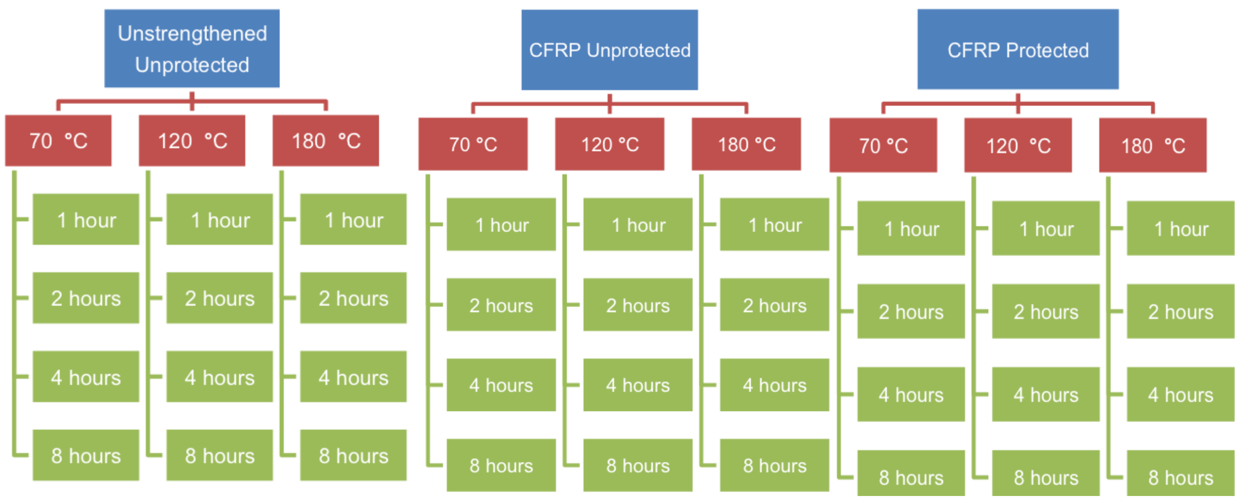

Figure 2: Three testing sets exposed to various temperatures and durations

2.3 Experimental Set up

The CFRP strengthened unprotected set was prepared by applying the CFRP laminates on the tension side of the beam, only covering 60 cm of the total length of the beam. The CFRP unprotected set was prepared the same way but with additional layer on top of the CFRP laminate of 20 mm of cement-based dry mix mortar. The experimental program consists mainly of the flexural testing using the three-point loading flexure test according to ASTM C293, after exposing the concrete specimens to elevated temperatures in the furnace. A furnace with heating capacity up to 1000 ° C is used where the specimens will be heated. After the testing the concrete specimens at the designated temperature for each control group, the furnace is turned off and the specimens are allowed to cool outside the furnace in the laboratory for one hour to be easily handled later. The concrete specimens are then taken each on the three-point loading machine. The flexural strength of the concrete specimens was tested according to ASTM C 293/C78. The readings of the flexural strength of each group are collected followed by calculation of the stresses.

3 RESULTS

The flexural testing results were analyzed by observing the failure loads at which each system failed for each temperature and duration being exposed to. Figure 3 shows the failure load values of the three tested systems at 70 °C. At 70°C, the CFRP strengthened protected beams exhibited the highest failure loads in comparison with the unstrengthened unprotected and the CFRP strengthened unprotected. It is unveiled that the failure load increased with adding CFRP strengthening and cementitious layer protection. The higher failure loads attained by the CFRP strengthened unprotected and protected beams may be due to the behavior of the epoxy adhesive after exceeding its Tg. When the epoxy adhesive is exposed for temperature higher than Tg, it becomes more deformable. This in fact might have increased the strength of the bond as the stiffness of the adhesive itself may be have decreased.

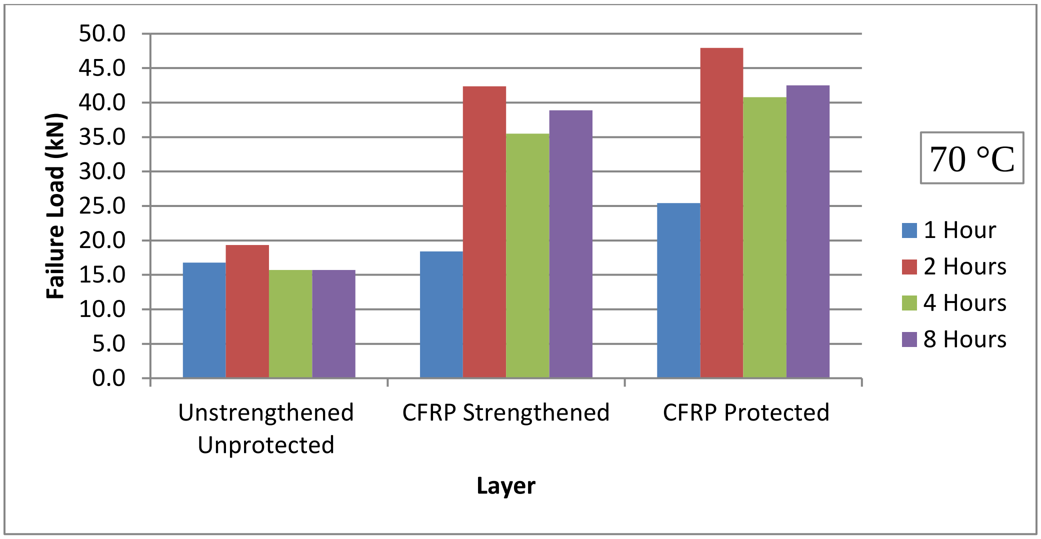

Figure 3: Flexural strength for the three tested systems at 70 °C

The high failure load values recorded at 70 °C for the CFRP strengthened protected beams continued to prevail at 120°C with some exceptions. Figure 4 shows the failure load values for the three tested systems at 120 °C. The highest failure load values were attained by the CFRP strengthened protected beams exposed to 120 °C for two, four and eight hours. At 120 °C, although the Tg of the adhesive will be exceeded by a higher value, but still the stiffness of the bond will be subject to decrease and hence increase its deformability. This in return may have increased the failure loads for the CFRP strengthened protected and unprotected beams.

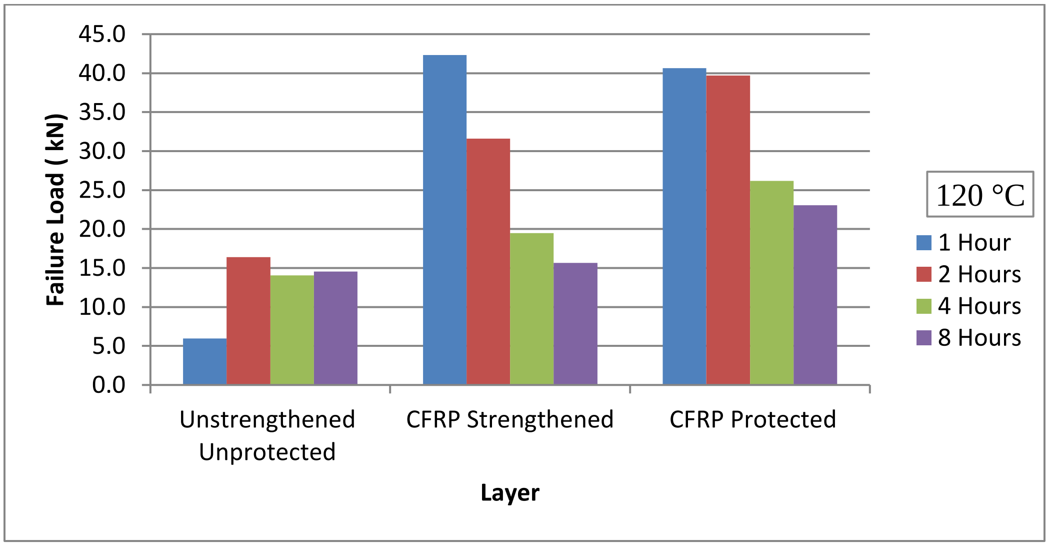

Figure 4: Flexural strength for the three tested systems at 120 °C

The high failure loads for the CFRP strengthened protected beams recorded at 70 and 120 °C did not prevail for the temperature of 180 °C. Figure 5 shows the flexural failure load values of the three tested systems at 180 °C. The CFRP strengthened protected beams at 180 °C only after exposure for two hours recorded the highest failure load. At 180 °C, the Tg of the epoxy adhesive have been highly exceeded, although there were some improvements in the flexural strength at exposure of one and two hours. When the exposure exceeded the two hours, there was a significant drop in the flexural strength of the CFRP unprotected beams. The reason might not be the only the Tg of epoxy adhesive but also the ability of the cementitious mortar to stick to the concrete beam and CFRP at such exposure at 180 °C.

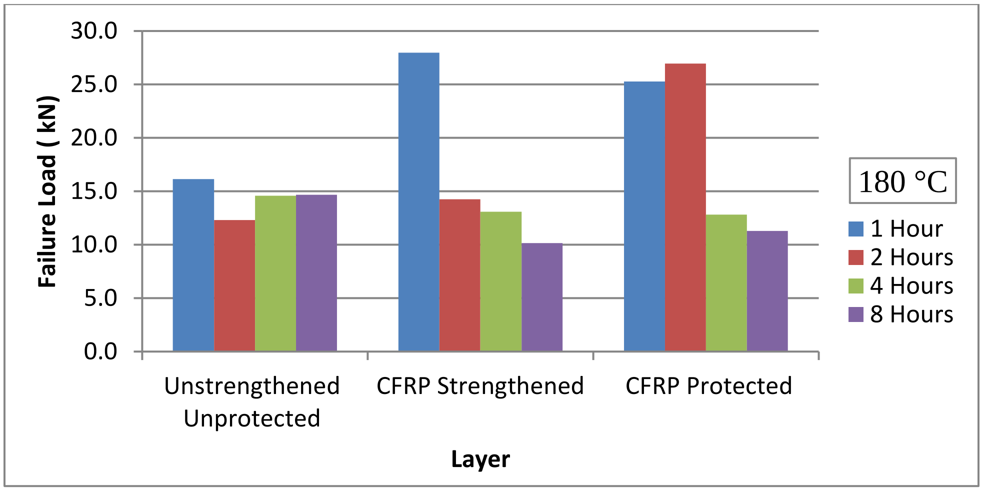

Figure 5: Flexural strength for the three tested systems at 180 °C

3.1 Flexural Enhancement Ratio

In attempt to interpret the response of the cementitious protected strengthened beams to the elevated temperature. The flexural strength enhancement ratio was calculated by dividing the failure load of the CFRP strengthened protected over the CFRP strengthened unprotected beams. If the ratio exceeds one, this indicates the success of cementitious material in providing the required protection against elevated temperature. The flexural strength enhancement ratios were calculated and plotted at the three different temperatures 70, 120 and 180 °C, respectively. Figure 6 illustrates the flexural strength enhancement ratio at 70 °C provided by the cementitious material. A ratio of 1.4 was recorded after exposure to 70 °C for one hour, the ratio decreased to 1.1 after two hours of exposure to 70°C and the ratio maintained almost the same value after exposure to 70°C for four and eight hours, respectively.

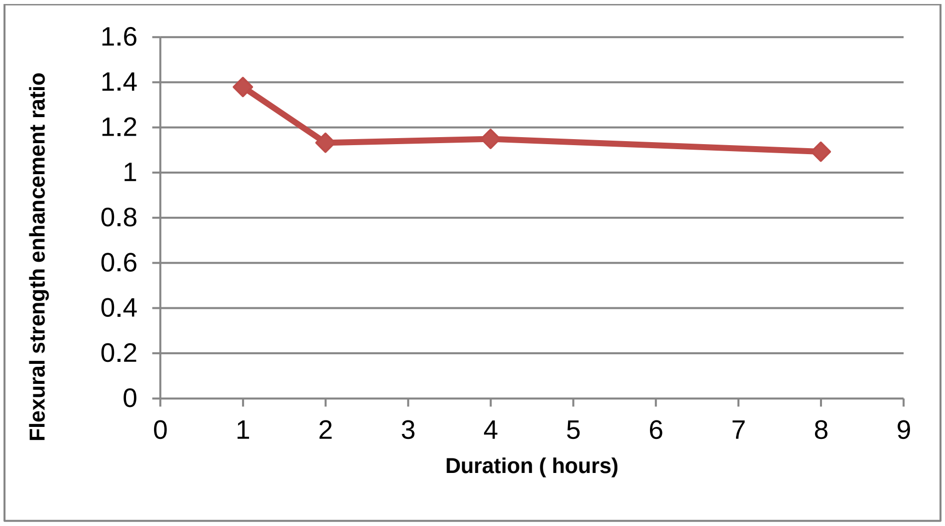

Figure 6: Flexural strength enhancement ratio between CFRP unprotected and CFRP protected beams at 70 °C

The flexural enhancement ratio at 120 °C for the different durations of exposure is illustrated in Figure 7. After one hour exposure to 120 °C, the cementitious layer failed to provide protection to the CFRP strengthened beam. On the other hand, the flexural enhancement ratios exceeded one and provided protection against the elevated temperature for two, four and eight hours, respectively.

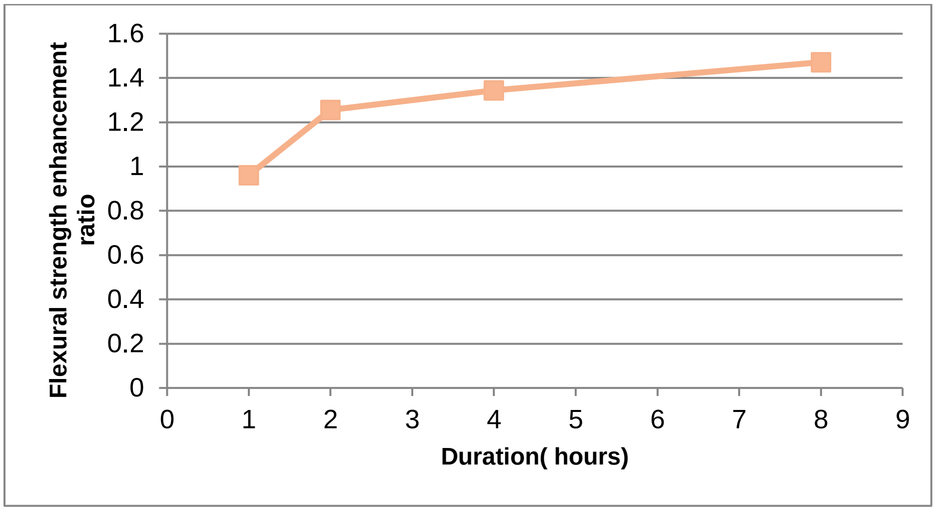

Figure 7: Flexural strength enhancement ratio between CFRP unprotected and CFRP protected beams at 120 °C

The flexural strength enhancement ratio at 180 °C is illustrated in Figure 8. After one hour exposure to 180 °C, the cementitious layer failed to provide protection against the elevated temperature. After two hours exposure to 180 °C, the cementitious provided protection with flexural enhancement ratio of 1.9. The ratio decreased to reach 0.9 after four hours of exposure to elevated temperature. On the other hand, after eight hours exposure to elevated temperature, the ratio exceeded 1, indicating the protection provided by the cementitious material to the CFRP strengthened beams.

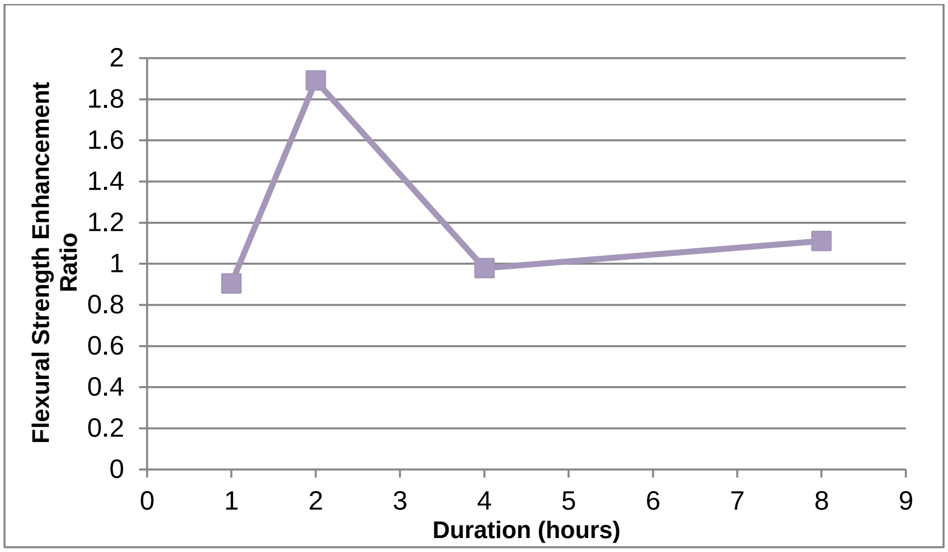

Figure 8: Flexural strength enhancement ratio between CFRP unprotected and CFRP protected beams at 180 °C

4 DISCUSSION

Examining failure modes of the protected CFRP strengthened beams; the protected sets exhibited flexural failure with the crack being initiated near the bottom end of the plate and propagating longitudinally through the beam. The behavior of the CFRP laminates varies between the separation from the concrete surface and peeling off at the flexural failure interface.By observing the flexural failure of the CFRP strengthened protected beams, it is worth mentioning that deterioration and separation of the fire protection layer itself followed the flexural failure instantly. Figure 9 shows the typical failure mode for the protected CFRP beams. The complete deterioration and separation of the cementitious fire-protecting layer were roughly exhibited for most of the beams irrespective of the temperature and duration of exposure.The fire protection layer broke into pieces and was separated from the concrete surface; while keeping the CFRP laminate and small layer of the concrete surface attached to it. As for the beams exposed 180 °C for eight hours, cracks on the cementitious fire protecting layer were observed directly after taking the specimens out of the furnace prior to any flexural test. Figure 10 shows the crack on the specimen and the weak adherence of the layer to the concrete beams. The cementitious fire protection layer was completely separated from the concrete surface and utterly deteriorated.

Figure 9: Typical failure mode for the CFRP protected beams

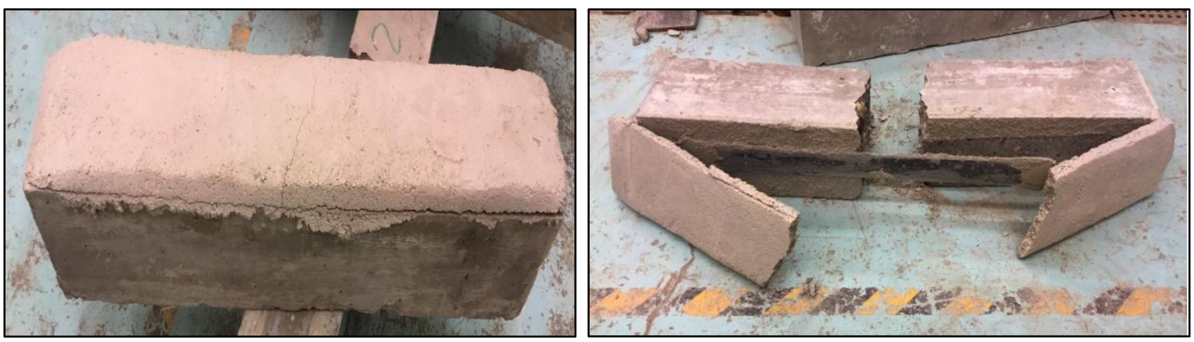

Figure 10: Crack in the cementitious layer and complete deterioration after exposure to 180°C for 8 hours

5 COST ANALYSIS

A simplified cost analysis was conducted by calculating the cost of the CFRP strengthened beams and the cost of the fire protected CFRP strengthened beams. This was followed by identifying the ability of each system to restore the lost flexural strength upon exposure to elevated temperatures of 70, 120 and 180 °C. The percentage of restored flexural strength was then compared with the percentage variation of each system. The results of the comparisons between both systems in terms of strength and price are presented in Table 1. On average the CFRP strengthened unprotected beams provided higher flexural strength than the unstrengthened unprotected concrete beams by 40% upon exposure to 70 °C for the four different durations. The cost of the CFRP strengthened beams recorded 90% higher than the cost of the unstrengthened unprotected concrete beams. The CFRP strengthened beams continued to provide higher restoration of the flexural strength by 40% of the strength of the unstrengthened unprotected concrete beams after exposure to 120 °C for the various durations. On the contrary, the CFRP laminates failed on average to restore the flexural strength lost due to exposure to 180 °C for various durations, it only restored 0.01% of the flexural strength of the bare beams.

Evaluating the ability of the cementitious protection to endure the effect of the elevated temperatures for the various durations is represented by the percentage restored of the flexural strength lost upon exposure to elevated temperatures. The protected beams restored 20 % of the lost strength by the CFRP strengthened beams when exposed to 70 °C on average for the four durations. The ability of the protected beams to restore the lost flexural strength when exposed to 120 °C slightly exceeded 20 %. When the fire protected beams were exposed to 180 °C, they only restored 11.1% of the lost flexural strength by the CFRP strengthened beams. The costs of the protected CFRP strengthened beams are higher than the CFRP unprotected beams by 16%.

Table 1*:* Comparison between Performance of CFRP protected and unprotected beams

Temperature(°C)	CFRP unprotected restored flexural strength (%)	Increase in Price (%)	CFRP protected restored flexural strength (%)	Increase in Price (%)
70	40	90	20	16
120	40	90	20	16
180	0.01	90	11	16

6 CONCLUSIONS

Based on the materials incorporated, procedures followed and other parameters associated with this study and taken into consideration work limitations as well as experimental and statistical variations, the following conclusions can be stated:

1. The use of CFRP in external strengthening of beams introduces pronounced increase in the flexural strength of concrete beams. This is a well-established finding since more than two decades.
2. Exposure to elevated temperature up to 180 °C introduces little/no significant decrease in the flexural strength of unstrengthened; unprotected beams.
3. Exposure to elevated temperature at various degrees (70, 120 and 180 °C) introduces a significant drop in the flexural strength for the CFRP strengthened beams. This drop, in general, is proportional to the both the increase in temperature as well as the increase in the duration of exposure.
4. Using the cementitious coating provided a protection against elevated temperature for the 70 and 120 °C but does not seem to provide a real protection for 180 °C exposure.
5. Exposure to elevated temperature causes the cementitious protective material to inflate and produce air bubbles; thus suggesting air to act as a barrier providing the protection. However, this needs to be studied on its own through microscopic investigation.
6. Visual examination as well test results both suggest that an interaction occurs between the cementitious material and the CFRP at elevated temperature. Such interaction seems to introduce some damage thereby reducing the flexural strength.
7. Looking at the results herein as well as previous work conducted at AUC and elsewhere, cementitious materials provide a good protection up to mild temperature rise (less than 100 °C). The extent of protection of the cementitious materials is questionable for higher temperatures unless higher layer thicknesses are investigated.

The simplified cost study that was conducted herein reveals that cementitious protection are truly feasible and represent a value-added benefit to CFRP exposed to mild temperature increase.

7 RECOMMENDATIONS

As this study is by no means comprehensive, the following future work and investigations are highly recommended:

1. Expanding this study to cover other concrete elements with a wider array of protective materials at various thicknesses. Such wide-scale studies need to implement higher elevated temperatures at extended durations.
2. Investigating the effect of cyclic heat stresses and the impact of both gradual and abrupt cooling.
3. Tackling CFRP durability due to combined effects such as elevated temperature and aggressive chemicals that are often encountered in industrial applications.
4. Performing similar tests and examining the validity of the findings of this study for reinforced beams/elements to simulate this situation in structures where reinforcement have not been subjected to sever damage/corrosion

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