EXPERIMENTAL PROGRAMME

Prior research on the high temperature performance of externally bonded carbon/ epoxy FRP strengthening systems (Bisby et al., 2008) has shown that these systems are sensitive to exposure to temperatures in the range of their glass transition temperature (T_g). In flexural strengthening applications, when stressed to between 30% and 60% of their ultimate strength during heating (Bisby et al., 2008), exposure to temperatures of 45ºC (113ºF) to 100ºC (212ºF) can rapidly lead to failure by debonding due to softening of the epoxy adhesive. The temperature exposures chosen for the current research were therefore within the range of the T_g of currently available epoxy resin systems, and represent elevated service temperature environments or temperatures likely to be experienced by an insulated strengthening system during the early stages of a fire.

Details of the experimental program for the current study are given in Table 1. Thirty six concrete beams (unreinforced rectangular prisms) were fabricated from a single batch of concrete; nine of these were strengthened in bending with a single layer of CFRP strengthening system 1 (FRP1), 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 (FRP2) currently selling across Europe and North America, nine were strengthened using two layers of the FRCM system manufactured under the name Ruredil X Mesh Gold, and nine were left unstrengthened as control specimens. All beams were tested in triplicate to verify repeatability of the test results.

Table 1—Details of experimental programme.

Name	No. beams	Primer	Fibers	Adhesive/ matrix	Target soak temperature °C (ºF)[6]	Heating duration (hrs)
PC 20	3	--	--	--	20 (68)	--
FRP1 20	3	Primer 1[1]	Carbon fiber[3]	Saturant 1[1]		
FRP2 20	3	Primer 2[2]	Carbon fiber[3]	Saturant 2[2]		
FRCM 20	3	--	PBO fiber[4]	Mortar[5]		
PC 50	3	--	--	--	50 (122)	6
FRP1 50	3	Primer 1[1]	Carbon fiber[3]	Saturant 1[1]		
FRP2 50	3	Primer 2[2]	Carbon fiber[3]	Saturant 2[2]		
FRCM 50	3	--	PBO fiber[4]	Mortar[5]		
PC 80	3	--	--	--	80 (176)	6
FRP1 80	3	Primer 1[1]	Carbon fiber[3]	Saturant 1[1]		
FRP2 80	3	Primer 2[2]	Carbon fiber[3]	Saturant 2[2]		
FRCM 80	3	--	PBO fiber[4]	Mortar[5]		

[1] Commercially available epoxy primer and saturant systems currently selling in Italy.
[2] Commercially available epoxy primer and saturant systems currently selling in Europe and North America.
[3] Ruredil X Wrap 310 fabric (www.ruredil.it).
[4] Ruredil X Mesh Gold fabric (www.ruredil.it).
[5] Ruredil M750 mortar (www.ruredil.it).
[6] Refer to Fig. 6.

Concrete beam specimens

Dimensions and details of the concrete beams are provided in Figure 1. These were designed such that the results could be compared against previous testing performed by the industrial partner. The compressive strength of the concrete at the time of testing, as determined from three uniaxial compression tests on standard 100mm (4in) diameter by 200mm (8in) tall cylinders, was 41.0MPa (5950 psi) with a standard deviation of ±5.1MPa (740psi) at 20˚C (68ºF). No internal steel reinforcement was provided. All beams had a small, triangular 36mm (1.4in) wide × 18mm (0.71in) deep notch at midspan to act as a crack initiator. The beams were three months old at the time of strengthening.

Strengthening systems

Nine beams were left unstrengthened as control specimens; the remaining beams were strengthened with one of the two externally bonded carbon/epoxy FRP systems or with the FRCM system. Surface preparation consisted of light abrasion with an angle grinder followed by high pressure water blasting.

Externally-bonded carbon/epoxy FRP systems—As shown in Table 1 and Figure 1, eighteen beams (nine with each of the respective FRP systems) were strengthened with a single layer of carbon/epoxy FRP strengthening system using an epoxy primer and epoxy saturant/adhesive. The full widths of the beams' soffits were plated with FRP. Both FRP systems were applied using a hand lay-up procedure at room temperature and ambient relative humidity. The primer was applied to the beams soffits and was allowed to cure for 24 hours before the carbon FRP fabric (Ruredil X Wrap 310 in both cases) was saturated using paddle rollers and applied with the beams oriented upside-down. The beams were cured for four months in the laboratory at room temperature and ambient relative humidity prior to testing.

FRCM system—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 150mm (6in) with two layers on each beam, as shown in Figure 1 – was selected to provide similar axial stiffness of the strengthening system as for the FRP strengthened beams; this was done to achieve comparable flexural stiffness as the beams with FRP.

The FRCM was installed according to the manufacturer's recommendations. After the surface preparation was completed the beam's surface was moistened with water to achieve a saturated-surface-dry condition. A bond breaker consisting of polymer adhesive tape was applied within the notch to prevent bond between the adhesive mortar and the concrete, allowing the notch to act as a crack initiator (refer to Figure 2(a)). The mortar was mixed using a hand drill with a mixing paddle, and an approximately 4mm (0.16in) layer of mortar was applied to the beam's soffit (again, the beams were strengthened upside-down for ease of application). One layer of open-weave PBO fabric was placed on the beam's soffit and gently pressed into the mortar using a finishing trowel (Figure 2(b)). A second 4mm (0.16in) layer of mortar was applied to the surface of the beam, and a second layer of PBO mesh was gently pressed into the mortar. Finally, a final topcoat of mortar approximately 4mm (0.16in) thick was applied (Fig. 2(c)). The strengthened beams were allowed to cure under plastic sheets at approximately 20°C (68°F) and ambient relative humidity for 48 hours before being stored in the laboratory under ambient conditions until testing (approximately three months later).

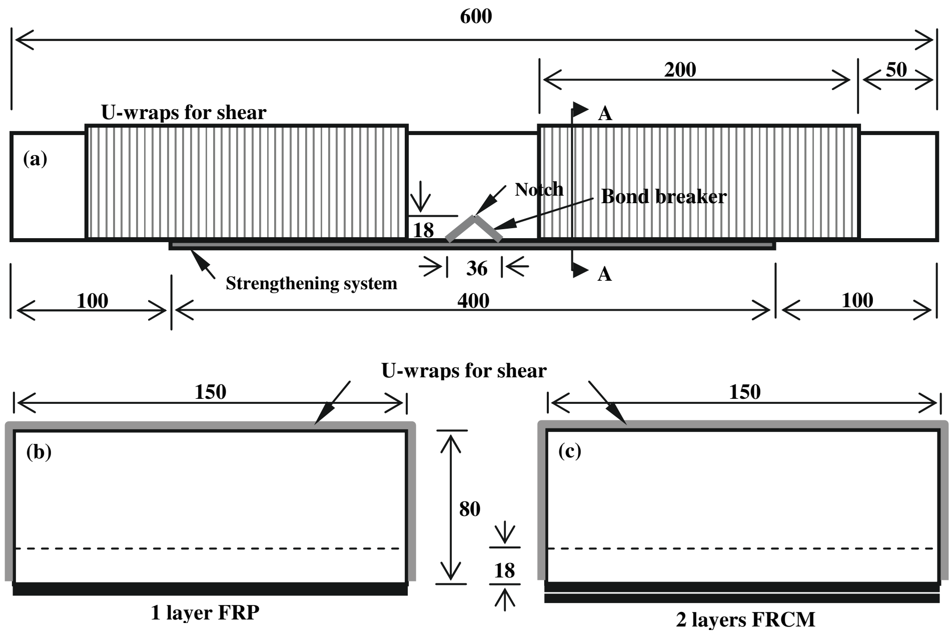

Figure 1—Schematics showing (a) side elevation view of details of flexural test specimens and Section A-A views for (b) FRP strengthened and (c) FRCM strengthened specimens (all dimensions are in mm, 1in = 25.4mm).

<u>Remedial shear strengthening</u>

Initial pilot tests performed on two FRP strengthened beams showed that the strengthened beams tested at room temperature experienced an undesirable global shear failure mode. A shear crack initiated at the end of the FRP strengthening system, as shown in Figure 3, and resulted in sudden failure of the beams outside the strengthened area. This failure mode is undesirable since it means that failure is largely independent of the strengthening system used (FRP1, FRP2, or FRCM). In an attempt to prevent this failure mode in subsequent tests an inverted U-wrap shear strengthening scheme was applied to all remaining beams prior to testing (refer to Figure 1). Inverted U-wraps, while clearly not as effective as conventional U-wraps, were used so as to avoid anchoring the flexural strengthening systems and to permit examination of the effects of temperature on the performance of the respective systems in bond-critical applications.

In all cases the inverted U-wraps consisted of a single layer of Ruredil X Wrap 310 CFRP fabric saturated and bonded with epoxy saturant from the FRP1 system. The shear strengthening scheme was not expected to significantly influence bond failure of the FRP or FRCM strengthening systems but was expected only to contribute to marginally higher strengths for the beams and perhaps prevent premature global shear failure prior to debonding of the strengthening systems.

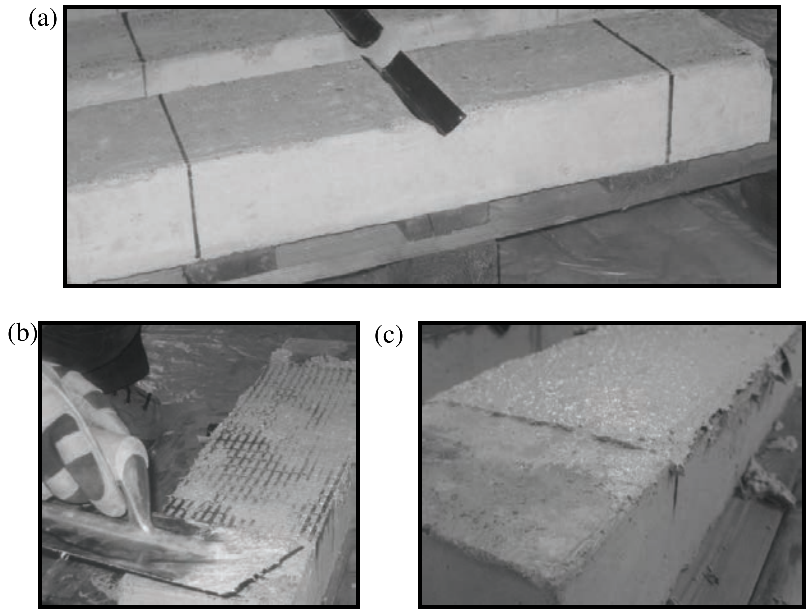

Figure 2—Steps in the installation of the FRCM system.

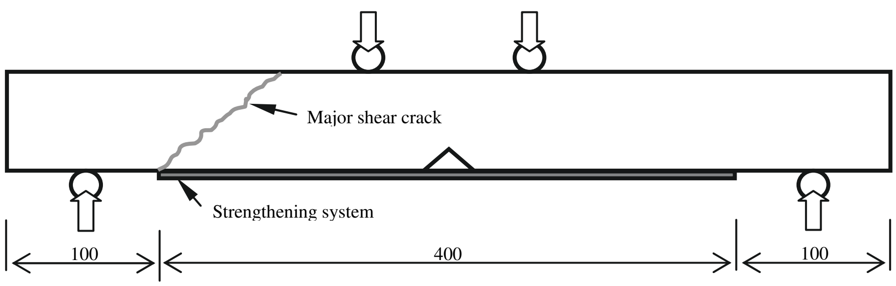

Figure 3—Shear failure mode experienced in initial tests (all dim. in mm, 1in = 25.4mm).

Test setup, instrumentation and procedures

All 36 beams were tested monotonically to failure in four-point bending with the setup shown in Figure 4. Load, vertical displacement (crosshead stroke), and strengthening system temperature were all recorded during testing. Three beams of each type were tested at room temperature to determine the level of strengthening achieved and the room temperature failure modes. All beams were tested under crosshead displacement control to failure at a rate of 0.5mm/min (0.020 in/min). The remaining 24 specimens were tested under crosshead displacement control at a rate of 0.5 mm/min (0.020 in/min) after being heated for six hours (without any applied load) in a convection drying oven at either 50°C (122°F) or 80°C (176°F). These temperatures as well as the total heating time of six hours were essentially arbitrary but were chosen so as to ensure uniform member temperatures above, below, and in the region of T_g during testing.

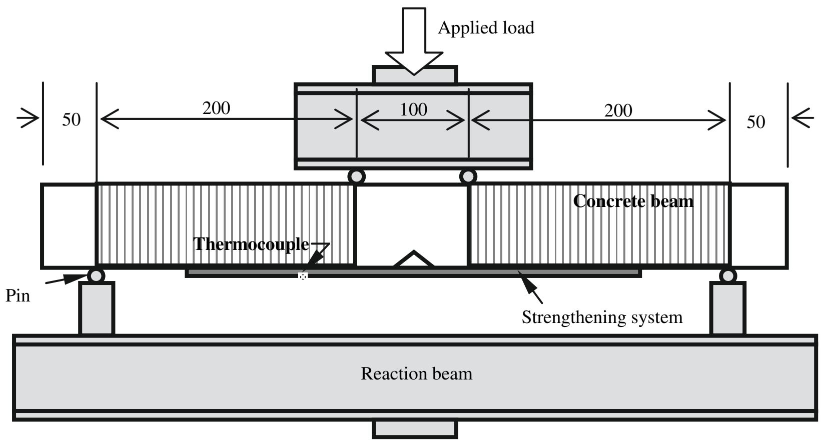

Figure 4—Test setup and instrumentation (all dimensions in mm, 1in = 25.4mm).

RESULTS

Tests at 20°C (68°F)

Table 2 provides a full numerical summary of the test data. Figure 5 shows the total applied load versus vertical deflection (crosshead stroke) behavior for all 12 beams tested at 20°C (68°F). The unstrengthened control beams (PC 20) displayed typical unreinforced flexural behavior for concrete with very low ultimate loads due to failure as soon as the cracking moment was exceeded. All PC 20 beams displayed post-peak softening load-deflection responses due to frictional longitudinal restraint at the support points; these allowed rotation but prevented lateral displacements leading to mild arching action and causing the softening phase rather than immediate failure.

The strengthened beams exhibited strength increases of more than 1000% as compared with the unstrengthened control beams. This amount of strengthening falls well above sensible strengthening levels that are permitted for design of FRP strengthening systems in real situations (ACI, 2008); strength increases for internally reinforced concrete elements are normally limited to less than about 60% depending on the imposed-to-permanent load ratio. While it is therefore unlikely that such a high level of strengthening would be attempted in practice, it was intentional in the current study since it allowed examination of the use of FRP and FRCM strengthening systems as *primary* reinforcement, such that damage to the bond strength or mechanical properties of the strengthening system due to elevated temperature exposure would be clearly observed.

Table 2—Numerical summary of test data.

Specimen ID	Ultimate load kN (kips)	Ave. ult. load ± std. dev. kN (kips)	Normalized load capacity[1] (%)	Ave. normalized load capacity ± std. dev. (%)	Failure mode[2]
PC 20-1	2.3 (0.52)	2.2 ± 0.3 (0.49 ± 0.07)	10	9 ± 1	FF
PC 20-2	2.4 (0.54)		10		FF
PC 20-3	1.9 (0.43)		8		FF
FRP1 20-1	26.1 (5.87)	24.5 ± 1.4 (5.51 ± 0.31)	107	100 ± 6	SF
FRP1 20-2	23.3 (5.24)		95		SF
FRP1 20-3	24.1 (5.42)		98		SF
FRP2 20-1	20.8 (4.68)	23.5 ± 2.4 (5.28 ± 0.54)	85	96 ± 10	SF
FRP2 20-2	24.6 (5.53)		100		SF
FRP2 20-3	25.3 (5.69)		103		SF
FRCM 20-1	24.1 (5.42)	24.5 ± 2.4 (5.51 ± 0.54)	98	100 ± 10	SF
FRCM 20-2	22.3 (5.01)		91		SF
FRCM 20-3	27.1 (6.09)		110		SF
PC50-1	1.9 (0.43)	1.8 ± 0.3 (0.40 ± 0.07)	8	7 ± 1	FF
PC50-2	2.1 (0.47)		8		FF
PC50-3	1.4 (0.31)		6		FF
FRP1 50-1	10.6 (2.38)	13.2 ± 2.3 (2.97 ± 0.52)	43	54 ± 9	DB
FRP1 50-2	14.1 (3.17)		58		DB
FRP1 50-3	14.9 (3.35)		61		DB
FRP2 50-1	22.7 (5.10)	21.3 ± 2.3 (4.79 ± 0.52)	93	87 ± 9	SF
FRP2 50-2	18.6 (4.18)		76		SF
FRP2 50-3	22.6 (5.08)		92		SF
FRCM 50-1	21.8 (4.90)	23.3 ± 1.6 (5.24 ± 0.36)	89	95 ± 7	SF
FRCM 50-2	23.1 (5.19)		94		SF
FRCM 50-3	25.0 (5.62)		102		SF
PC 80-1	0.7 (0.15)	1.4 ± 0.7 (0.31 ± 0.16)	3	6 ± 3	FF
PC 80-2	1.5 (0.34)		6		FF
PC 80-3	2.1 (0.47)		8		FF
FRP1 80-1	5.9 (1.32)	5.9 ± 1.3 (1.12 ± 0.29)	0	16 ± 14	DB
FRP1 80-2	6.8 (1.53)		28		DB
FRP1 80-3	5.0 (1.12)		20		DB
FRP2 80-1	8.9 (2.00)	8.9 ± 0.8 (2.00 ± 0.18)	36	37 ± 3	DB
FRP2 80-2	9.7 (2.18)		40		DB
FRP2 80-3	8.2 (1.84)		34		DB
FRCM 80-1	17.4 (3.91)	17.5 ± 1.2 (3.92 ± 0.27)	71	71 ± 5	SF
FRCM 80-2	18.7 (4.20)		76		SF
FRCM 80-3	16.3 (3.66)		66		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.

All strengthened beams tested at room temperature (FRP1 20, FRP2 20, and FRCM 20) failed by sudden shear failure in the concrete without any influence of the strengthening systems (i.e. the remedial shear strengthening scheme discussed previously was not successful at preventing the undesirable shear failures). Failure initiated at the termination of the FRP in most cases (Figure 3) with the strengthening systems remaining essentially intact. Since no bond failures were observed at 20ºC (68ºF) it was not possible to directly compare the bond strengths of the strengthening systems at this temperature.

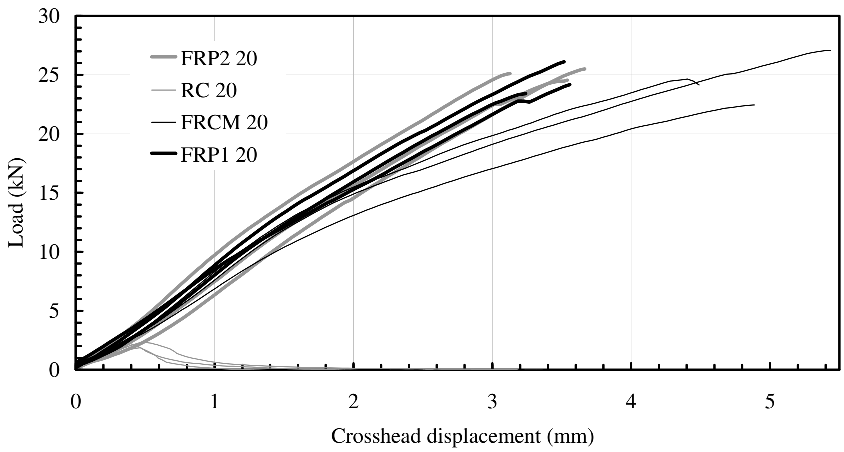

Figure 5—Load vs vertical crosshead stroke for beams tested at 20ºC (68ºF).

The FRCM beams were slightly less stiff than the FRP strengthened beams and displayed correspondingly larger midspan displacements (on average approximately 40% larger) prior to failure (refer to Figure 5). The FRP strengthened beams showed a considerably stiffer post-cracking response; 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 due to its installed thickness being about 6 mm more than the FRP systems. The reasons for this remain unclear, although it seems likely that micro-cracking of the FRCM's cementitious mortar resulted in partial redistribution of tensile strains in the PBO fibers as the load increased, with a subsequent reduction in the system's effective axial stiffness. Tests on beams of various depths and sizes with different levels of FRCM strengthening are needed to verify this hypothesis and to better understand the mechanical response of the FRCM systems to loading. The two FRP systems demonstrated similar responses. Typical 20ºC (68ºF) failure modes for each type of beam are shown in Figure 6, where the undesirable shear failures are clearly evident, despite the remedial shear strengthening scheme.

Tests at 50°C (122ºF)

Figure 7 shows typical temperature profiles recorded during heating on the surface of the strengthening systems for both temperature conditions. The desired temperature of 50°C (122ºF) was achieved during the 6 hour preconditioning regime, whereas the specimens 80°C (176ºF) exposure actually achieved peak temperatures of 78°C (172ºF).

The beam temperatures were not sensitive to the type of strengthening used. Figure 7 also shows that the surface temperature of the applied strengthening system, which was recorded by a thermocouple bonded to the surface of the beam with high temperature aluminium adhesive tape, fell by up to 10°C (18°F) during structural testing (since the beams had to be removed from the oven and placed in the testing frame outside the oven).

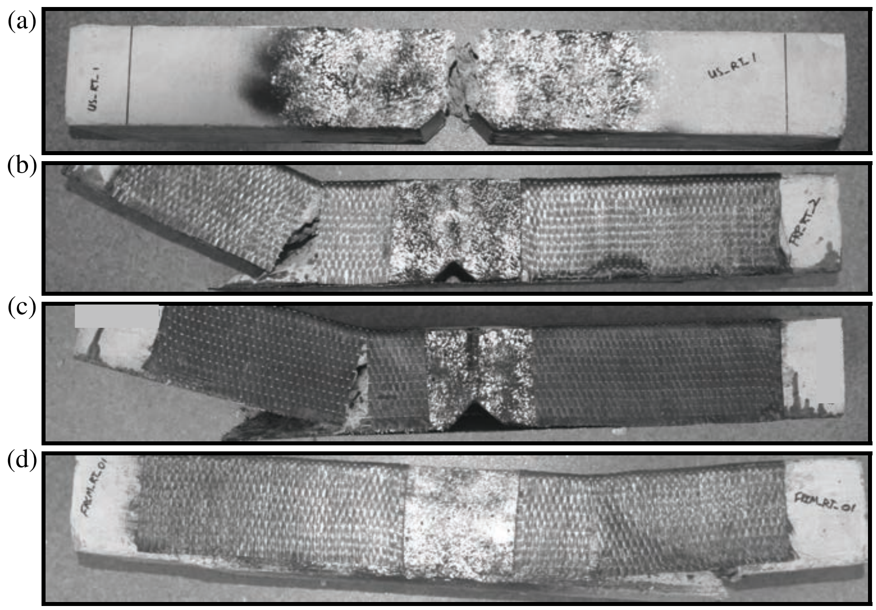

Figure 6—Typical 20ºC (68ºF) failures: (a) control, (b) FRP1, (c) FRP2, and (d) FRCM.

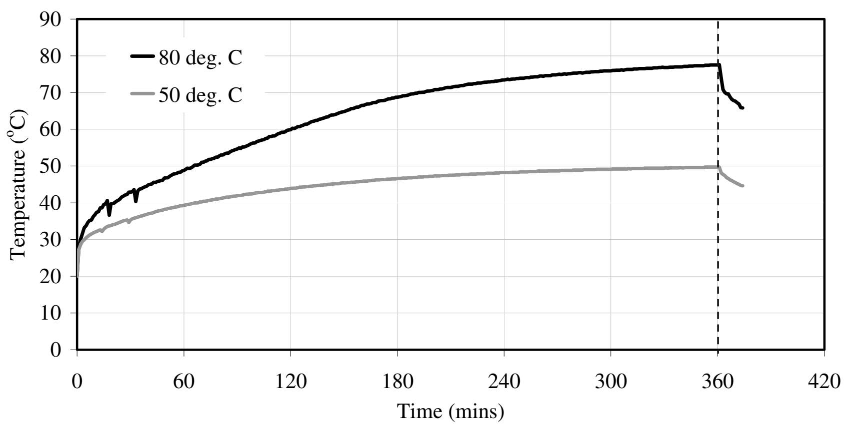

Figure 7—Average surface temperature vs time of heating for specimens tested at target temperatures of 50°C (122°F) and 80°C (176°F).

Figure 8 shows the total applied load versus crosshead stroke behavior for all beams tested at 50°C (122ºF). The unstrengthened beams (PC 50) displayed virtually identical behavior as the PC 20 beams but with slightly lower strength on average. The FRCM beams were as (or more) strong and stiff than any of the FRP strengthened beams tested at 50°C (122°F). The FRCM and FRP2 strengthened beams again failed by sudden shear failure of the concrete beams, again typically initiating at the termination of the strengthening system with the strengthening system remaining essentially intact. FRP1 beams experienced considerable reductions in strength and stiffness, and also experienced a change of failure mode from global shear failure of the concrete to debonding failure of the strengthening system followed by flexural failure of the beam at midspan. This change in failure mode is clear evidence of softening of the adhesive and reductions in the FRP1-to-concrete bond strength and stiffness at 50°C (122°F). Typical failure modes for each type of beam at 50°C (122°F) are shown in Figure 9.

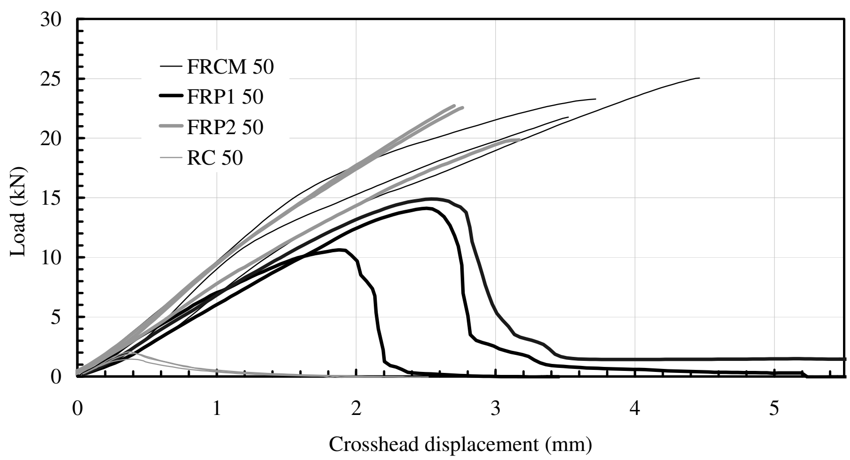

Figure 8—Load vs vertical crosshead stroke for beams tested at 50ºC (122ºF).

Tests at 80°C

Figure 10 shows the total applied load versus vertical crosshead displacement for all beams tested at 80°C (176ºF). Again the unstrengthened beams displayed similar behavior as the unstrengthened beams tested at 20°C (68ºF), although again with lower strength on average. The strengthened beams exhibited large strength increases compared with the unstrengthened control beams, although the increases were considerably reduced for both FRP systems and also slightly reduced for the FRCM system. FRCM 80 beams were strongest and stiffest at this temperature; they continued to fail by sudden shear failure of the concrete beams initiating at the termination of the strengthening system and with the strengthening system remaining intact. FRP1 80 and FRP2 80 beams experienced considerable reductions in both strength and stiffness. All FRP strengthened beams tested at 80°C (176ºF) failed by debonding rather than shear failure of the concrete – clear evidence of softening of the adhesive and major reductions in the FRP-concrete bond strength and stiffness. Typical failures at 80°C (176ºF) are shown in Figure 11.

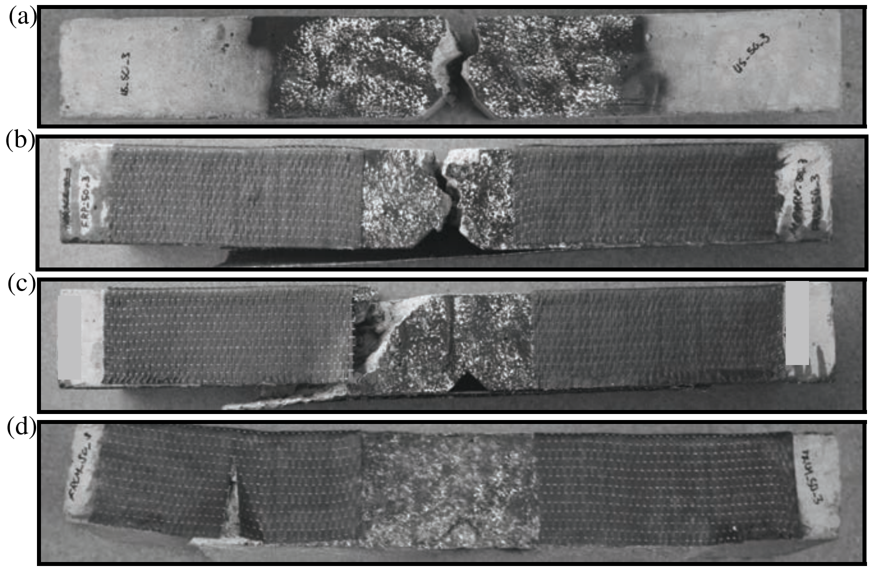

Figure 9—Typical 50ºC (122ºF) failures: (a) control, (b) FRP1, (c) FRP2, and (d) FRCM.

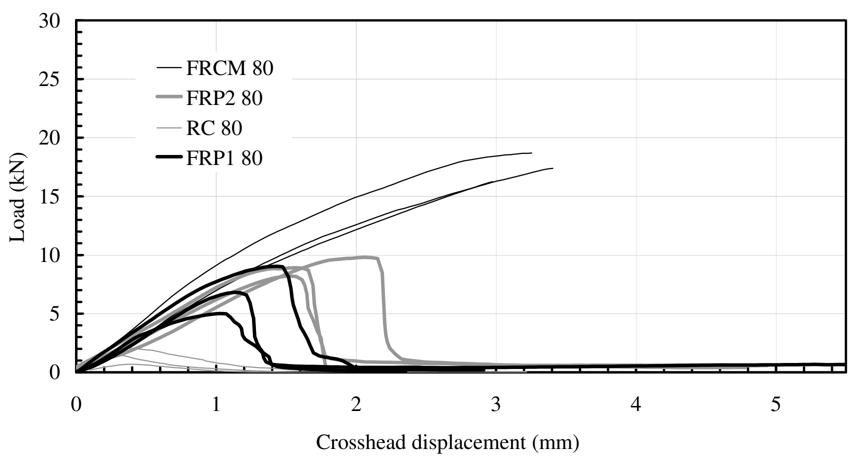

Figure 10—Load vs vertical crosshead stroke for beams tested at 80ºC (176ºF).

EFFECT OF TEMPERATURE

The specific effect of temperature on the respective strengthening systems is shown by visual comparison in Figures 12 and 13. Figure 12 provides a visual comparison of the strengths of all tested beams and includes trend lines tracking the average strength for each type of beam at each temperature. The superior performance of the FRCM strengthening system as compared with the FRP systems at 50°C (122ºF) and 80°C (176ºF) is clear. Figure 13 shows the same data as Figure 12 however the data have been