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Effects of elevated temperature on near surface mounted and externally bonded FRP strengthening systems for concrete

Paul J. Burke [a], Luke A. Bisby [b,*], Mark F. Green [c]

[a] Harbourside Engineering Consultants, 17 Prince Street, Dartmouth, Nova Scotia, Canada B2Y 4W2
[b] BRE Centre for Fire Safety Engineering, University of Edinburgh, The King's Buildings, Edinburgh EH9 3JL, UK
[c] Department of Civil Engineering, Queen's University, 58 University Avenue, Kingston, Ontario, Canada K7L 3N6

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ABSTRACT

Near surface mounted (NSM) fibre reinforced polymer (FRP) reinforcement is an effective technology for strengthening concrete structures in both flexure and shear, and has numerous advantages over externally bonded FRP. Available research on NSM systems for concrete has focused predominantly on overall member behaviour and/or parameters affecting NSM bond performance; relatively little research has been performed to study the response of NSM systems at elevated temperatures, as would be experienced during a fire. All FRP strengthening systems are susceptible to deterioration of mechanical and bond properties at elevated temperatures due to the comparatively high sensitivity of polymer adhesives and matrices to temperatures in the range of their glass transition temperature (T_g). It has been suggested in the literature that, thanks to superior bond performance and thermal protection from embedment within the concrete cover, NSM systems may outperform externally bonded FRP systems at elevated temperatures, particularly if inorganic adhesives are used; little research is available to support these claims. Experiments were performed to investigate and compare the performance of NSM and externally bonded FRP flexurally strengthened concrete beams under sustained load at temperatures exceeding the matrix/adhesive polymers' T_g. Results suggest that both NSM and externally bonded FRP strengthening systems are susceptible to elevated temperature, but that their performance can be considerably better than is commonly believed.

1. Introduction and objectives

Widespread research in recent years (e.g., [1–6]), has confirmed that strengthening reinforced concrete structures with near surface mounted (NSM) fibre reinforced polymers (FRPs) is an efficient, effective and easily applied means to increase the shear and/or flexural capacity of a reinforced concrete member. In these applications, slots are cut into the concrete cover, typically using a diamond cutting disc, and an FRP bar, strip, or tape is inserted along with an epoxy adhesive. In addition, studies have been presented in the literature describing attempts to use cementitious grouts or inorganic adhesives in place of more costly epoxies (e.g. [7]). In both cases, the goal is to reliably anchor the NSM reinforcement to the concrete and to promote robust force transfer between the concrete cover and the FRP. Near surface mounted techniques are increasing in popularity due to specific advantages over more conventional FRP strengthening techniques involving externally bonded plates or sheets. Advantages include superior bond properties, which can lead to more effective use of the FRPs' strength while preventing early debonding failures [1], and embedment within the concrete cover, providing protection of the FRP from the environment, vandalism, and (notably for the purposes of the current paper) fire [5,6,8].

Most structures must be designed to resist the effects of a credible worst-case fire in order to ensure life safety (and sometimes property protection). While both NSM and externally bonded FRP strengthening systems for concrete have been proven effective and are now seeing widespread application globally, a common hindrance to application of these systems is their perceived unsatisfactory or unknown performance in fire. Considerable research has been carried out in recent years to develop fire-rated, insulated, externally-bonded FRP strengthening systems for concrete structures, and fire-rated systems are now available [9]. However, most design guidelines (e.g. [10]) suggest that the structural effectiveness of FRP strengthening systems (either externally bonded or NSM) should be ignored during fire unless it can be proven that these systems would remain effective under the expected high temperature conditions.

Unfortunately, very little information exists regarding the ability of FRP strengthening systems to retain structural effectiveness *under sustained service loads* at elevated temperature. While the

* Corresponding author. Tel.: +44 (0)131 6505710; fax: +44 (0)131 6506781.
E-mail address: luke.bisby@ed.ac.uk (L.A. Bisby).

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results of full scale fire tests on a small number of externally bonded [11,12] and NSM FRP [13] strengthened reinforced concrete beams are available in the literature, these tests are not particularly useful for understanding the structural performance of the FRP strengthening system at elevated temperature. Large scale studies have also been performed on NSM FRP strengthened beams exposed to standard fires [5] and slabs exposed to a real fire [6], however in both cases it is difficult to discern the specific performance of the FRP system and its ability to anchor the FRP at elevated temperature. It is thus extremely difficult at present to *prove* that an FRP system will remain *active* at elevated temperature, and as a result costly and time consuming full scale loaded fire resistance tests are necessary to gain fire approvals for specific FRP strengthening applications.

Furthermore, there is considerable debate within the FRP strengthening industry as to how service temperature limits for FRP strengthening systems should be defined and what specific limits should be prescribed. Temperature limits are typically defined with respect to the glass transition temperature, T_g, of the epoxy primer, saturant/matrix, or adhesive. Available guidance (e.g. [10]) suggests that service temperatures should be less than about $T_g - 15$ °C, although there is little experimental evidence to support these limits and it is not clear whether they are either conservative or overly restrictive.

It has been suggested in the literature that NSM systems may have distinct advantages over externally-bonded systems in fire [8], due mostly to protection provided by embedment in concrete, although little experimental research is available to support this idea [4,13]. Thus, a purely experimental study was conducted to better understand the performance of NSM strengthening systems at elevated temperatures such as might be expected for a *well-insulated* FRP strengthening system during a standard fire scenario [9]. The understanding of the response of adhesives to elevated temperature and the consequences for bonded FRP systems is not yet sufficient to enable defensible modelling of the performance under elevated temperature, and thus no modelling is presented in this paper. The study presented herein was performed under the assumption that an *uninsulated* (i.e. fire exposed) FRP system, whether externally-bonded or NSM, would lose structural effectiveness within the first few minutes of a standard fire [14]. With the above points in mind, the specific objectives of the present study were to:

- experimentally investigate the performance of loaded externally bonded and NSM FRP flexural strengthening systems for reinforced concrete structures at temperatures that they might experience if *well-insulated* and exposed to a standard fire scenario (in bond-critical applications without supplemental anchorage);
- investigate the claim that NSM FRP strengthening systems may display superior performance in a standard fire scenario as compared with externally bonded FRP systems;
- investigate the possibility that the high temperature performance of the NSM FRP strengthening system used in the current study could be improved by using a cementitious, rather than an epoxy, adhesive; and
- shed light on the relationship between T_g, load, exposure temperature, and structural effectiveness for both externally bonded and NSM FRP strengthening systems for concrete structures.

Much of the discussion presented in this paper deals with the bond performance of FRP strengthening systems for flexural strengthening applications. This area has received considerable research attention, and numerous models are available to describe the bond between FRP and concrete at ambient temperature, both for NSM (e.g. [15,16]) and externally bonded FRP (e.g. [17]) systems. However, none of the available models is sufficiently advanced to deal with resin softening at elevated temperature; bond models are therefore not discussed herein and the focus is instead placed on observations from tests and the possible implications for the future development of fire-safe FRP strengthening systems.

2. Experimental program

Table 1 provides an overview of the specific specimens, materials and systems, loading regimes, and parameters varied during testing. The current paper considers tests on 16 reinforced concrete beam specimens, 14 of which were strengthened in flexure with either a single strip of a commercially available carbon FRP NSM tape (Hughes Bros. Aslan 500),[1] or with a single ply of a commercially available carbon FRP externally bonded fabric (Sikawrap Hex 230C) (see footnote 1). The beams were tested either under monotonic load to failure (room temperature tests) or under sustained service load with increasing temperature to failure (transient high temperature tests). The parameters of interest were:

1. the overall effects of NSM and externally bonded flexural strengthening of the reinforced concrete beams;
2. the thermal and loading exposure conditions at the time of testing (21 °C under stroke control to failure, or 100 °C or 200 °C under sustained service load to failure);
3. the type of FRP strengthening system (NSM or externally bonded); and
4. the type of adhesive system used for NSM FRP strengthening (epoxy or cementitious).

The transient elevated temperature tests were specifically designed to observe the correlation (or lack thereof) between structural failure and the glass transition temperature of the adhesive or FRP matrix polymer. Near surface mounted FRP strengthened beams were tested in duplicate, since the response of NSM strengthened members was the focus of the experimental program, whereas only a single specimen was tested for each of the externally bonded FRP strengthened tests.

2.1. Test specimens

Fig. 1 shows the dimensions and reinforcement details of the concrete beam specimens. All beams were identical prior to strengthening. They were designed to represent strips of scaled down one-way reinforced concrete slabs with deficient internal flexural steel reinforcement, such as might require strengthening with an NSM or externally bonded system. The goal of the beam design was to proportion the internal steel reinforcement to avoid crushing of the concrete or shear failure of the FRP strengthened specimens such that the respective FRP systems would reach strain levels close to or exceeding those sufficient to cause debonding failure according to the requirements of ACI 440.2R-08 [10], prior to overall failure of the member. Currently imposed strengthening limits (e.g. [10]) were intentionally violated during design of the test specimens to ensure that the structural effectiveness of the FRP systems was *required* to prevent overall member failure under service loads at elevated temperature; this would not typically be considered prudent engineering design. The resulting beams had an internal steel reinforcement ratio, ρ_s, of only 0.24%. The compressive strength of the concrete at the time of testing, f'_c, was

[1] The specific FRP strengthening systems used are stated purely for the purposes of factual accuracy.

Table 1
Details of experimental program.

No.	Specimen name[a]	Loading regime	Adhesive type	Test temp. (°C)
1	C-21-1	2 mm/min	–	21
2	C-21-2	2 mm/min	–	21
3	E-21-1	2 mm/min	Epoxy 1[c]	21
4	E-21-2	2 mm/min	Epoxy 1[c]	21
5	G-21-1	2 mm/min	Grout[d]	21
6	G-21-2	2 mm/min	Grout[d]	21
7	EB-21-1	2 mm/min	Epoxy 2[e]	21
8	E-100-1	2 kN/min to 20 kN hold	Epoxy 1	100
9	G-100-1	2 kN/min to 20 kN hold	Grout	100
10	EB-100-1	2 kN/min to 20 kN hold	Epoxy 2	100
11	E-200-1	2 kN/min to 20 kN hold	Epoxy 1	200
12	E-200-2	2 kN/min to 20 kN hold	Epoxy 1	200
13	E-200-3[b]	2 kN/min to 20 kN hold	Epoxy 1	200
14	G-200-1	2 kN/min to 20 kN hold	Grout	200
15	G-200-2	2 kN/min to 20 kN hold	Grout	200
16	EB-200-1	2 kN/min to 20 kN hold	Epoxy 2	200

[a] Adhesive-Testing Temperature-Specimen Number: C – control, E – NSM with epoxy adhesive, G – NSM with grout adhesive, EB – externally bonded FRP, 21 – room temperature (21 °C), 100 – 100 °C high temperature exposure, 200 – 200 °C high temperature exposure.
[b] Specimen E-200-3 was accidentally tested in a unique condition as described in the text.
[c] KEMKO® 038 Crack Injection Epoxy (www.chemcosystems.com)[1].
[d] Target® 1118 Grout (www.targetproducts.com)[1].
[e] Sikadur® 330 Epoxy (www.sika.com)[1].

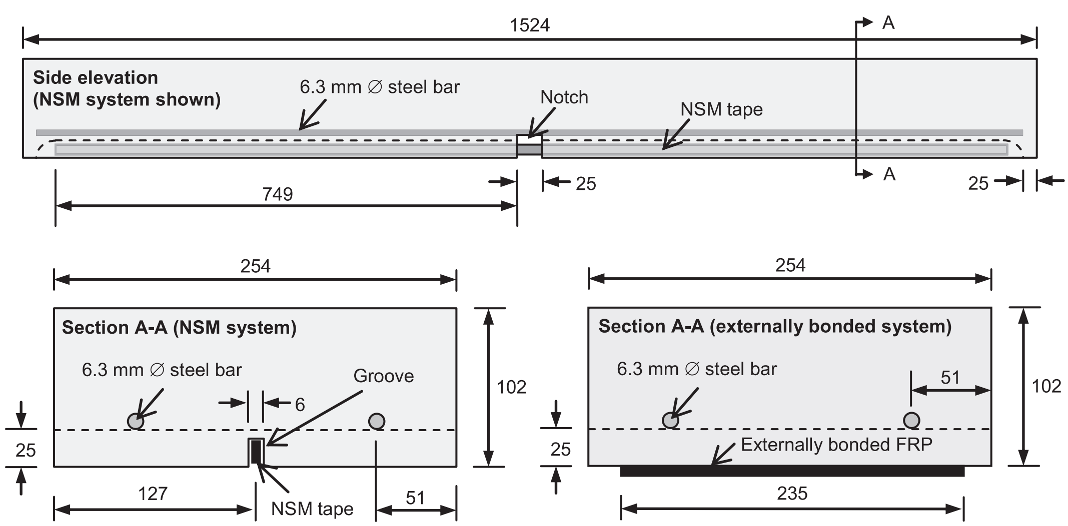

Fig. 1. NSM and externally bonded FRP strengthened reinforced concrete beams (all dimensions are in mm).

46.3 ± 1.6 MPa (mean ± standard deviation) at 21 °C, determined from three standard cylinder tests. The internal steel reinforcement consisted of D5 (6.4 mm diameter) deformed steel wire with an average 0.2% offset yield strength of 667 ± 12 MPa, as measured by the authors from five direct tensile tests. The dimensions of the beams and the NSM grooves were chosen to meet the edge distances and groove dimensions recommended by ACI 440.2R-08 [10]. All beams had a 25 mm wide × 25 mm deep lateral notch at midspan. This was cast into the beams to act as a crack initiator and to allow for installation of a bonded foil strain gauge on the NSM FRP within the constant moment region of the beams.

2.2. FRP strengthening

Table 2 shows details of the two specific FRP products used to strengthen the respective beams. Two beams were left unstrengthened as control specimens, and three distinctly different FRP strengthening *systems* were used on the remaining 14 beams; these are compared in the sections that follow:

1. NSM carbon FRP tape with an epoxy adhesive (Epoxy 1);
2. NSM carbon FRP tape with a cementitious grout adhesive (Grout); and
3. wet lay-up externally bonded carbon FRP fabric system with an epoxy adhesive (Epoxy 2).

For the NSM installations, grooves were cut along the centre lines of the beams' soffits by hand using a tuck-point grinder with a 6.35 mm (1/4″) wide diamond concrete cutting disc. An aluminum guide was used to ensure straightness and consistent groove depth (21 mm).

Six beams were strengthened using a single NSM carbon/vinylester FRP tape bonded into the groove using an epoxy adhesive (Epoxy 1). The epoxy was a commercially available epoxy resin used for crack injection of concrete structures. This specific product, sold under the trade name Kemko® 038, was selected through discussion with an industry research partner. The benefit of this epoxy is to enable a novel NSM installation procedure wherein the NSM FRP was installed by placing the FRP into a

Table 2
Selected characteristics of strengthening systems.

Property	NSM CFRP + Epoxy [E]	NSM CFRP + Cementitious [C]	Externally bonded CFRP [EB]
Trade name	Aslan 500 #2[a]	Aslan 500 #2[a]	Sikawrap Hex 230C[b]
Matrix resin	Vinylester	Vinylester	Epoxy
Matrix T_g (°C)	122[c]	122[c]	59[c]
Adhesive	Kemko 038	Target 118	Sikadur 300
Adhesive T_g (°C)	69[c]	–	59[c]
Adhesive flexural modulus (MPa)	3972	38970[e]	3800
Width (mm)	16	16	235
Design thickness (mm)	2	2	0.381
Cross sectional area (mm^2)	31.2	31.2	89.5
Tensile strength, f_{fu}^* (MPa)	2068 (2360)[d]	2068 (2360)[d]	715 (833)[d]
Tensile modulus, E_f (MPa)	124000 (129000)[d]	124000 (129000)[d]	61012 (56462)[d]
Ultimate strain, ε_{fu}^* (%)	1.70 (1.70)[d]	1.70 (1.70)[d]	1.09 (1.48)[d]

[a] Supplied by Hughes Bros, Inc., Seward, NB.
[b] Supplied by Sika Canada Inc., Montreal, QC.
[c] Determined by the Authors using dynamic mechanical analysis (DMA) with T_g taken as Tan δ Peak on the first heating cycle (see discussion below).
[d] Values in brackets are as determined by the Authors by testing 5 samples each in accordance with ACI 440.3R-04 [18].
[e] Based on an assumed cementitious grout compressive strength of 75 MPa and taking $E = 4500\sqrt{f'_c}$. The flexural elastic modulus of the Aslan 500 NSM tape is quoted by the manufacturer as 3200 MPa.

dry groove and then sealing the groove and applying the resin under pressure using standard crack injection equipment and procedures. This technique has the advantages of using smaller amounts of adhesive (hence reducing project costs), faster resin set times, concurrent strengthening of the substrate concrete during the NSM bonding process, and ease, speed, cleanliness, and aesthetics of the installation. The glass transition temperature of Epoxy 1 was determined by the authors to be 69 °C based on dynamic mechanical analysis (DMA) of rectangular resin samples tested in a single cantilever flexural mode at a frequency of 1 Hz and a heating rate of 2 °C/min. The glass transition temperature was defined using the peak Tan δ value observed during the first DMA heating cycle up to 180 °C. The significance of the specific test method and criterion used to define T_g is discussed later in this paper.

Six beams were strengthened using a single NSM FRP tape bonded using a commercially available cementitious (unsanded silica fume) grout sold under the trade name Target® 1118[1]. This product was also selected with the intent that the adhesive could be applied under pressure using conventional crack grouting equipment. The advantages of using the cementitious grout adhesive include lower material costs, concurrent substrate concrete strengthening during bonding of the NSM, reduced environmental hazards during installation, improved aesthetics of the completed installation (virtually invisible), and ease of installation. It was also expected that, compared to the epoxy, the grout adhesive would lead to superior performance at high temperature under sustained service loads, provided that it could perform adequately at ambient temperature.

The rationale for expecting superior high temperature performance for the grout adhesive system is as follows. The key issue for any bond-critical FRP strengthening system at elevated temperature is maintaining a sufficient bond between the FRP and the concrete [14] because the FRP adhesives are invariably the components most affected by elevated temperatures. Because the FRP tape is manufactured by pultrusion and therefore cured at elevated temperature during the manufacturing process, the tape's vinylester resin matrix has a considerably higher T_g than essentially any available ambient temperature cure epoxy adhesive; it will thus be less affected by elevated temperature than the ambient-cure epoxies used as adhesives in either NSM or externally bonded FRP strengthening applications. Indeed, the authors measured the T_g for the NSM tape using DMA (in this case with rectangular samples of the tape tested in a single cantilever flexural mode at a frequency of 1 Hz and a heating rate of 2 °C/min), and determined T_g to be 122 °C (again based on Tan δ peak during the first heating cycle to 180 °C). Therefore, the only resin used in the cementitious NSM application, the FRP strip's matrix resin, has a T_g in the range of twice that of either of the ambient cure adhesive epoxies used for bonding the other two strengthening systems. Furthermore, in contrast to ambient-cure epoxy adhesives, cementitious grout adhesives can be assumed to be essentially unaffected by short term exposures up to at least 200 °C [19]. NSM FRP bonded using cementitious grout adhesive can therefore be expected to display superior retention of mechanical properties at elevated temperature compared to that of systems with epoxy adhesives.

Finally, three beams were strengthened with a wet lay-up externally bonded carbon/epoxy FRP fabric strengthening system sold under the trade name Sikawrap® Hex 230C. This system was saturated and bonded using Sikadur® 330 epoxy[1] (Epoxy 2). Surface preparation consisted of light sandblasting. The width of the externally bonded sheet was 235 mm and was chosen so as to obtain the same design flexural strength as the NSM strengthened beams according to guidance set out in ACI 440.2R-08 [10]; again, ignoring strengthening limits. The T_g of Epoxy 2 was determined, in the same manner as for Epoxy 1, to be 59 °C.

2.3. Test setup & instrumentation

All 16 beams were tested upside down in four-point bending as shown in Fig. 2. This approach was required to enable attempts at monitoring the FRP strengthening systems' bond performance using a digital image correlation technique (which unfortunately proved unsuccessful). Total applied load, crosshead displacement, vertical displacements, strains over the height of the cross-section at midspan, and strain in the FRP system within the midspan notch were all recorded during testing using conventional instrumentation (as noted in Fig. 2).

2.3.1. Ambient temperature tests

Seven beams were tested at ambient temperature (approximately 21 °C) to determine the levels of strengthening achieved for the various systems, the FRP strain at failure, and the failure mode (refer to Table 1). Ambient temperature tests were also used to determine a suitable sustained load to be applied during transient high temperature tests of each of the three strengthening systems. All ambient temperature beams were tested to failure under crosshead displacement control at a rate of 2 mm per minute.

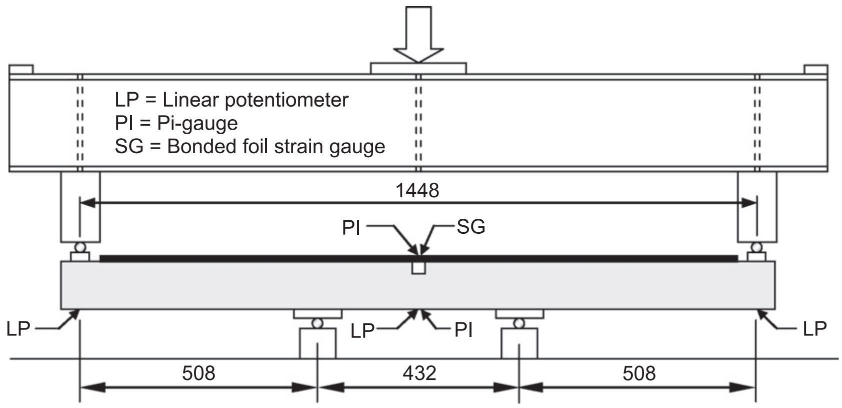

Fig. 2. Test setup and instrumentation (shown for externally bonded case, all dimensions in mm).

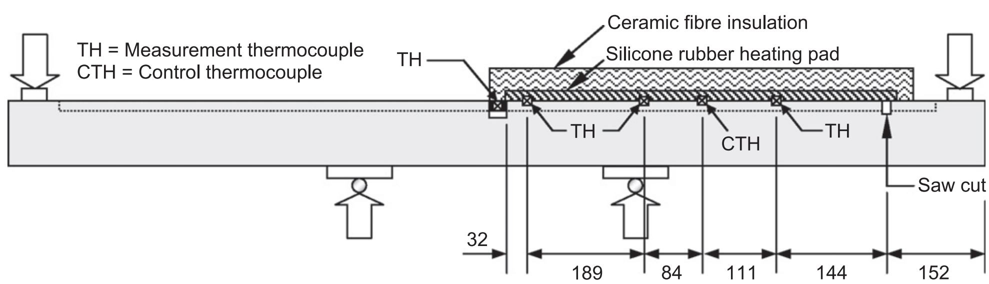

Fig. 3. High temperature heating assembly and thermal instrumentation (shown for NSM system, dimensions are in mm).

2.3.2. Transient elevated temperature tests

The remaining nine specimens were tested under sustained load with increasing temperature exposure. For these tests, the beams were initially loaded at ambient temperature under load control at a rate of 2 kN/min to a sustained load of 20 kN. The beams were more than six months old at the time of testing. The 20 kN sustained load was chosen based on the results of the ambient temperature tests to ensure that the FRP strengthening systems experienced sustained midspan tensile strain levels between 40% and 60% of ultimate while being heated; such strains are at the upper end of in-service strain levels likely to be experienced by carbon FRP strengthening systems in real applications. For instance, ACI 44.2R-08 [10] suggests a sustained plus cyclic service load stress limit of 55% of ultimate for carbon FRP reinforcement. The 20 kN sustained load, which was greater than the failure load of any of the unstrengthened beams tested (refer to Section 3.1), also ensured that failure would occur should the bond integrity or strength of the FRP strengthening system be lost during heating. The magnitude of reduction in effectiveness needed to cause failure is a topic of considerable interest, and is discussed below with reference to the DMA test results on the polymer matrices/adhesives.

Using the high level of sustained load with transient heating allowed conservative determination of the temperatures at which the FRP strengthening systems became ineffective under sustained service load.

Once the 20 kN sustained load was reached, the beams were allowed to stabilize for two minutes and the heating was applied using a resistance heater which was applied over the FRP strengthening systems as shown in Fig. 3. An Omegalux® silicone rubber fibreglass reinforced heating blanket was applied to the tension face of one end of the beam specimens (i.e., over one half of the length of the FRPs' bonded region). Heating only one end gave the advantage of more control over the failure location. Temperature was controlled using a Type-J thermocouple located under the heating pad at its midpoint on the top surface of the beam (Location CTH in Fig. 3). A layer of FiberfraxTM ceramic fibre insulation was placed on top of the heating pad to prevent heat loss away from the beams. The temperature of the top surface of the concrete was monitored throughout the tests at various locations using four Type-T thermocouples. For the EB system, thermocouples were placed on top of the FRP. The surface temperature of the FRP strengthening system was raised as quickly as possible (at approximately 10–20 °C/min) and then held constant at the predetermined soak temperature (100 °C or 200 °C) until failure occurred under the sustained load.

The choice of soak temperatures requires some explanation. The 100C soak temperature was selected based on actual observed FRP strengthening system temperature histories recorded during full scale fire tests of *insulated* FRP-strengthened reinforced concrete members [9]. In previously conducted full scale fire tests, it has been demonstrated that, with sufficient thickness of a proprietary supplemental fire insulation system, the temperature of the concrete surface can be maintained close to 100 °C for up to 4 h of exposure to a standard fire. The 200 °C soak temperature was the maximum possible temperature that could be achieved for the silicone rubber resistance heating system used in the current study. While neither of the chosen soak temperatures is representative of the temperatures likely to be experienced by an unprotected FRP strengthening system in a standard fire, previous research has suggested that to attempt to preserve the effectiveness of the FRP in such situations would be futile and that the FRP system would be lost within minutes [20], even for NSM systems. Therefore, the results in this paper apply specifically to insulated FRP-strengthened reinforced concrete members in fire scenarios.

3. Experimental results

3.1. Ambient temperature tests

Fig. 4 gives the applied load versus midspan deflection behaviour of all seven beams tested at room temperature. Table 3

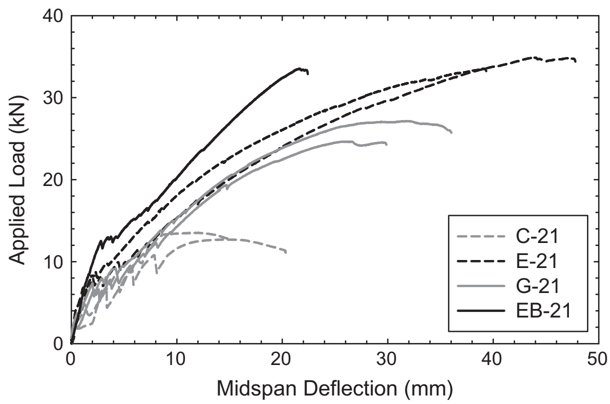

Fig. 4. Applied load versus midspan deflection for beams tested to failure at room temperature.

provides selected data from these tests, including failure load, failure moment, FRP strain at failure (measured at midspan), and FRP strain at failure as a percentage of the average coupon tensile rupture strain.

The unstrengthened control beams (C-21-1 and C21-2) displayed typical under-reinforced flexural behaviour, eventually failing due to concrete crushing within the constant moment region after considerable yielding of the internal steel reinforcement. It is noteworthy that the average peak load for these specimens was 12.1 kN. This represents about 60% of the sustained load of 20 kN which was applied during the transient elevated temperature tests and shows that both the externally bonded FRP and NSM FRP strengthened beams would be expected to fail in the absence of the strengthening systems.

The externally bonded (EB-21-1) and NSM (E-21-1 and E-21-2) strengthened beams that were strengthened using epoxy adhesives achieved very similar strengths at ambient temperature, although the externally bonded specimen had a considerably higher first cracking load and a stiffer response throughout the test. This additional stiffness was likely a consequence of the 30% larger equivalent axial stiffness of the FRP strengthening for the externally bonded system (refer to Table 2) as well as its slightly larger flexural lever arm. E-21-1 and EB-21-1 both failed by FRP debonding, which was violent and coincided with tensile rupture of the FRP and global shear failure of the cross-section at one of the loading points. It remains unclear whether global shear failure of the beams induced the bond failure or vice versa in these tests, but it was noted that a large flexural-shear crack had formed before failure (at very large curvatures), and this likely played an important role in initiating member failure. Beam E-21-2 failed by splitting bond failure of the NSM FRP strengthening system in the concrete adjacent to the epoxy–concrete interface. The similarity of failure load and strain in the FRP at failure suggests that either of these two failure modes may be expected for a given beam tested under these conditions. In any case, all three beams using epoxy adhesives exhibited very large strength increases of more than 163% as compared to the control specimens.

The NSM strengthened beams that used cementitious adhesive (G-21-1 and G-21-2) achieved strength increases of 105–120% over the control specimens, notably with ultimate capacities in excess of 20 kN. Beams strengthened using cementitious adhesive showed less stiff response than the epoxy adhesive strengthened beams because of the extensive cracking of the grout adhesive that was observed. Failure was clearly initiated in the bond for these beams and resulted in pullout of the NSM strip at the adhesive-strip interface. The observed behaviour demonstrated less efficient use of the NSM tape for the cementitious adhesive as compared with the epoxy adhesive, since the strain in the NSM FRP at failure was only 50–55% of the ultimate tensile strain (as compared with 74–83% for the epoxy adhesive).

It is important to clearly note that the level of strengthening achieved for all of the ambient temperature specimens described above falls well outside reasonable strength increases currently permitted for design in real FRP strengthening applications [10]. These would normally be in the range of 40–60%, and it is therefore unlikely that such a high level of FRP strengthening would be attempted in practice (using any of the systems discussed herein). However, this unusually high level of strengthening was intentional since it permitted the study of the structural effectiveness of externally bonded and NSM FRPs in these situations. In all cases duplicate tests demonstrated good repeatability.

3.2. Transient elevated temperature tests

Fig. 5 provides temperature recorded at the centreline of the tension surface for all beams tested under elevated temperature exposure, and shows that while the ramp and soak phases were essentially achieved in all cases, there were some minor discrepancies observed for the individual specimens. However, the data shown represent averages of three point thermocouples installed along the centreline of the slab beneath the silicone resistance heater (refer to Fig. 3), and it is possible that some variation in surface heating of the pad was experienced during heating, resulting in the observed variation in temperature. To check the spatial variability of temperature applied by the silicone resistance heater, eight thermocouples were installed on the FRP surface during the test of EB-200-1, and the surface temperatures were observed to vary by less than 15 °C at any given location. The slower ramp rate recorded for the externally bonded specimens is difficult to explain, but it may be due to the cooling effects of concrete pore moisture trapped beneath the vapour-impermeable FRP wrap.

Table 3
Selected results of ambient temperature testing.

Specimen[a]	Failure load (kN)	Failure moment (kN m)	Strength increase (%)[b]	FRP strain @ failure (%)	% of ultimate strain in FRP[c]	Failure Mode
C-21-1	12.7	3.2	–	–	–	Crushing (under-reinforced)
C-21-2	11.4	2.9	–	–	–	Crushing (under-reinforced)
E-21-1	33.5	8.5	178	1.26	74	Shear crack induced debond/failure
E-21-2	34.9	8.9	190	1.41	83	Debonding by epoxy/concrete split
G-21-1	24.6	6.3	104	0.85	50	Debond @ grout-strip interface
G-21-2	27.1	6.9	125	0.94	55	Debond @ grout-strip interface
EB-21-1	33.4	8.5	162	0.70	64	Shear crack induced debond/failure

[a] C – control, E – epoxy, G – grout, EB – externally bonded.
[b] Compared against the average of control samples tested at room temperature.
[c] Based on manufacturer-specified ultimate strain values (see Table 2).

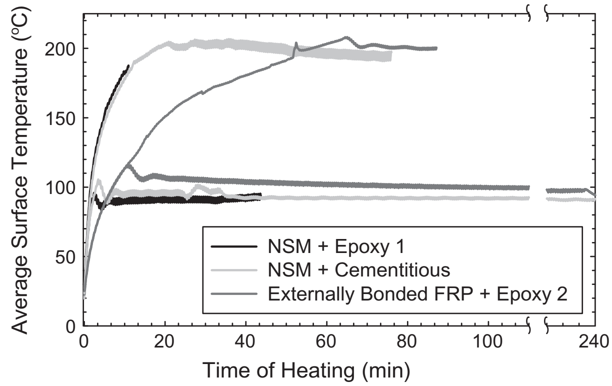

Fig. 5. Typical temperature at the exterior surface of the NSM groove versus heating time.

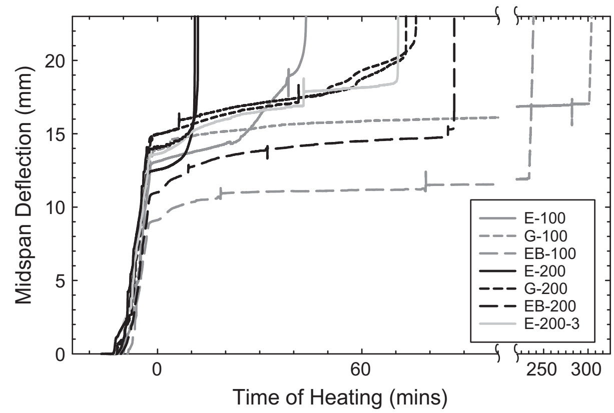

Fig. 6. Midspan deflection versus heating time for beams tested at high temperature under sustained load.

Table 4 and Fig. 6 show selected data obtained during testing at elevated temperature. Table 4 shows that the midspan strain in the FRP systems was between 0.49% and 0.62%. This corresponds to between 29% and 32% of the design ultimate tensile strain for the NSM systems and between 53% and 57% for the externally bonded system. The measured strains were observed to decrease by up to 80% during the ramp phase of the heating. It is suspected, however, that these strain readings were erroneous once heating began due to electromagnetic interference from the heating pad and strain gauge debonding due to elevated temperature (the gauges were not high-temperature rated, and other variables such as stroke and displacement did not show similarly drastic changes during the ramp phase).

Fig. 6 shows the relative performance of the three different FRP strengthening systems at elevated temperature by providing plots of beam midspan vertical deflection versus time of heating for all specimens tested at elevated temperature while under sustained load. This figure includes midspan deflections recorded during the initial loading up to 20 kN (i.e. before time "zero" when the heating pad was turned on). Fig. 6 confirms that the grout adhesive NSM specimens were slightly less stiff than the epoxy adhesive specimens, and that the externally bonded strengthened beams were stiffer than any of those strengthened using NSM FRP (for the reasons noted previously). Small fluctuations observed in the traces shown in Fig. 6 are due to minor fluctuations in the load control function of the servo-controller used in testing, and can reasonably be ignored in terms of their influence on the experimental results. Initial increases in midspan deflection during heating (increases with decreasing deflection rates, i.e. concave down in shape) are due to thermal bowing of the beams resulting from heating of their tensile faces, rather than from deterioration of the strengthening systems. Deflections with increasing rates (i.e. concave up in shape) can be attributed to gradual, progressive failure of the FRP-concrete bond.

3.2.1. NSM FRP strengthened beams with Epoxy 1 adhesive

All of the transient elevated temperature tests terminated due to bond failure, either in the vinylester matrix of the NSM tape or in the epoxy adhesives. Epoxy bonded NSM strengthened specimens E-100-1, E-200-1, and E-200-2 had the least satisfactory high-temperature performance, failing under the 20 kN sustained load at 44 min, 11 min, and 12 min of heating, respectively. In these cases, bond failure appeared to be *adhesive* in nature and initiated at the epoxy–concrete interface along a smooth, distinct failure surface. Conversely, room temperature bond failures in beams strengthened with NSM FRP and epoxy adhesive (E-21-1 and E-21-2) were *cohesive* in nature and occurred about 1 mm into the substrate concrete from the epoxy–concrete interface. This change in failure mode is a clear indication of deteriorating mechanical and/or adhesive properties of the epoxy at elevated temperature. The movement of pore water from the concrete toward the adhesive interface and in the adhesive under exposure to elevated temperatures may also play a role in influencing the reduction in bond properties due to heating. This idea is supported by research presented previously on the residual bond strength between externally bonded FRP and concrete after heating [14], where a detrimental effect of moisture diffusion toward or into the adhesive zone was hypothesized.

It is notable that the surface temperature of the NSM strengthening system at failure was considerably greater than the temperature recorded at the base of the groove (refer to Table 4). For instance, whilst the surface temperature of the NSM strengthening

Table 4
Selected results from transient elevated temperature testing.

Test	Target temp. (°C)	FRP strain at beginning of heating (%)[a]	Time heated at failure (min)	Surface temp. at failure (°C)	Groove base temp. at failure (°C)[b]	Adhesive T_g (°C)	Failure load (kN)
E-100-1	100	0.58	44	94	35	69	20.0
G-100-1	100	0.56	No fail @ 300	91	48	–	27.3
EB-100	100	0.62	No fail @ 240	95	N/A	59	30.1
E-200-1	200	0.49	11	185	42	69	20.0
E-200-2	200	0.56	12	166	34	69	20.0
E-200-3	200	0.50	71	N/A	N/A	69	20.0
G-200-1	200	0.52	73	179	69	–	20.0
G-200-2	200	0.58	76	197	54	–	20.0
EB-200	200	0.49	84	201	N/A	59	20.0

[a] Centreline strain based on a single foil strain gauge.
[b] Approximate values based on standalone heating validation tests performed after structural testing.

system was 94 °C (25° *above* the epoxy adhesive T_g) for E-100-1 at the instant of failure, the base of the NSM groove was at only 35 °C (34° *below* the epoxy adhesive T_g). In the case of the E-200 beams, surface temperatures of 166–185 °C (more than 93 °C above T_g) were observed prior to failure, although groove base temperatures remained in the range of 34–42 °C (more than 28 °C below T_g).

The fact that the surface and groove base temperatures were so drastically different at the instant of failure makes it difficult to draw correlations between adhesive T_g and loss of structural effectiveness of the NSM FRP, particularly because the amount of *effective* adhesive required to maintain bond integrity under the sustained service load of 20 kN is not known. E-200 beams had considerably higher surface temperatures at failure, but failed at much shorter durations of heating (by a factor of 4). This occurred because the E-200 specimens experienced a steeper thermal gradient in the adhesive such that the groove base remained relatively cool while the surface temperature was drastically above T_g. A further complication in interpreting the data for these tests is the well known and difficult to generalize stress–temperature–time dependency of creep strains in polymer adhesives [21]. Steady state tests, wherein the specimens are heated to a constant temperature *before* being loaded to failure, will be required to shed additional light in this area.

Specimen E-200-3, which was in fact the first specimen tested at elevated temperature, was anomalous but is worthy of discussion. Because of an error in the testing procedures, this specimen was inadvertently tested with approximately 50 mm of the NSM bond length remaining unheated (at the free end). As a result, this specimen was able to support the sustained load for more than one hour (or approximately seven times the otherwise identical epoxy adhesive NSM strengthened specimens). This result confirms the previously observed result that only short lengths of unheated bonded regions are required to maintain the structural effectiveness of bond-critical FRP strengthening systems under service loads at high temperature [11]. Thus, it may not be necessary to insulate the full length of an NSM FRP strengthening system to provide protection against fire; only partial insulation may be sufficient in some cases. Additional research is required to support this concept and to understand the synergistic effects of stress, temperature, time, creep, and reductions in strength and stiffness of both the FRPs and their adhesives.

3.2.2. NSM FRP strengthened beams with cementitious adhesive

Beam G-100-1 displayed an increase in midspan deflection during the first hour of heating (due to thermal bowing as noted previously) but the deflection leveled off and the beam held the sustained load for more than five hours of heating at 100 °C. At five hours, with the specimen showing no signs of failure, the load was increased until failure occurred at 27.3 kN by debonding/pullout at the grout-strip interface. Thus, this specimen actually tested stronger under a heated condition than either of the corresponding beams tested at ambient temperature. This indicates that heating to 100 °C for more than 5 h had no discernable negative impact on performance of the system.

NSM FRP specimens G-200-1 and G-200-2 displayed superior performance compared with epoxy–bonded NSM FRP strengthened specimens, failing under the 20 kN sustained load after 73 and 76 min of heating, respectively. Failure was by pullout for the NSM tape at the FRP-grout interface (adhesive failure).

The considerably enhanced performance of the cementitious adhesive NSM system at elevated temperature can be attributed, as expected, to the fact that the weak link in the case of this adhesive is the vinylester resin matrix of the NSM tape, which has considerably better resistance to high temperature than the room temperature cure Epoxy 2 adhesive (as previously discussed). This further suggests that cementitious adhesives could provide good options for NSM FRP strengthening applications in warm climates, certain elevated temperature industrial applications, or to provide enhanced fire performance for FRP strengthening systems with supplemental insulation.

3.2.3. Externally bonded FRP strengthened beams with Epoxy 2 adhesive

Both externally bonded FRP strengthened beams failed by combined *adhesive/cohesive* bond failure in the Epoxy 2 adhesive during high-temperature testing. The externally bonded FRP strengthened beams displayed surprisingly robust performance at elevated temperature, with Beam EB-200 actually outperforming G-200-1 and G-200-2 by 11 min and 8 min of heating, respectively. This is particularly surprising given that the T_g for the Epoxy 2 adhesive was measured as only 59 °C, approximately 140 °C less than the soak temperature at which this specimen was able to hold the 20 kN sustained load for more than one hour. It is likely that the superior performance of EB-200 was due to the much larger bond area for the externally bonded system, such that a much lower proportion of the ambient temperature strength and stiffness needed to be maintained in order to transfer stresses from the FRP to the concrete; this idea is discussed in detail in the following section. As mentioned previously, the required adhesive properties to maintain bond performance under sustained load are not currently known and warrant further investigation. Nevertheless, the initial testing presented herein, along with the DMA test results and discussion presented in the following section, suggest that massive reductions in adhesive strength and stiffness may be tolerable under short term exposure to elevated temperatures.

Specimen EB-100 carried the 20 kN load for more than 4 h, at which point the load was increased up to failure at an ultimate value of 30.1 kN, which represents 90% of the strength of the equivalent beam tested at ambient temperature (EB-RT) and suggests relatively little damage to the bond performance at 100 °C (at about 40 °C *above* the adhesive's T_g). Reasons for the superior performance are thought to be the same as discussed previously.

4. Structural effectiveness and T_g

Fig. 7 shows data recorded during DMA testing of the various resins discussed in the current study. Fig. 7(a) shows the normalized reductions of storage modulus (flexural elastic modulus) experienced for the three resins with increasing temperature, and Fig. 7(b) shows normalized Tan δ curves. A full description of DMA testing procedures and parameters is beyond the scope of the current paper, although the results are instructive and worthy of discussion. It is common to define T_g based on the peak in the Tan δ plot, and this is the approach that has been taken in the current paper (refer to the peak temperature values noted in Fig. 7(b)). It should be noted, however, that if T_g is defined on this basis then the resins will have lost a considerable proportion of their initial elastic (storage) modulus (99% for Epoxy 1, 98% for Epoxy 2, and 65% for the NSM tape) by the time T_g is reached (refer to Fig. 7(a)). These data show, at least for the externally bonded FRP strengthening system with Epoxy 2 resin, that more than 98% of the adhesive's elastic modulus can be lost without loss of bond under the (relatively severe) loading conditions of the tests presented herein. For the NSM FRP strengthening system the situation is complicated by the thermal gradient that is present over the depth of the NSM groove, although again the resistance to temperature in excess of T_g is surprisingly good given the resulting reductions in resin stiffness at temperatures close to T_g, particularly when using a cementitious adhesive.

The primary reason for the superior performance of the externally bonded FRP strengthening is thought to be that the bonded

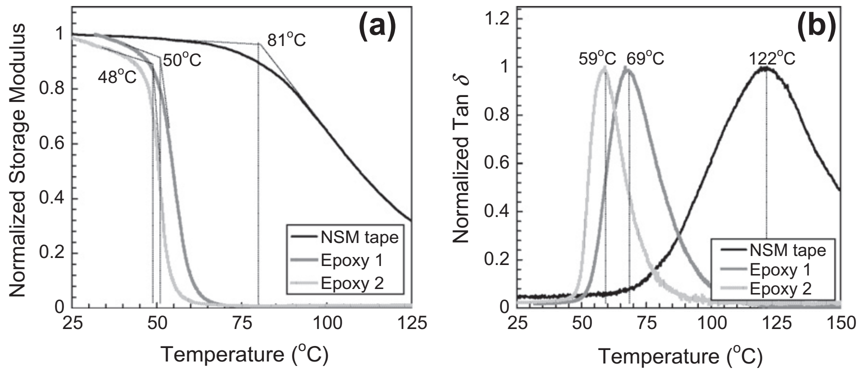

Fig. 7. Determination of glass transition temperatures for the respective resins treated in the current paper based on (a) normalized onset storage modulus loss and (b) normalized Tan δ peak.

Table 5
Summary of average bond stresses in the adhesives at the onset of heating.

Test	Target temp. (°C)	FRP strain at beginning of heating (%)[a]	Tensile load in FRP at beginning of heating (kN)[b]	Bond area (m^2)[c]	Ave. bond stress (MPa)
E-100-1	100	0.58	71.9	0.026	4.4
G-100-1	100	0.56	69.4	0.018	6.0
EB-100	100	0.62	76.9	0.124	0.96
E-200-1	200	0.49	60.7	0.026	3.7
E-200-2	200	0.56	69.4	0.026	4.2
G-200-1	200	0.52	64.5	0.018	5.5
G-200-2	200	0.58	71.9	0.018	6.2
EB-200	200	0.49	60.8	0.124	0.76

[a] Centreline strain based on a single foil strain gauge.
[b] Determined by multiplying strain in the FRP by the manufacturers tensile modulus values given in Table 2.
[c] Determined by taking the approximate area of the failure surface during tests at elevated temperature for each of the respective systems.

area was much greater than that for the NSM strengthening systems. Data supporting this hypothesis are given in Table 5. The total bond interface area for the epoxy bonded NSM system for one half of the beam was about 0.026 m^2, whereas for the externally bonded system it was approximately five times larger at 0.124 m^2. Given the strains recorded in the respective FRP strengthening systems at the beginning of heating (refer to Table 4), the average shear stresses in the adhesives (determined by dividing the total force in the NSM at midspan by the bonded are from the free end of the FRP strengthening system to the loading point) were 3.7–4.2 MPa for the NSM system with Epoxy 1 adhesive but only 0.76–0.96 MPa for the externally bonded system using Epoxy 2. Thus, despite the higher T_g of Epoxy 1 and its slightly higher elastic modulus at ambient temperature (refer to Table 2) the externally bonded system with Epoxy 2 adhesive experienced bond stresses of only about 20% of the NSM system with Epoxy 1 adhesive, and was thus able to withstand a much greater deterioration in mechanical properties of the adhesive due to heating before experiencing bond failure.

As already mentioned, full-scale real and standard fire tests on insulated externally bonded FRP strengthened reinforced concrete beams, columns, and slabs have been reported by several authors [9,11,13,21]. Among other things, these tests have shown that currently available spray-applied or board insulation systems of sufficient thickness (50-60 mm) and robustness are capable of maintaining the temperature of an FRP strengthening system at temperatures near 100 °C for more than 4 h. These data, when considered along with the results presented above, provide compelling evidence that it may indeed be possible to maintain the structural effectiveness of insulated FRP strengthening systems during exposure to a standard fire. Clearly, additional research is needed to understand the influences of resin heating on bond performance, particularly since elevated temperature not only decreases the resins' stiffness, but also decreases strength and increases deformability [22].

5. Conclusions

This paper has presented the results of a series of tests on NSM and externally bonded FRP strengthened reinforced concrete beams under sustained load at elevated temperature. Based on the data presented, the following conclusions can be drawn:

1. At ambient temperature, the Epoxy 1 adhesive provides superior bond performance as compared with the cementitious grout adhesive for NSM FRP strengthening systems for concrete. The cementitious adhesive provided reasonably good performance, however it resulted in less efficient use of the FRP material. If cementitious adhesives are used instead of epoxy adhesives, more stringent strain limits are required to prevent debonding failures. Additional testing is needed to better understand bond development for both types of adhesives.
2. If well insulated against the thermal effects of fire, it may be possible for NSM FRP strengthening systems to achieve structural fire endurance ratings of several hours, even in cases where the FRP is required retain sufficient bond and strength to resist sustained service load stresses. Based on the limited data presented herein:
   a. the NSM carbon FRP strengthening system bonded using Epoxy 1 may be capable of withstanding over 40 min at 100 °C, but less than 10 min at 200 °C. This system fails at elevated temperature by debonding at the adhesive-concrete interface.

b. the performance at high temperature of NSM FRP strengthening systems can be improved considerably by using a cementitious grout adhesive rather than an ambient temperature cure epoxy (assuming satisfactory performance of the system at room temperature). For the system tested herein, the cementitious adhesive system was able to support the sustained load for more than four hours at 100 °C and for more than 70 min at 200 °C. Failure was by debonding at the FRP-adhesive interface; and
c. the externally bonded FRP strengthening system bonded with Epoxy 2 was capable of withstanding more than 4 h at 100 °C and more than 80 min at 200 °C. The externally bonded FRP system had the best performance at elevated temperature of any of the systems tested, and eventually failed by debonding at the adhesive-concrete interface; this is likely attributable to the much lower average bond stresses in the adhesive for this system.

3. For the specific FRP strengthening systems tested under the conditions presented herein, it appears that the FRP systems are able to maintain their structural effectiveness, under sustained service load levels, for short term exposures (periods of hours) to temperatures considerably exceeding the T_g of their epoxy adhesives.
4. The relationship between the matrix/adhesive polymer T_g and the structural load carrying capacity of different types of FRP strengthening systems in bond critical applications remains poorly understood and requires additional investigation. Additional testing is needed to better understand the complex interactions between load, temperature, stress, and time which influence the performance of both externally bonded and NSM FRP strengthening systems at elevated temperatures. Once available, such data can be used to make defensible and conservative recommendations on service temperature limits for both externally bonded and NSM FRP strengthening systems.

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