# Comparative performance of Fibre Reinforced Polymer and Fibre Reinforced Cementitious Mortar Strengthening Systems in Elevated Temperature Service Environments

**Citation for published version:**
Bisby, L, Stratford, T, Smith, J & Halpin, S 2010, Comparative performance of Fibre Reinforced Polymer and Fibre Reinforced Cementitious Mortar Strengthening Systems in Elevated Temperature Service Environments. in Structural Faults and Repair 2010. Engineering Technics Press, Edinburgh, Structural Faults and Repair 2010, Edingburgh, United Kingdom, 15-17 June.



**Published In:**
Structural Faults and Repair 2010

# COMPARATIVE PERFORMANCE OF FIBRE REINFORCED POLYMER AND FIBRE REINFORCED CEMENTITIOUS MORTAR STRENGTHENING SYSTEMS IN ELEVATED TEMPERATURE SERVICE ENVIRONMENTS

Dr Luke Bisby, Dr Tim Stratford, Joanna Smith & Sarah Halpin
University of Edinburgh
Joint Research Institute for Civil and Environmental Engineering
School of Engineering
Edinburgh EH9 3JL
Scotland

Luke.Bisby@ed.ac.uk

KEYWORDS: Concrete structures, strengthening, high temperature, fibre reinforced polymers, fibre reinforced cementitious mortars, bond.

ABSTRACT
Fibre reinforced cementitious mortar (FRCM) strengthening systems have recently emerged as novel means of strengthening damaged or deficient masonry and/or concrete structures. These unique systems consist of open-weave polybenzoxozole (PBO) fibre fabrics which are applied to the surfaces of structural elements, walls, domes, tunnels, or shells using specialized inorganic cementitious mortars. FRCM systems have a number of advantages over alternative strengthening systems such as externally bonded fibre reinforced polymers (FRPs), most notably their breathability, inherent non-combustibility, non-flaming characteristics, and their performance in elevated service temperature environments. However, while FRCM systems have seen some application in Europe, additional research is needed, most importantly on their high temperature performance and durability, before they can be widely applied with confidence. This paper reports the initial results of an ongoing experimental study into the performance of a specific FRCM structural strengthening system for concrete. Tests on strengthened small scale concrete beams at ambient and elevated temperatures are presented. A comparison against currently available externally bonded FRPs is included. The superior bond performance of FRCM strengthening systems at elevated temperatures of between 50ºC and 80ºC is clearly demonstrated.

## INTRODUCTION

Textile reinforced mortar (TRM) systems have emerged as novel means of strengthening damaged or deficient masonry or reinforced concrete (RC) structures (Triantafillou & Papanicolaou 2006). These systems consist of open weave fibre fabrics which are applied to the surfaces of structural elements using specialized inorganic mortars. Until recently the open weave fabrics for these systems normally consisted of carbon fibres, which led to comparatively poor utilization of the fibres due to fibre pullout at relatively low load levels. Fibre reinforced cementitious matrix (FRCM) systems, which are based on non-woven polybenzoxozole (PBO) fibre rovings, have more recently been introduced (Fallis 2009). The unique chemical structure of the PBO fibres allows them to bond directly to cementitious mortar matrices, thus eliminating the need for an epoxy resin to bond the fibres to an inorganic substrate (Fallis 2009). These PBO-based FRCM systems have several advantages over alternative systems such as externally-bonded fibre reinforced polymer (FRP) systems, most notably their breathability and superior performance in fire (in particular their non-combustibility). However, while these systems have been applied in several projects in Europe, research on both their ambient and high temperature performance in flexural strengthening applications remains scarce.

Strengthening RC or masonry structures with externally bonded FRPs is widely recognized for its effectiveness and ease of application (Bisby et al. 2008). FRP sheets or plates can be bonded to the exterior faces of RC members or masonry walls using ambient-cure epoxy adhesives. In these applications (and also in FRCM strengthening applications) the goal is to provide well-anchored supplementary tensile reinforcement to a reinforced concrete or masonry substrate. Either externally bonded FRP, TRM, or FRCM techniques can be used to provide shear or flexural strengthening for RC or masonry members (Triantafillou & Papanicolaou 2006, Fallis 2009) or for confinement and axial load enhancement of RC columns (Bournas et al. 2007).

A key issue in the design of any structural strengthening system for use in buildings is its mechanical and thermal performance during fire. Fire-rated, insulated externally bonded FRP strengthening systems have been tested and are now available for use (Kodur et al. 2006), although current design guidelines conservatively suggest that the structural effectiveness of FRP strengthening systems should be ignored during fire (ACI 2008) unless it can be shown (which has not yet been done for any currently available FRP system) that they would remain effective at the temperatures to be expected during a fire. Hence, applications of FRPs for strengthening concrete buildings, parking garages, and certain industrial structures with elevated service temperatures are hindered by a lack of knowledge regarding the ability of FRP systems to maintain structural effectiveness under service loads at high temperature.

It has been suggested (Fallis 2009) that TRM or FRCM systems may outperform FRP systems at elevated temperature or during fire due to their inherent non-combustibility, and possibly to superior strength retention at elevated temperatures. Limited studies on the performance of specific FRCM systems under sustained loads and exposure to temperatures up to 120°C have shown that these systems outperform FRP strengthening systems under these conditions (Ruredil 2009). This paper presents the results of testing conducted at ambient and mildly elevated temperatures (50°C or 80°C) specifically to compare the performance of a currently available FRCM structural strengthening system with two currently available FRP strengthening systems in flexural strengthening applications for reinforced concrete members.

In the context of performance in elevated temperature service environments it is important to note that a key advantage of FRCM systems is their inherent non-combustibility (Instituto Giordano 2008). Previous research on FRP strengthening systems in fire has shown that loss of the strengthening systems' mechanical performance during fire may not be critical provided that sensible strengthening limits are imposed during design of the strengthening system (ACI 2008). However, structural performance in fire is only one of a host of concerns that must be addressed when considering application of any structural material in a building. Fire severity, flame spread, and smoke generation and toxicity cannot be ignored since they are critical to preserving tenable conditions and to allow safe evacuation of a building's occupants in the early stages of a fire. Unprotected externally bonded FRP strengthening systems, all of which incorporate polymer adhesives/matrices, will burn vigorously if directly exposed to fire, will contribute fuel, increase flame spread, and generate toxic smoke. FRP strengthening systems therefore require protection by fire-rated flame-spread coatings in all interior applications in buildings to meet life-safety objectives. FRCM systems bonded with inorganic mortars are inherently non-combustible and can therefore be used unprotected; considerably reducing their material and installation costs and improving the aesthetics of the strengthening solution.

## OBJECTIVES

With the above points in mind, the objectives of the preliminary research study presented herein are:

(1) to experimentally investigate the relative performance at ambient temperature of EB FRP and FRCM flexural strengthening systems for RC structures (in bond-critical applications without supplemental anchorage); and

(2) to experimentally investigate the hypothesis that FRCM systems may provide superior retention of mechanical and/or bond properties at elevated temperatures, after short term exposure to an elevated service temperature environment, as compared against externally bonded FRP systems.

## TESTING PROGRAM

Research on the high temperature performance of both externally bonded and near surface mounted carbon/epoxy FRP strengthening systems has been presented previously (Bisby et al. 2008). This prior research has shown that both externally bonded and near surface mounted FRP strengthening systems, which rely on a polymer adhesive/matrix in bond-critical situations, are sensitive to exposure to temperatures between 45°C and 100°C in flexural strengthening applications when stressed to between 30% and 60% of their ultimate strength during heating (Bisby et al. 2008). Heating to temperatures above the glass transition temperature of polymer adhesives used in these applications (under sustained loads) typically results in rapid failure of both externally bonded and near surface mounted carbon FRP strengthening systems. The current study was therefore intend to investigate the comparative performance of FRP and FRCM systems within the range of the glass transition temperatures of currently available epoxy resin systems.

The tests performed for the current study were designed to be similar (with a few minor differences) to those used in previous in-house testing by the supplier of the FRCM strengthening system (Ruredil Spa, Milan, Italy), so that the results from the current testing could be used to corroborate this previous work. Details of the experimental program for the current study are given in Table 1. Thirty six unreinforced concrete beam specimens (prisms) were fabricated. Nine of these were strengthened in bending with a single layer of CFRP strengthening system Nº1, a commercially available EB carbon/epoxy unidirectional FRP fabric strengthening system currently selling in Italy, nine were strengthened in bending with a single layer of a different commercially available EB carbon/epoxy unidirectional FRP fabric strengthening system currently also selling in Italy (CFRP strengthening system Nº2), nine beams were strengthened using two layers of the proprietary Ruredil X Mesh Gold FRCM strengthening system, and nine beams were left unstrengthened and used as control specimens for defining the level of strengthening that was achieved for each of the respective systems.

All tests were performed under monotonic load to failure, in crosshead displacement control mode at 0.5 mm per minute. Table 1 provides an overview of the specific specimens, materials and systems, loading regimes, and parameters that were varied during the experimental program.

Table 1 Details of the experimental program.

| Specimen ID | Primer | Fibre system | Adhesive system | Target test temp. (°C)[4] | Duration of heating (hrs) | No. of beams |
|---|---|---|---|---|---|---|
| PC 20 | -- | -- | -- | 20 | -- | 3 |
| FRP Nº1 20 | Primer Nº1[1] | Carbon fibre[3] | Saturant Nº1[1] | | | 3 |
| FRP Nº2 20 | Primer Nº2[2] | Carbon fibre[3] | Saturant Nº2[2] | | | 3 |
| FRCM 20 | -- | X Mesh Gold | X Mesh M750 | | | 3 |
| PC 50 | -- | -- | -- | 50 | 6 | 3 |
| FRP Nº1 50 | Primer Nº1[1] | Carbon fibre[3] | Saturant Nº1[1] | | | 3 |
| FRP Nº2 50 | Primer Nº2[2] | Carbon fibre[3] | Saturant Nº2[2] | | | 3 |
| FRCM 50 | -- | X Mesh Gold | X Mesh M750 | | | 3 |
| PC 80 | -- | -- | -- | 80 | 6 | 3 |
| FRP Nº1 80 | Primer Nº1[1] | Carbon fibre[3] | Saturant Nº1[1] | | | 3 |
| FRP Nº2 80 | Primer Nº2[2] | Carbon fibre[3] | Saturant Nº2[2] | | | 3 |
| FRCM 80 | -- | X Mesh Gold | X Mesh M750 | | | 3 |

[1] Commercially available epoxy primer and saturant systems currently selling in Italy.
[2] Commercially available epoxy primer and saturant systems currently selling in Italy.
[3] Commercially available unidirectional carbon fibre fabric currently selling in Italy.
[4] Refer to Fig. 6.

## Beam specimens

The dimensions and details of the concrete beam specimens are provided in Fig. 1. The beams were designed, such that the results could be compared against previous in-house testing performed by the industrial partner. The compressive strength of the concrete at the time of testing was 41.0 MPa with a standard deviation of ±5.1 MPa at 20˚C, as determined from three uniaxial compression tests on standard 100 mm diameter by 200 mm tall concrete cylinders. There was no internal steel reinforcement whatsoever in the beams. All beams had a small, triangular (36 mm wide × 18 mm deep) notch at midspan to act as a crack initiator within the constant moment region during testing (see Figs 1 and 4).

Strengthening systems

Nine beams were left unstrengthened as control specimens and the remaining beams were strengthened with one of the two externally bonded carbon/epoxy FRPs or with the FRCM strengthening system. Surface preparation consisted of light grinding by hand (using an angle grinder) followed by high pressure water blasting. Table 1 provides details of the three specific strengthening systems used.

*Externally-bonded carbon/epoxy FRP systems*

As shown in Table 1 and Fig. 1, eighteen beams were strengthened with a single layer of one of two different externally bonded carbon/epoxy FRP strengthening systems using an epoxy primer and epoxy saturant/adhesive. The full width of the beams' soffits were plated with FRP. Both systems were applied using a wet lay-up procedure at ambient conditions (i.e. no post cure) in the laboratory. The primer was allowed to cure for 24 hours before the carbon FRP fabric (Ruredil X Wrap 310) was saturated and applied using a hand lay-up procedure. The beams were cured for four months in the laboratory (at room temperature and ambient relative humidity) prior to testing.

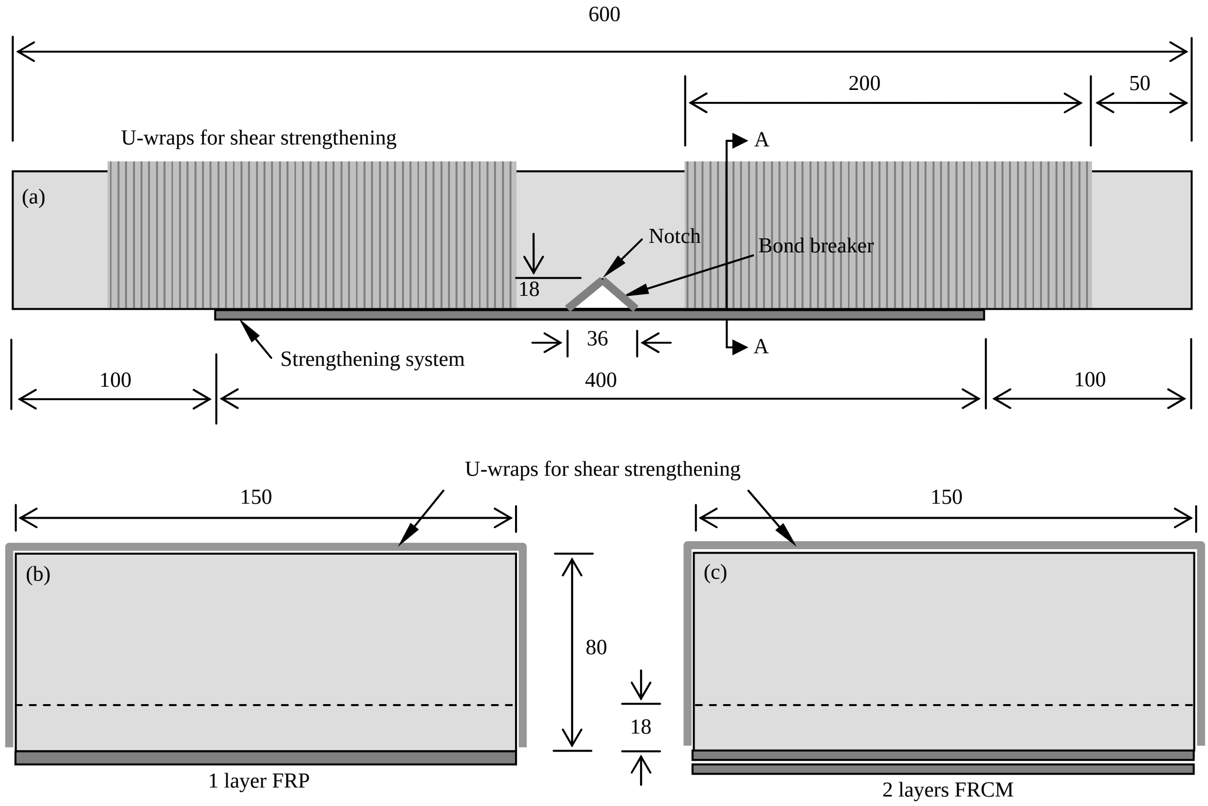



Fig. 1 Schematics showing (a) side elevation view of details of flexural test specimens and Section A-A views for (b) FRP strengthened and (c) FRCM strengthened specimens (all dimensions are in mm).

*Ruredil X Mesh Gold FRCM*

As shown in Table 1 and Fig. 1, nine beams were strengthened with the Ruredil X Mesh Gold FRCM strengthening system. The amount of FRCM fabric used to strengthen the beams (a full width of 150 mm with two layers on each beam as shown in Fig. 1) was chosen to provide a similar axial stiffness as the two CFRP strengthening systems, so as to achieve similar flexural stiffness as the FRP strengthened beams. The FRCM was installed using the following general procedure (refer to Fig. 2):

1. Once surface preparation was completed as described previously, the beam's surface was moistened with water to achieve a saturated-surface-dry (SSD) condition.

2. A bond breaker, consisting of polymer adhesive tape, was applied within the notch so as to prevent bond between the mortar and the concrete within the notch (and thus to allow the notch to function as a crack initiator) (refer to Fig. 2b).
3. The Ruredil X Mesh M750 mortar/adhesive was mixed using a hand drill with a mixing paddle (Fig. 2c) and a thin layer of mortar, approximately 4 mm thick, was applied to the beam's soffit (note that the beams were strengthened upside-down for ease of application).
4. One layer of open-weave Ruredil X Mesh PBO fabric (shown in Fig. 2a) was placed on the beam's soffit and gently pressed into the inorganic mortar using a finishing trowel (Fig. 2d).
5. A second 4 mm layer of mortar was applied to the surface of the beam.
6. A second layer of PBO mesh was gently pressed into the mortar.
7. A final topcoat of mortar, again approximately 4 mm thick, was applied (Fig. 2e).
8. The strengthened beams were allowed to cure under plastic sheets at approximately 20°C and ambient relative humidity for 48 hours before being stored in the laboratory under ambient conditions until testing (approximately three months later).

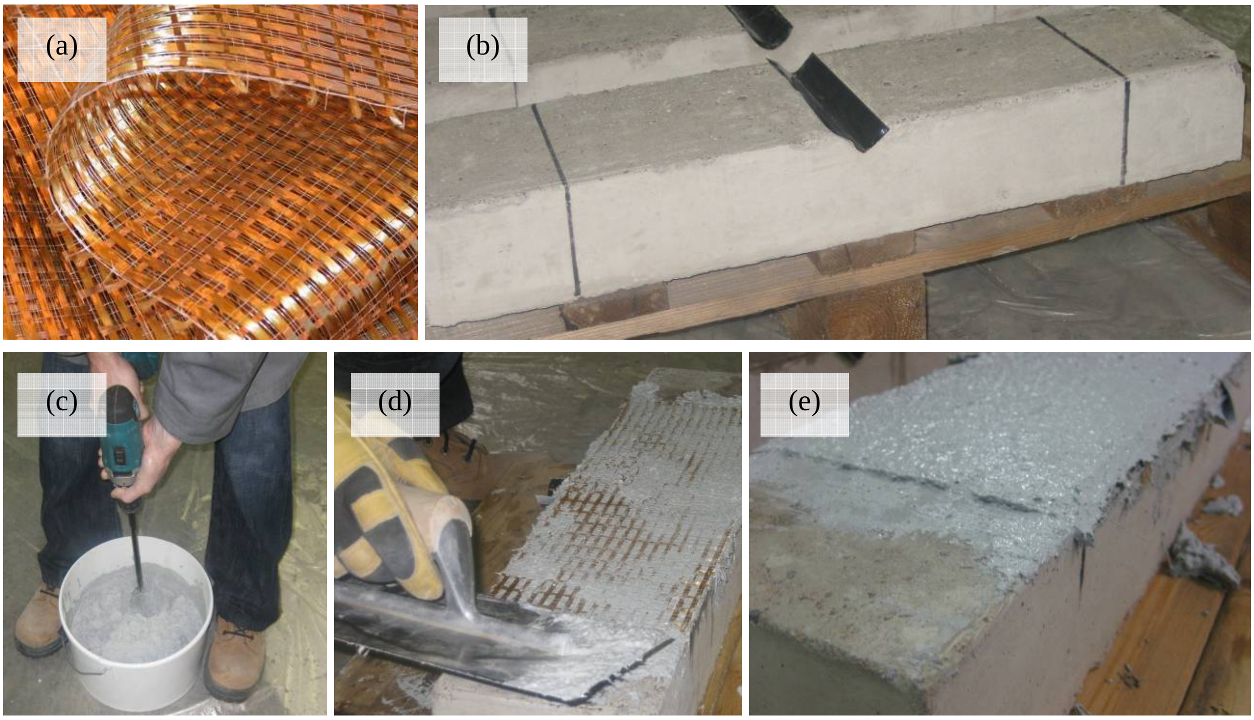



Fig. 2 (a) Open-weave PBO fibre fabric and (b, c, d, e) steps in the installation of the FRCM system.

Shear strengthening scheme (Retrofit)

Initial pilot tests performed on two FRP strengthened beams showed that at room temperature the strengthened beams experienced a shear failure mode which initiated at the end of the FRP strengthening system; this is shown schematically in Fig. 3, below.

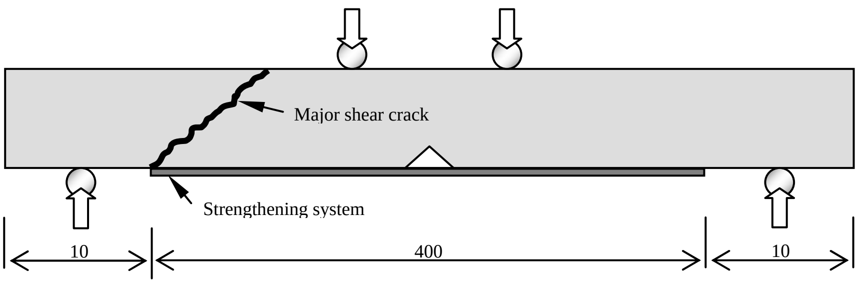



Fig. 3 Shear failure mode experienced in initial tests which led to the shear strengthening scheme used on the remaining specimens.

This type of failure was clearly undesirable, because it meant that the observed failure mode was largely independent of the strengthening system used at room temperature. To attempt to prevent this failure mode, without using typical U-wraps which would anchor the strengthening system (recall that the goal of the current study was to examine the effects of temperature on the performance of the respective strengthening systems in bond-critical applications *without* any supplemental anchorage), an inverted U-wrap shear strengthening scheme was applied to all remaining beams prior to testing (see Fig. 3). This consisted of a single layer of CFRP fabric bonded with epoxy saturant from the FRP Nº1 system. This shear strengthening scheme was not expected to influence bond failure of the FRP or FRCM strengthening systems, but would only contribute to marginally higher strengths for the beams and perhaps prevent premature shear failure (however the beams continued to fail in shear at room temperature despite the shear strengthening scheme, as described below).

Test setup, instrumentation and procedures

All 36 beams were tested in four-point bending as shown in Fig. 4. Conventional instrumentation was used to collect load (load cell), vertical displacement (crosshead stroke displacement), and temperature (thermocouples) data during testing (refer to Fig. 4). A total of 12 beams were tested at ambient temperature (3 of each type) to determine the level of strengthening achieved and the failure mode(s). All beams were tested monotonically under crosshead displacement control to failure, at a rate of 0.5 mm/min. The remaining 24 specimens tested monotonically under crosshead displacement control to failure at a rate of 0.5 mm/min, after being heated for six hours (without any applied load) in an electrical drying oven at either 50°C or 80°C. These temperatures, as well as the total heating time of six hours, were essentially arbitrary but were chosen so as to ensure a uniform member temperature prior to testing.

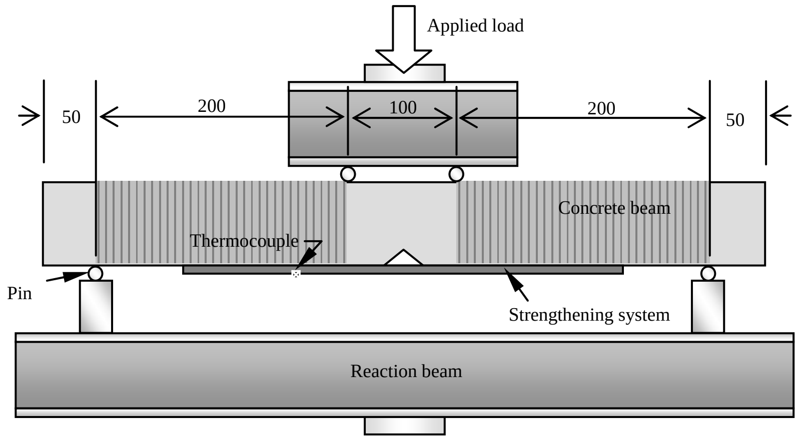



Fig. 4 Test setup and instrumentation (all dimensions are in mm).

EXPERIMENTAL RESULTS

The experimental results are divided into tests at ambient temperature, tests at 50°C, and tests at 80°C. Table 2 provides a numerical summary of the experimental results for all tests. The specific effects of elevated temperature exposure are discussed in a subsequent section.

Tests at ambient temperature (20°C)

Fig. 5 shows the total applied load versus midspan vertical deflection (based on crosshead stroke data) behaviour of all 12 beams tested at ambient temperature. The unstrengthened control beams (PC 20) displayed typical unreinforced flexural behaviour for concrete, with very low ultimate load due to failure as soon as the cracking moment was exceeded. These beams displayed a post-peak softening load-deflection response due to friction at the external supports (which allowed rotation but prevented lateral displacements), leading to mild arching action during the softening phase.

The strengthened beams exhibited strength increases of more than 1000% as compared with the unstrengthened control beams. Clearly, this amount of strengthening falls well above the levels that are permitted (or sensible) for design of FRP strengthening systems in real engineering applications (ACI 2008). Maximum allowable strength increases are normally in the range of 40 to 60%, depending on the ratio of live loads to dead loads. While it is highly unlikely that such a high level of strengthening would be attempted in practice, the very high level used in the current study was intentional since it allowed the authors to study the use of FRP and FRCM strengthening systems under a very severe loading application, such that any damage to the bond strength due to elevated temperature exposure would be easily observed. All strengthened beams tested at room temperature failed by sudden shear failure in the concrete outside the strengthened length (i.e. the remedial shear strengthening scheme was unsuccessful in preventing the undesirable shear failure). Failure initiated at the termination of the FRP (Fig. 3), with the strengthening systems remaining essentially intact in all cases. It was thus not possible to compare the relative bond strengths of the respective strengthening systems at ambient temperature.

Table 2. Summary of test results.

| Specimen ID | Ultimate load (kN) | Average ult. load ± std. dev. (kN) | Normalized load capacity[1] (%) | Average normalized load capacity ± std. dev. (%) | Failure mode[2] |
|---|---|---|---|---|---|
| PC 20-1 | 2.3 | | 10 | | FF |
| PC 20-2 | 2.4 | 2.2 ± 0.3 | 10 | 9 ± 1 | FF |
| PC 20-3 | 1.9 | | 8 | | FF |
| FRP Nº1 20-1 | 26.1 | | 107 | | SF |
| FRP Nº1 20-2 | 23.3 | 24.5 ± 1.4 | 95 | 100 ± 6 | SF |
| FRP Nº1 20-3 | 24.1 | | 98 | | SF |
| FRP Nº2 20-1 | 20.8 | | 85 | | SF |
| FRP Nº2 20-2 | 24.6 | 23.5 ± 2.4 | 100 | 96 ± 10 | SF |
| FRP Nº2 20-3 | 25.3 | | 103 | | SF |
| FRCM 20-1 | 24.1 | | 98 | | SF |
| FRCM 20-2 | 22.3 | 24.5 ± 2.4 | 91 | 100 ± 10 | SF |
| FRCM 20-3 | 27.1 | | 110 | | SF |
| PC 50-1 | 1.9 | | 8 | | FF |
| PC 50-2 | 2.1 | 1.8 ± 0.3 | 8 | 7 ± 1 | FF |
| PC 50-3 | 1.4 | | 6 | | FF |
| FRP Nº1 50-1 | 10.6 | | 43 | | DB |
| FRP Nº1 50-2 | 14.1 | 13.2 ± 2.3 | 58 | 54 ± 9 | DB |
| FRP Nº1 50-3 | 14.9 | | 61 | | DB |
| FRP Nº2 50-1 | 22.7 | | 93 | | SF |
| FRP Nº2 50-2 | 18.6 | 21.3 ± 2.3 | 76 | 87 ± 9 | SF |
| FRP Nº2 50-3 | 22.6 | | 92 | | SF |
| FRCM 50-1 | 21.8 | | 89 | | SF |
| FRCM 50-2 | 23.1 | 23.3 ± 1.6 | 94 | 95 ± 7 | SF |
| FRCM 50-3 | 25.0 | | 102 | | SF |
| PC 80-1 | 0.7 | | 3 | | FF |
| PC 80-2 | 1.5 | 1.4 ± 0.7 | 6 | 6 ± 3 | FF |
| PC 80-3 | 2.1 | | 8 | | FF |
| FRP Nº1 80-1 | | | 0 | | DB |
| FRP Nº1 80-2 | 6.8 | 5.9 ± 1.3 | 28 | 16 ± 14 | DB |
| FRP Nº1 80-3 | 5.0 | | 20 | | DB |
| FRP Nº2 80-1 | 8.9 | | 36 | | DB |
| FRP Nº2 80-2 | 9.7 | 8.9 ± 0.8 | 40 | 37 ± 3 | DB |
| FRP Nº2 80-3 | 8.2 | | 34 | | DB |
| FRCM 80-1 | 2.3 | | 10 | | SF |
| FRCM 80-2 | 2.4 | 2.2 ± 0.3 | 10 | 9 ± 1 | SF |
| FRCM 80-3 | 1.9 | | 8 | | SF |

[1] Determined based on the average strength of FRCM 20-1, FRCM 20-2, and FRCM 20-3.
[2] SF = shear failure in the concrete, DB = debonding initiating in the notch, FF = Flexural failure due to tensile rupture of the concrete in the notch.

The FRCM beams were slightly less stiff than the FRP strengthened beams, and displayed correspondingly larger midspan displacements prior to failure (refer to Fig. 5). The FRP strengthened beams showed a considerably stiffer post-cracking responses; this despite the fact that the FRCM strengthening system was designed on the basis of equivalent axial stiffness and had a slightly larger flexural lever arm (because of its additional installed thickness as compared to the FRP system). While the reasons for the less stiff response of the FRCM strengthened beams are not known with certainty, it seems likely that micro-cracking of the FRCM's cementitious mortar resulted in partial redistribution of tensile strains in the FRCM as the load increased, with a subsequent reduction in the system's effective flexural stiffness. Additional testing on beams of various depths/sizes with different levels of FRCM strengthening is required to verify this hypothesis. The two different FRP adhesive systems showed similar responses to each other. Typical shear failure modes for each type of beam at room temperature are shown in Fig. 9.

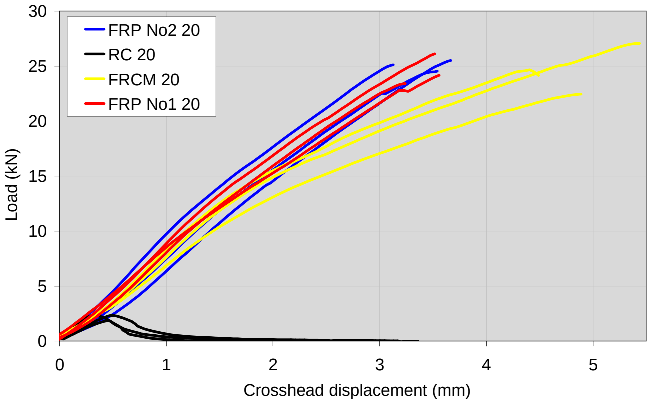



Fig. 5 Load versus vertical deflection at midspan for specimens tested at ambient temperature.

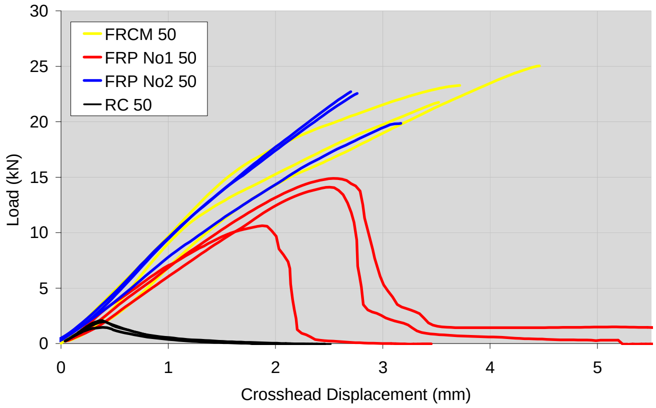



Fig. 7 Load versus vertical deflection at midspan for specimens tested at 50°C.

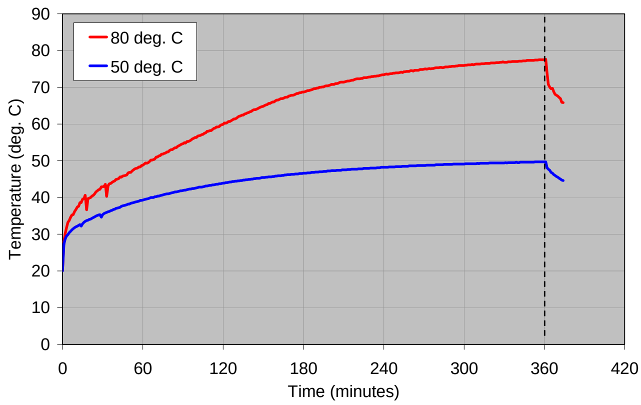



Fig. 6 Average surface temperature versus time of heating for specimens tested at target temperatures of 50°C and 80°C.

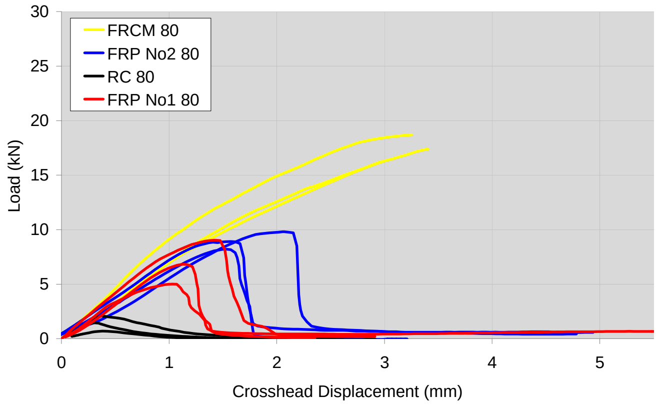
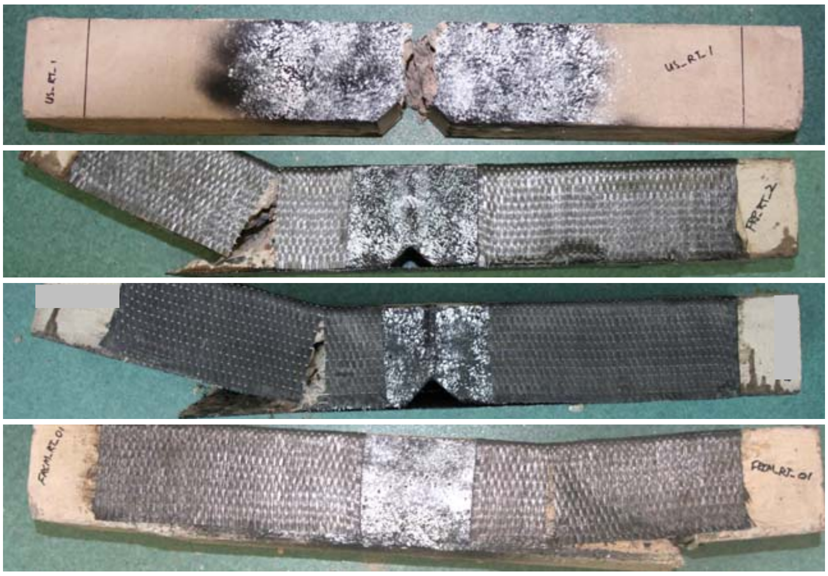



Fig. 8 Load versus vertical deflection at midspan for specimens tested at 80°C.

Tests at 50°C

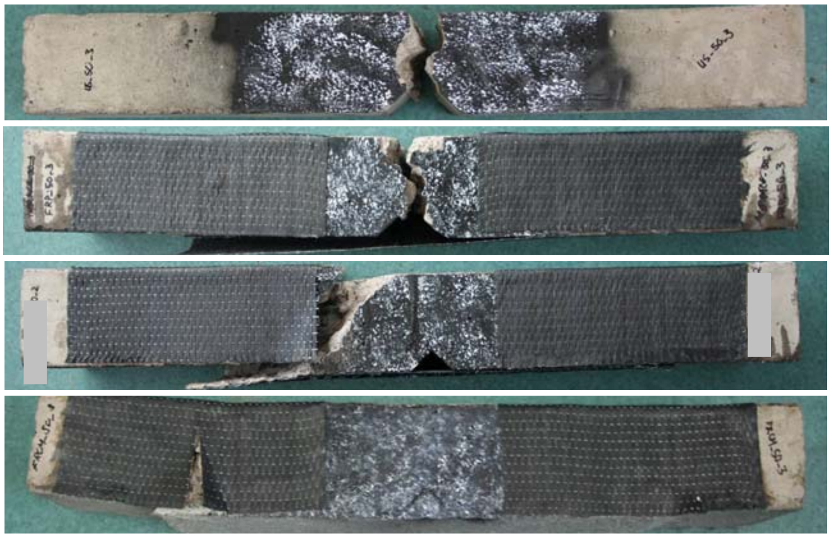
Fig. 6 shows traces of temperatures recorded on the surface of the strengthening system for typical beam heated for 6 hours to 50°C or for six hours to 80°C. The figure shows that the desired specimen temperature of 50°C was achieved after six hours, but that the specimens intended to reach 80°C actually reached peak temperatures of 78°C. The recorded temperatures were very similar in all cases and were not sensitive to the type of strengthening system applied to the beams. Fig. 6 also shows that the surface temperature of the applied strengthening system dropped by up to 10°C (for the 80°C tests) during testing (since the beams had to be removed from the oven and quickly placed in the testing frame and tested). However, it is unlikely that the bond line temperature dropped by more than one or two degrees during testing.

Fig. 7 shows the total applied load versus midspan vertical deflection behaviour of all 12 beams tested at 50°C. The unstrengthened control beams (PC 50) displayed similar behaviour as the unstrengthened beams tested at room temperature, although with slightly lower strength on average (discussed below). The strengthened beams again exhibited large strength increases compared with the unstrengthened control beams, however with lower ultimate strengths on average.



(a)
(b)
(c)
(d)

Fig. 9 Typical failure modes: (a) unstrengthened, (b) FRP Nº1, (c) FRP Nº2 & (d) FRCM at ambient.



(a)
(b)
(c)
(d)

Fig. 10 Typical failure modes: (a) unstrengthened, (b) FRP Nº1, (c) FRP Nº2 & (d) FRCM at 50°C.

(a)

(b)

(c)

(d)

Fig. 11 Typical failure modes: (a) unstrengthened, (b) FRP Nº1, (c) FRP Nº2 & (d) FRCM at 80°C.

At 50°C the FRCM beams were as (or more) strong and stiff as either of the FRP strengthened sets. The FRCM and FRP Nº2 strengthened beams again failed by sudden shear failure of the concrete beams, again initiating at the termination of the strengthening system (Fig. 3), with the strengthening systems remaining essentially intact. The FRCM beams were no longer less stiff than the FRP strengthened beams (refer to Fig. 7). The beams strengthened with FRP Nº1 experienced considerable reductions in strength and stiffness, and also displayed a debonding failure mode rather than shear failure of the concrete; this is clear evidence of softening of the adhesive and reductions in the FRP Nº1-concrete bond strength and stiffness at 50°C. Typical failure modes for each type of beam at 50°C are shown in Fig. 10.

<u>Tests at 80°C</u>

Fig. 8 shows the total applied load versus midspan vertical deflection behaviour of all 12 beams tested at 80°C. The unstrengthened control beams (PC 80) displayed similar behaviour as the unstrengthened beams tested at room temperature, although again with slightly lower strength on average. The strengthened beams again exhibited large strength increases compared with the unstrengthened control beams, although the strength increases were drastically reduced for both of the FRP strengthening systems, and slightly reduced for the FRCM strengthened beams.

At 80°C the FRCM strengthened beams were clearly the strongest and stiffest set. The FRCM strengthened beams continued to fail by sudden shear failure of the concrete beams, initiating at the termination of the strengthening system (Fig. 3), with the strengthening system apparently remaining intact. The beams strengthened with FRP Nº1 or FRP Nº2 experienced considerable reductions in strength and stiffness, and also displayed debonding failure modes rather than shear failure of the concrete; again, clear evidence of softening of the adhesive and major reductions in the FRP-concrete bond strength and stiffness at 80°C for both FRP systems. Failure modes for each type at 80°C are shown in Fig. 11.

## DISCUSSION: EFFECT OF TEMPERATURE

The effect of increasing temperature exposure on the respective strengthening systems is shown visually in Figs 12 (PC beams), 13a (FRP Nº1 strengthened beams), 13b (FRP Nº2 strengthened beams), and 13c (FRCM strengthened beams). These figures clearly demonstrate the superior performance of the FRCM strengthening system as compared with the FRP systems at both 50°C and 80°C. Fig. 14 compares the strengths of all beams tested in the current study, and also provides trend lines which represent the average strength for each type of beam at each exposure temperature. Again, the superior performance of the FRCM strengthened beams is clear. Fig. 15 shows the same data as are given in Fig. 14, although the data have been normalized against the average room temperature strength of the FRCM strengthened beams so as to give a relative comparison of the performance of the FRCM strengthened beams against the beams strengthened with FRP. Also shown in Fig. 15 is a horizontal line giving the approximate load level at which the beam failures transitioned from shear failure in the concrete outside the strengthened length to debonding failure of the strengthening system. This load level was about 65% of the room temperature average strength of the FRCM strengthened beams. Thus, any beam failing above the 65% line may not have experienced any reduction in strength of the strengthening system, since the failure was in the concrete.

Fig. 15 appears to indicate a reduction in strength of the FRCM system with increasing exposure temperatures. However, Fig. 16 shows the reduction in strength observed for the unstrengthened concrete beams, wherein a reduction in strength of about 15% was observed at 50°C and about 35% at 80°C. This suggests that the tensile strength of the plain concrete beams themselves was significantly reduced at these exposure temperatures. Since the FRCM strengthened beams continued to fail in shear at both 50°C and 80°C (with similar load capacity reduction magnitudes as those observed for the unstrengthened beams), it appears that the reduction in strength for the FRCM strengthened beams may represent a reduction in the tensile/shear strength of the concrete, rather than in the mechanical or bond properties of the FRCM system. Additional testing, at higher temperatures, would be required to clearly define the temperatures above which the FRCM system experiences reductions in mechanical and bond properties.

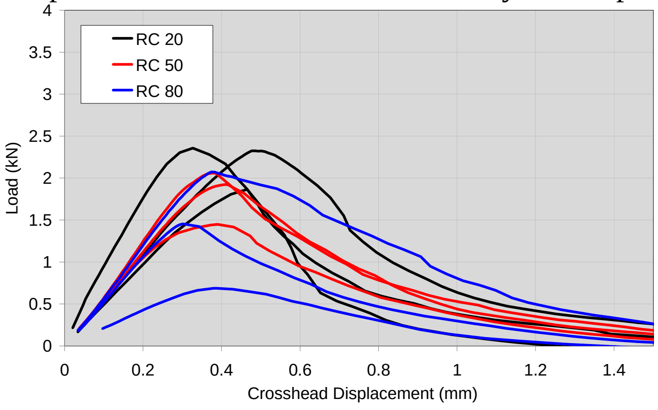



Fig. 12 Load versus vertical deflection at midspan for all unstrengthened specimens.

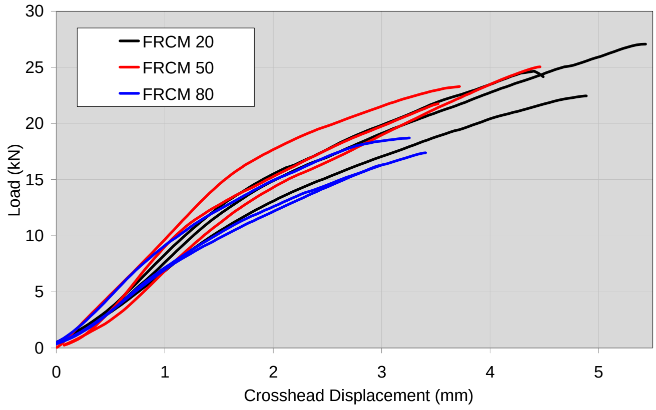
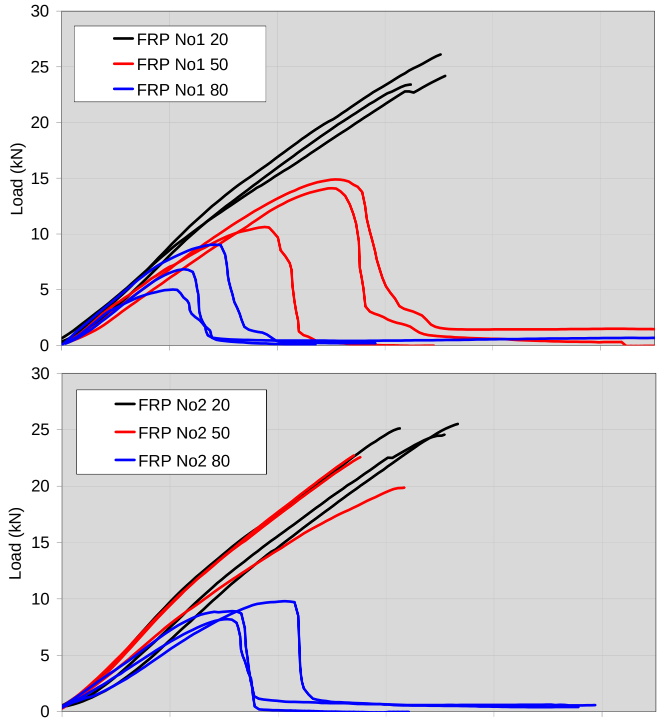



Fig. 13 Load versus vertical deflection at midspan for (a) all FRP Nº1 strengthened specimens, (b) all FRP Nº2 specimens, and (c) all FRCM specimens.



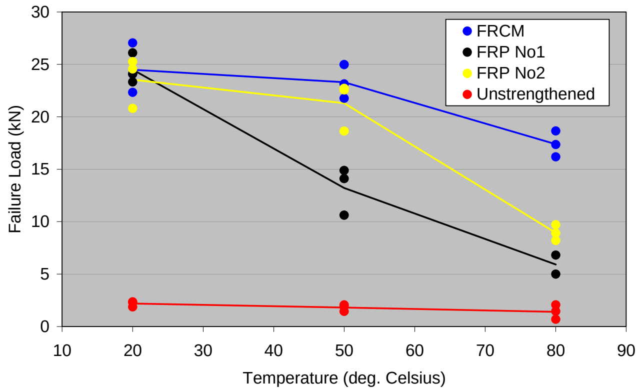




Fig. 14 Reductions in load capacity with increasing exposure temperature for all strengthened specimens (lines show averages).

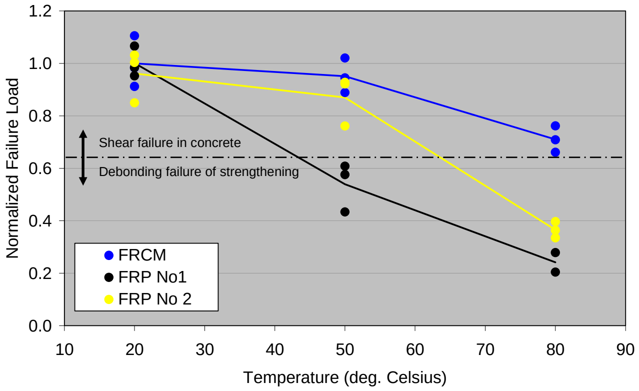



Fig. 15 Reductions in load capacity with increasing exposure temperature for all strengthened specimens (normalized to the average room temperature strength of the FRCM strengthened beams, lines show averages).

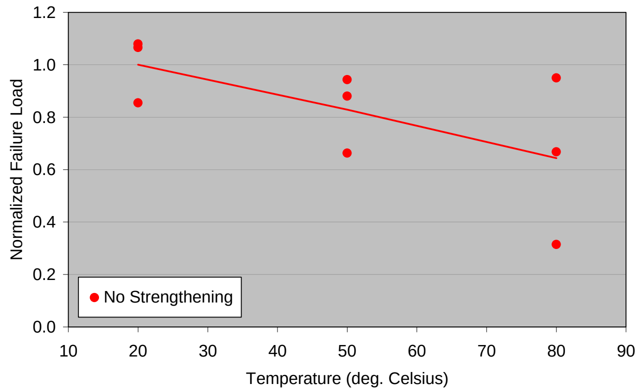



Fig. 16 Reductions in load capacity with increasing exposure temperature for unstrengthened specimens (normalized to ave. room temp. strength of unstrengthened beams, line shows average).

The comparable mechanical performance of FRCM systems with respect to FRP strengthening systems at ambient temperatures, and their superior performance in elevated temperature environments up to 80°C, combined with their inherent non-combustibility, makes them a very attractive option for structural strengthening, particularly in warm climates or in industrial environments with elevated service temperatures above the glass transition temperature of available FRP strengthening systems.

## CONCLUSIONS

The following conclusions can be drawn on the basis of the testing presented in this paper:

- The FRCM strengthening system studied herein can be effectively used, without supplemental anchorage, to strengthen RC beams in bending.
- Unlike currently available TRM systems based on carbon FRP textiles, the PBO-based FRCM system tested herein was able to provide similar strength enhancement as compared with an EB carbon/epoxy FRP strengthening system (although two layers were needed compared with a single layer for the FRP).
- The FRP Nº1 strengthening system experienced strength reductions of 52% at 50°C and 74% at 80°C.
- The FRP Nº2 strengthening system experienced strength reductions of 10% at 50°C and 64% at 80°C.
- The Ruredil X Mesh Gold FRCM strengthening system experienced strength reductions of 6% at 50°C and 28% at 80°C. However, the tensile strength of the plain concrete was clearly reduced at these exposure temperatures. Since the FRCM strengthened beams continued to fail in shear at both 50°C and 80°C it the reduction in strength for the FRCM strengthened beams may represents a reduction in the strength of the concrete rather than damage to the FRCM system.
- The FRCM system tested herein appears to be a strong candidate for use in strengthening applications where exposure to elevated service temperatures in the range of 50°C to 80°C is a realistic concern. Its inherent non-combustibility and superior performance at temperatures up to 80°C make it an attractive system for structural strengthening in buildings.

## ACKNOWLEDGEMENTS

The Scottish Funding Council is acknowledged for its support of the Joint Research Institute, part of the Edinburgh Research Partnership in Engineering and Mathematics (ERPem). The authors would like to acknowledge the financial, physical, and technical support of Ruredil Spa, Milan, Italy. We would also like to thank the School of Engineering, University of Edinburgh, Derek Jardine, and Jim Hutcheson. L Bisby gratefully acknowledges the support of the Ove Arup Foundation and the Royal Academy of Engineering.

REFERENCES


ACI (2008), *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, 440.2R-08*. American Concrete Institute.

Bisby, L., Burke, P. & Green, M. (2008), Comparative performance of externally-bonded and near surface mounted FRP strengthening systems at high temperatures. *5th Int. Conf. on Advanced Comp. Mat. in Bridges & Struct.*, Winnipeg, Canada, September 22-24.

Bournas, D.A., Lontou, P.V., Papanicolaou, C.G. & Triantafillou, T. (2007), Textile-reinforced mortar versus FRP confinement in reinforced concrete columns. *ACI Struct. J.*, 104(6): 740-748.

Fallis, G.J. (2009), Innovation for renovation: Cementitious matrix is used to bond high-strength polymeric mesh to concrete and masonry. *Concrete Int.*, 31(4): 62-64.

Instituto Giordano (2008), *Classification Report No. 237540: Classification of reaction to fire of construction products in accordance with UNI EN 13501-1:2007*.

Kodur, V.K.R., Bisby, L.A. & Green, M.F., FRP retrofitted concrete under fire conditions. *Concrete Int.*, 28(12): 37-44.

Ruredil (2009), *X Mesh Gold Data Sheet*. Ruredil SPA, Milan, Italy.

Triantafillou, T.C. & Papanicolaou, C.G. (2006), Shear strengthening of reinforced concrete members with textile reinforced mortar jackets. *Mat. & Struct.*, 39(1): 93-103.