

STRUCTURAL PERFORMANCE OF NEAR SURFACE MOUNTED FRP STRENGTHENED CONCRETE SLABS AT ELEVATED TEMPERATURES

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ABSTRACT

Near surface mounted (NSM) FRP reinforcement has recently emerged as a promising technology for strengthening concrete structures in both flexure and shear. This technique has numerous potential advantages over externally bonded FRP strengthening systems, and is typically able to more fully employ the strength of FRP materials because of superior bond performance. Research to date has focused primarily on overall member behaviour and/or the various parameters that affect the bond performance of available NSM systems. FRP strengthening systems are known to be susceptible to deterioration of mechanical and bond properties at elevated temperatures. This can be attributed to relatively poor performance of both adhesive and FRP matrix polymers at temperatures in the range of their glass transition temperatures. While it has been suggested in the literature that NSM systems may outperform externally bonded FRP strengthening systems at elevated temperatures, no research has apparently been presented to support these claims. An experimental program was conducted to investigate the flexural performance of NSM FRP strengthened reinforced concrete slabs under sustained load at temperatures close to or exceeding the glass transition temperatures of the matrix and adhesive polymers. Results suggest that insulated NSM FRP strengthening systems using cementitious adhesives perform considerably better than otherwise identical epoxy-bonded systems under high temperature exposures.

INTRODUCTION & OBJECTIVES

Thanks to widespread research in recent years (e.g., De Lorenzis and Teng, 2006; ACI, 2007; Burke, 2008), strengthening reinforced concrete structures with near surface mounted (NSM) FRPs is becoming more widely recognized for its efficiency, effectiveness, and ease of application. In these applications, slots are cut into the concrete cover of a reinforced concrete member, typically using a diamond cutting disc, and an FRP bar, strip, or tape is inserted, along with an epoxy adhesive. More recently, several authors have attempted to use cementitious grouts or adhesives in place of the epoxy. In both cases, the goal is to provide well-anchored supplementary tensile reinforcement to the concrete. Either of these techniques can be used to provide shear or flexural (Barros et al., 2007) strengthening for reinforced concrete members. NSM techniques have become increasingly popular in recent years due to certain specific advantages, such as superior bond properties which can enable more effective use of the FRPs' strength while preventing debonding failures (De Lorenzis and Teng, 2006), as well as protection from the environment, vandalism, and fire.

Considerable research has been carried out in recent years to develop fire-rated, insulated, externally-bonded FRP strengthening systems for concrete structures, and these have been tested and are now available for use in North America (Kodur et al., 2006). However, most available design guidelines (e.g., ACI, 2008) rightly suggest that the structural effectiveness of FRP strengthening systems (either externally bonded or NSM) should be ignored during fire; this will remain the case until it can be proved that these systems would remain effective under the high temperature conditions to be expected during a standard fire. Applications of FRPs for

strengthening concrete buildings, parking garages, and many industrial structures are seriously hindered by a lack of knowledge regarding the ability of available FRP strengthening systems to retain structural effectiveness under service loads at elevated temperature. It has been suggested in the literature that NSM systems may have distinct advantages over externally-bonded systems in fire, due mostly to protection provided by partial embedment in concrete. No research has apparently been presented to support this idea; thus, an initial scoping study was conducted to improve the understanding of the performance of NSM strengthening systems at temperatures such as might be expected for a *well-insulated* FRP strengthening system in a standard fire scenario. It should be noted that the current study was performed under the justifiable assumption that an *uninsulated* (i.e., fire exposed) FRP system, whether externally-bonded or NSM, would likely to lose structural effectiveness almost immediately during a standard fire (Foster and Bisby, 2008).

With the above points in mind, the specific objectives of the current study were:

1. to experimentally investigate the performance of simulated well-insulated NSM flexural strengthening systems for reinforced concrete structures, under sustained load, at temperatures that they might experience under a standard fire scenario in a bond-critical application; and
2. to investigate the potential for the high temperature performance of NSM FRP strengthening systems to be improved by using cementitious rather than epoxy adhesives.

EXPERIMENTAL PROGRAM

The current paper represents one component of a larger study investigating the performance and durability of NSM and externally-bonded FRP strengthened reinforced concrete members subjected to a variety of extreme environmental conditions, including low temperature, high temperature, sustained load, repeated freeze-thaw cycling, and repeated wet-dry cycling. The current paper considers tests on 13 reinforced concrete slab strip specimens, 11 of which were strengthened in flexure with a single strip of a commercially available FRP tape NSM strengthening system. The slab strips were tested either at room temperature under monotonic load to failure, or under sustained load with increasing surface temperature to failure. Tables 1 and 2 give summaries of the various test specimens, materials and systems, loading regimes, and parameters varied during testing.

The variables of interest during this study were:

1. the overall effects of the NSM strengthening system on member performance, as compared against unstrengthened members at room temperature;
2. the thermal and loading exposure conditions at the time of testing, which included tests at 21°C under stroke control to failure and tests at 100°C or 200°C surface temperatures under sustained load to failure; and
3. the type of adhesive system used for bonding the NSM FRP strengthening system, which was either epoxy or cementitious grout.

Test Specimens

Figure 1 shows the dimensions and details of the slab strip specimens. These were designed to simulate scaled down one-way reinforced concrete slabs with deficient internal steel reinforcement (such as might require strengthening with an NSM system). The goal of the slab strip design was to proportion the internal steel reinforcement to avoid crushing of the concrete or shear failure of the FRP strengthened specimens. It was also intended that the NSM 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-Draft (ACI, 2008), prior to overall failure of the member. It is worth noting that currently imposed strengthening limits were intentionally violated to ensure that the effectiveness of the FRP system was required to prevent failure under service loads (discussed in detail below). The resulting slab strips were lightly reinforced internally, with a steel reinforcement ratio, ρ_s , of only 0.24%. The dimensions of the slab strips and the NSM groove were chosen to meet the edge distances and

groove dimensions currently recommended by ACI 440.2R-08-Draft (ACI, 2008). The compressive strength of the concrete at the time of testing, f_c' , was 46.3 ± 1.6 MPa at 21°C, as determined from three standard cylinder tests in each case. 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 tensile tests. All beams had a 25.4 mm wide \times 25.4 mm deep notch at midspan. This notch was created to act as a crack initiator and to allow for installation of a conventional foil strain gauge on the NSM FRP strips within the slab strips' constant moment region.

NSM FRP Strengthening

Two slab strips were not strengthened and were tested as control specimens (C-RT-1 and C-RT-2). The remaining 11 slab strips were strengthened with a commercially available FRP tape developed specifically for NSM concrete strengthening applications and with one of two different adhesive systems (epoxy or cementitious grout). Table 2 provides information on the specific products used.

Table 1 Details of room and high temperature slab strip testing program.

Test	Specimen name ^a	Loading regime	NSM groove width (mm)	Adhesive type	Test temp. (°C)
1	C-RT-1	2 mm/min	--	--	21
2	C-RT-2	2 mm/min	--	--	21
3	E-RT-1	2 mm/min	6.4	Epoxy 1 ^c	21
4	E-RT-2	2 mm/min	6.4	Epoxy 1 ^c	21
5	G-RT-1	2 mm/min	6.4	Grout ^d	21
6	G-RT-2	2 mm/min	6.4	Grout ^d	21
7	E-100-1	2 kN/min to 20 kN hold	6.4	Epoxy 1	100
8	G-100-1	2 kN/min to 20 kN hold	6.4	Grout	100
9	E-200-1	2 kN/min to 20 kN hold	6.4	Epoxy 1	200
10	E-200-2	2 kN/min to 20 kN hold	6.4	Epoxy 1	200
11	E-200-3 ^b	2 kN/min to 20 kN hold	6.4	Epoxy 1	200
12	G-200-1	2 kN/min to 20 kN hold	6.4	Grout	200
13	G-200-2	2 kN/min to 20 kN hold	6.4	Grout	200

^a Adhesive-Testing temperature: C – control, E – NSM with epoxy adhesive, G – NSM with grout adhesive, RT – room temperature, 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)

^d Target® 1118 Grout (www.targetproducts.com)

Table 2 Selected properties of near surface mounted (NSM) system used.

Property	NSM CFRP ^a
Trade name	Aslan® 500 #2
Matrix resin	Vinylester
Matrix T_g (°C)	N/A ^b
Adhesive resin	Kemko® 038 Epoxy
Adhesive T_g (°C)	51 ^b
Width (mm)	16
Thickness (mm)	2
Cross sectional area (mm ²)	31.2
Tensile strength, f_{tu}^* (MPa)	2068 (2360) ^c
Tensile modulus, E_f (MPa)	124000 (129000) ^c
Ultimate strain, ϵ_{fu}^* (%)	1.70 (1.70) ^c

^a supplied by Hughes Bros, Inc., Seward, NB (www.hughesbros.com)
^b determined by the authors as an average of three tests using differential scanning calorimetry (DSC) with T_g taken on the second heating cycle. It was not possible to determine T_g for the Aslan FRP's matrix resin using DSC
^c values in brackets are as determined by the authors by testing 5 samples each in accordance with ACI 440.3R-04 (ACI, 2004)

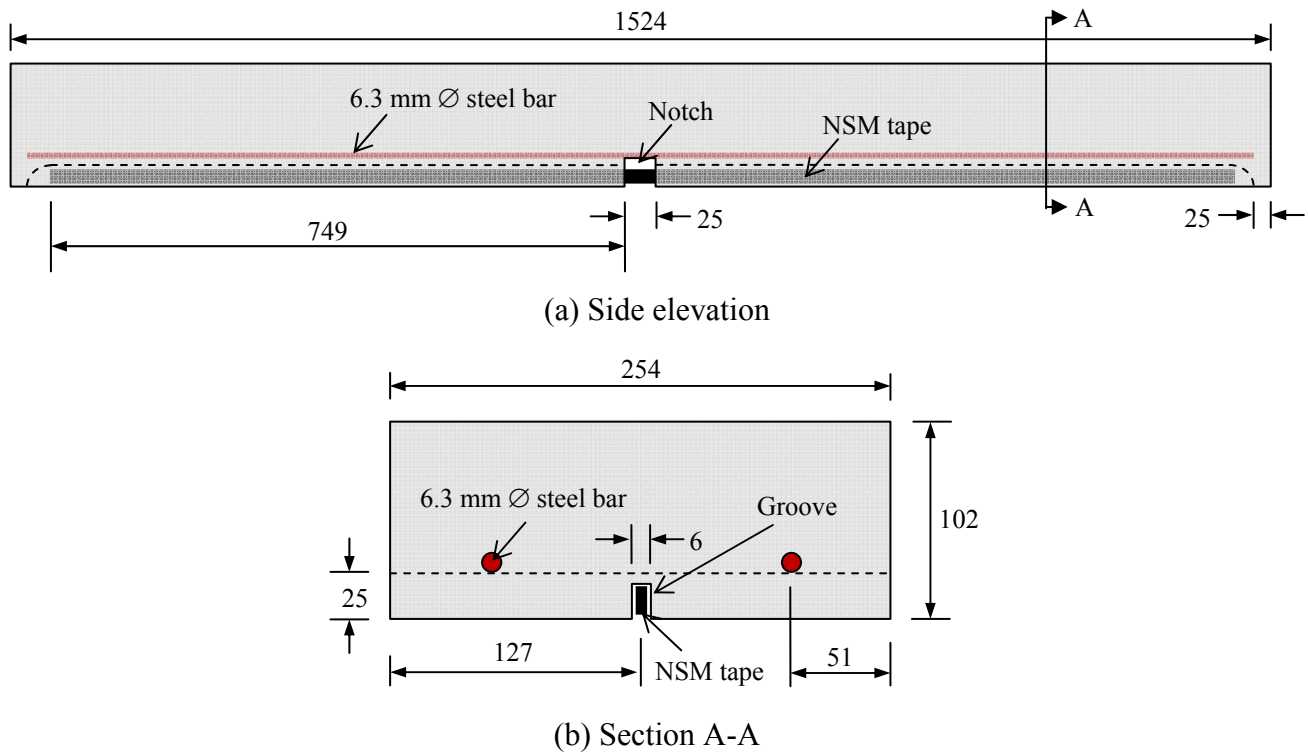


Fig. 1 NSM FRP strengthened reinforced concrete slab strips (all dimensions in mm).

To install the NSM FRP systems, grooves were cut along the centrelines of the slab strips using a tuckpoint grinder with a 6.35 mm (1/4") wide diamond concrete cutting disc. An aluminum guide was employed to ensure a straight cut with a consistent groove depth. Six slab strips were strengthened using a single Aslan® 500 #2 carbon/vinylester FRP tape, bonded into the groove using an epoxy adhesive. The specific epoxy product is sold under the trade name Kemko® 038 and is commercially available for crack injection of concrete structures.

It was selected through discussions with industry partners (Vector Construction, Winnipeg, Canada) who have developed a novel NSM installation procedure wherein the NSM FRP is installed by placing the FRP tape into a dry groove and then taping the groove and applying the resin under pressure using crack injection equipment. This technique has the advantages of using smaller amounts of adhesive (hence reducing costs), faster resin set times, and concurrent strengthening of the substrate concrete during the NSM bonding process by epoxy injection into cracks in the concrete cover in addition to ease, speed, cleanliness, and aesthetics of the installation. The glass transition temperature (T_g) of the cured epoxy adhesive was determined by the authors as 51°C based on an average of three tests using differential scanning calorimetry (DSC), with T_g taken on the second heating cycle at an age of seven days under ambient laboratory conditions.

The five remaining slab strips were also strengthened using a single Aslan® 500 #2 carbon FRP tape, but in this case the NSM was bonded using a commercially available cementitious unsanded silica fume grout which is sold under the trade name Target® 1118. This specific product was also selected through discussions with the industry partners. The intent in using this adhesive was again that the adhesive could be applied under pressure using crack injection equipment. The advantages of using the cementitious grout adhesive include considerably lower material costs, concurrent substrate concrete strengthening, reduced environmental hazards during installation, aesthetics of the completed installation (which is essentially invisible if care is taken during installation), and ease of installation for skilled contractors. Furthermore, the grout adhesive was anticipated to have superior performance at high temperature under sustained service loads, provided it could be shown to perform adequately under room temperature conditions as compared against epoxy adhesives.

The presumption of superior performance for the cementitious adhesive bonded NSM at elevated temperature stems from the recognition that the “weak link” in any bond-critical FRP strengthening system at elevated temperature is the bond between the FRP and the concrete. Polymer resins that are typically used as adhesives and matrix resins for FRP products and strengthening systems are usually the most affected system component at elevated temperatures. Because the Aslan FRP strips used in the current study are manufactured by pultrusion and cured at elevated temperature during this process, their vinylester resin matrix will be less affected by elevated temperature than the ambient-cure adhesive epoxies typically used in NSM FRP strengthening applications. Indeed, while it was not possible to determine T_g for the NSM tape’s matrix using DSC, its heat distortion temperature (HDT) is in the range of 2.5 times that of the Kemko epoxy used as an adhesive. 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 (Lie, 1992).

TEST SETUP & INSTRUMENTATION

All 13 beams were tested upside down in four-point bending as shown in Figure 2. This approach was required for monitoring of the bond performance using digital image correlation that was conducted as part of a larger experimental program. Data on load, crosshead stroke, vertical displacements, strains over the cross-section at midspan, and strain in the NSM FRP system in the notch at midspan were collected using conventional instrumentation (see Figure 2).

Six specimens were tested at room temperature to determine the level of strengthening achieved, FRP strain at failure, and failure mode. These data are presented in Table 3. Room temperature tests were also used to determine a suitable sustained load for high temperature testing for each of the two adhesive systems. Two control slab strips and two strengthened slab strips for each adhesive system were tested to failure under stroke control at a rate of 2 mm per minute.

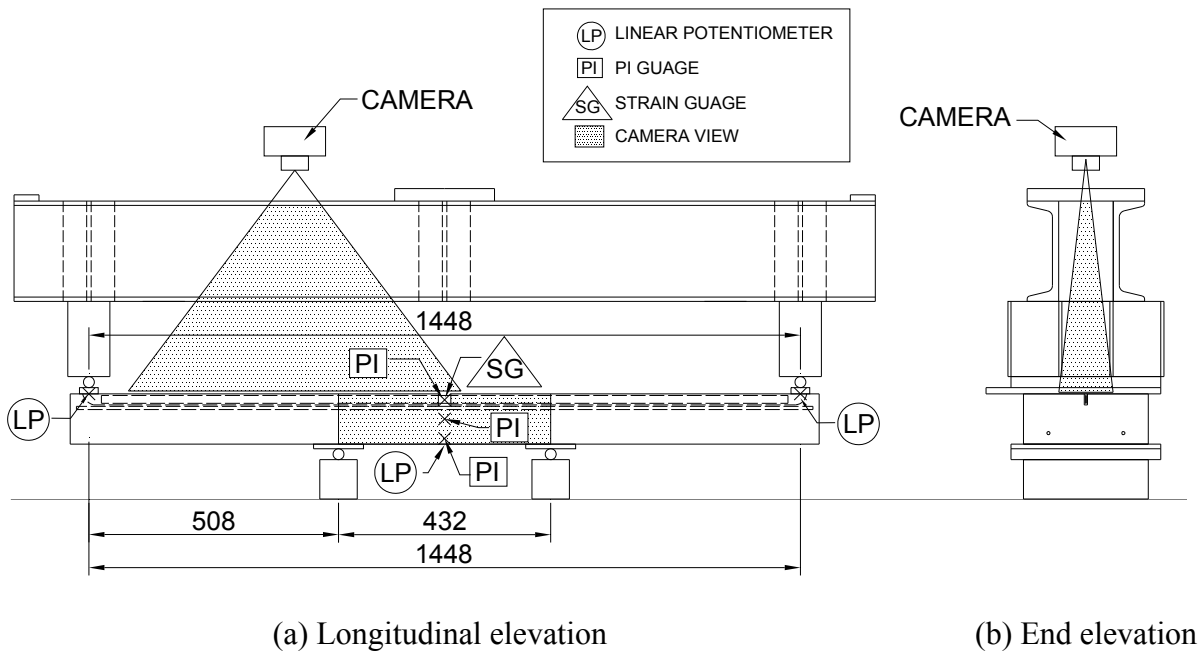


Fig. 2 Test setup and instrumentation (all dimensions in mm).

Table 3 Results of room 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-RT-1	12.7	3.2	N/A	N/A	N/A	Crushing (under-reinforced)
C-RT-2	11.4	2.9	N/A	N/A	N/A	Crushing (under-reinforced)
E-RT-1	33.5	8.5	178	1.26	74	Shear crack induced debond/failure
E-RT-2	34.9	8.9	190	1.41	83	Debonding by epoxy/concrete split
G-RT-1	24.6	6.3	104	0.85	50	Debond @ grout-strip interface
G-RT-2	27.1	6.9	125	0.94	55	Debond @ grout-strip interface

^a C- control, E- epoxy, G- grout, RT – room temperature
^b compared against the average of control samples tested at room temperature
^c based on manufacturer-specified ultimate strain values (see Table 2)

The remaining seven specimens were tested under sustained load under increasing temperature exposure. For these tests, the beams were initially loaded at room temperature under load control at a rate of 2 kN per minute to a sustained load of 20 kN. The 20 kN sustained load was based on results from room temperature tests, and was selected to ensure that the FRP strengthening systems experienced sustained strain levels between 40% and 60% of ultimate while being heated. The level of the sustained load was also selected to be higher than the failure load of the unstrengthened slab strips. Therefore, failure would occur as soon as the bond integrity or strength of the FRP was lost. In this manner, it was possible to conservatively determine the temperatures at which the FRP strengthening systems became ineffective.

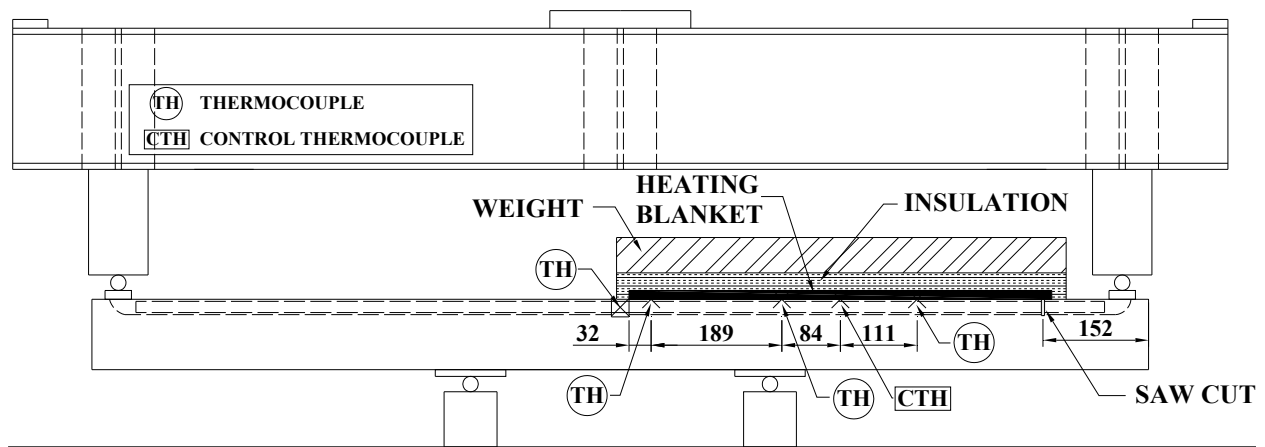


Fig. 3 High temperature heating assembly and thermal instrumentation (all dimensions in mm).

Once the 20 kN load was achieved, the load was allowed to stabilize for two minutes, and the heating commenced using a heating blanket up to a soak temperature of either 100°C or 200°C. The surface temperature of the FRP strengthening system was raised as quickly as possible (approximately 10-20°C per minute), and then held constant at the predetermined soak temperature until failure occurred under the sustained load. The 100°C soak temperature was selected based on actual FRP strengthening system surface thermal histories recorded during full scale fire tests of insulated FRP-strengthened reinforced concrete members conducted by the second and third authors (Kodur et al., 2006). These previous tests demonstrated that, with sufficient supplemental fire insulation, the temperature of the concrete surface could be maintained at or below 100 °C for up to 4 hours of exposure to a standard fire. The 200°C soak temperature was the maximum possible temperature that could be achieved for the heating system used.

Figure 3 shows the heating system for the high-temperature tests. An Omegalux[®] silicone rubber fibreglass reinforced heating blanket was applied to the tension face of one end of the slab strip specimens (i.e., over one half of the length of the NSM 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 slab strip (CTH in Figure 3). A layer of Fiberfrax[™] ceramic fibre insulation was placed on top of the heating pad to prevent heat loss away from the slab strips. The temperature of the top surface of the concrete was monitored throughout the tests at various locations using four Type-T thermocouples.

EXPERIMENTAL RESULTS

Figure 4 gives the applied load versus midspan deflection behaviour of all six slab strips tested at room temperature, and Table 3 provides selected data from these tests. The unstrengthened control slab strips (C-RT-1 and C-RT-2) displayed under-reinforced flexural behaviour, failing due to concrete crushing in the constant moment region after yielding of the internal steel reinforcement. The NSM slab strips strengthened using epoxy adhesives (E-RT-1 and E-RT-2) achieved much higher strengths compared to those strengthened with cementitious grout, exhibiting strength increases in the range of 180% over the control specimens.

One of these specimens failed by FRP debonding/rupture, coincident with global shear failure of the cross-section at one of the loading points. It remains unclear whether the shear failure induced the bond failure or vice versa in these tests, but it was noted that a large flexural-shear crack had formed prior to failure (at very large curvatures), and this likely initiated member failure. The other specimen failed by splitting bond failure of the FRP in the concrete adjacent to the epoxy-concrete interface.

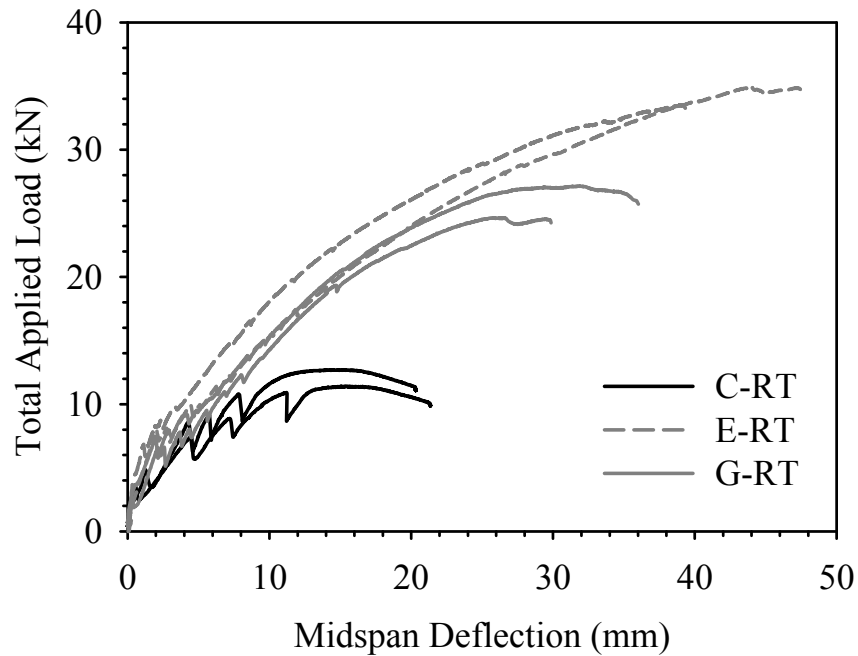


Fig. 4 Applied load versus midspan deflection for slab strips tested to failure at room temperature.

The NSM grout adhesive slab strips (G-RT-1 and G-RT-2) achieved more modest strength increases (in the range of 100% over the unstrengthened control specimens) with slightly less stiff responses than the epoxy adhesive strengthened slab strips. This behaviour is presumed to be a consequence of the extensive cracking of the grout adhesive that was observed during the tests, particularly at loads approaching ultimate. For these specimens, failure was initiated by debonding and resulted in pullout of the NSM strip at the grout-strip interface. Clearly, this represents a less efficient use of the NSM tape than for the epoxy adhesive case, since the strain in the FRP at failure was only 50-55% of the ultimate tensile strain (as compared with 74-83% for the epoxy adhesive).

In all cases, the level of strengthening achieved for the NSM strengthened specimens fell well outside the levels currently permitted for design of real FRP strengthening applications, which would normally be in the range of 40-60% for realistic live-to-dead load ratios (ACI, 2008). Thus, such a high level of FRP strengthening would not likely be attempted in practice. This unrealistic level of strengthening was intentional, however, since it allowed the authors to clearly study high temperature effects at load levels where the FRP was required to contribute to the strength to avoid failure. It should be noted with reference to Figure 4 that the 20 kN sustained load used in the heating tests would be expected to cause member failure in the absence of the FRP strengthening systems. Selecting this high level of sustained load meant that no high temperature control tests could have been conducted on unstrengthened specimens.

Figure 5 shows typical average concrete temperatures measured at the centerline of the tension face during the elevated temperature exposures for beams of both adhesive types, and shows that the ramp and soak phases were essentially achieved in all cases. The data represent averages of three point thermocouples installed along the centreline of the slabs beneath the heating blanket (see Figure 3).

Table 4 and Figure 6 show data obtained during testing at elevated temperatures. Table 4 shows that the strain in the FRPs at the beginning of heating was between 0.49% and 0.58% (this corresponds to between 29% and 34% of the ultimate tensile strain for this NSM system). These strains are in the upper range of likely service strains for FRP strengthening systems in practice.

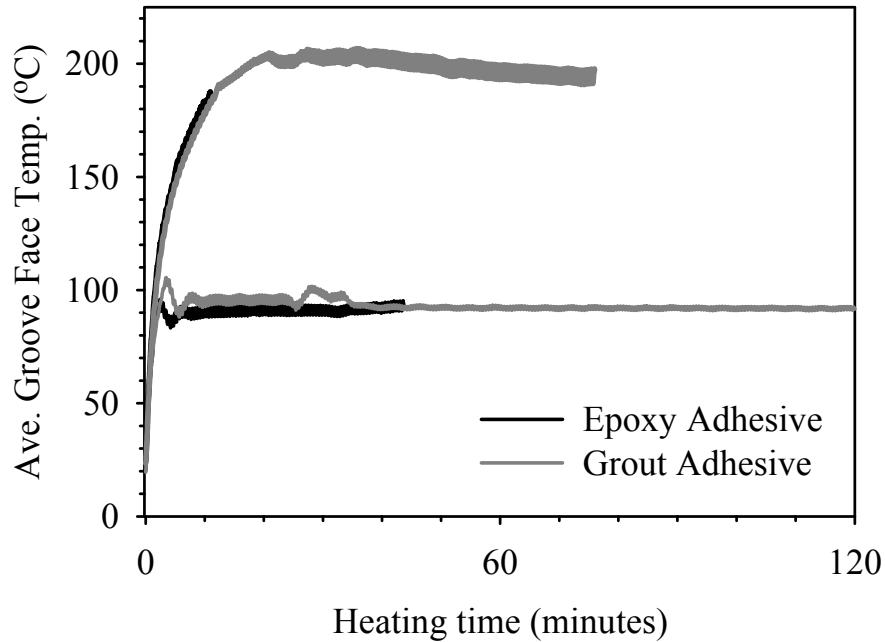


Fig. 5 Typical temperature at the exterior surface of the NSM groove versus heating time.

Figure 6 shows the relative performance of the two different adhesive systems at high temperature by comparing midspan vertical displacement versus heating time (including the temperature ramp phase) for all specimens tested at elevated temperature. This plot also includes the midspan deflections recorded during initial loading up to 20 kN (i.e., before turning on the heating system). This figure shows that the various specimens had similar stiffnesses up to the sustained load of 20 kN. Small fluctuations observed in the traces shown in Figure 6 were 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 results.

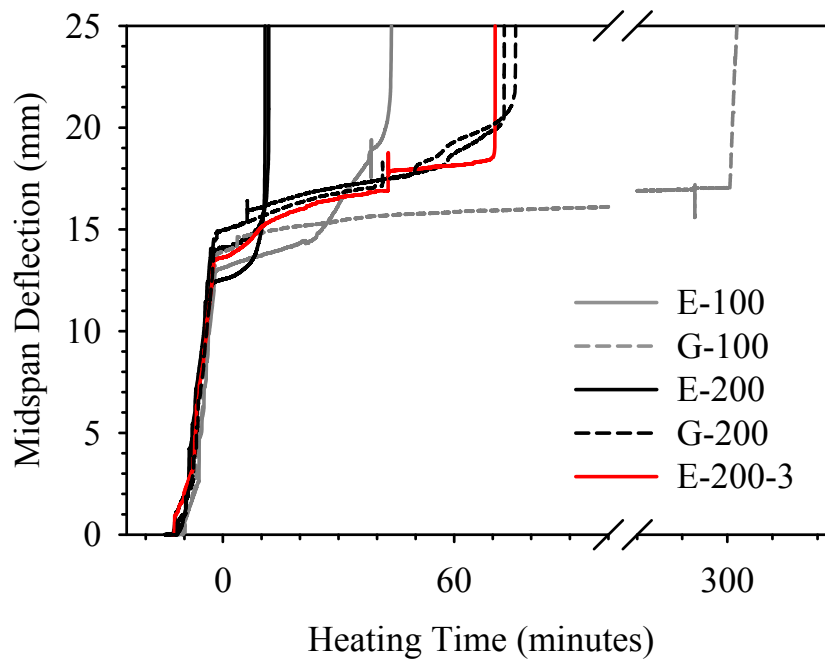


Fig. 6 Midspan deflection versus heating time for slab strips tested at high temperature under sustained load.

Table 4 Results of high temperature testing.

Test	Target temp (°C)	FRP strain @ beginning of heating (%) ^a	Time heated @ failure (min)	Surface temp @ failure (°C)	Groove base temp @ failure (°C) ^b	Adhesive T_g (°C)	Failure load (kN)
E-100-1	100	0.58	44	94	35	51 ^c	20.0
G-100-1	100	0.56	No fail @ 300	91	48	N/A ^d	27.3
E-200-1	200	0.49	11	185	42	51	20.0
E-200-2	200	0.56	12	166	34	51	20.0
E-200-3	200	0.50	71	N/A	N/A	51	20.0
G-200-1	200	0.52	73	179	69	N/A	20.0
G-200-2	200	0.58	76	197	54	N/A	20.0

^a centreline strain based on single foil strain gauge
^b approximate values based on standalone heating validation tests performed after structural testing
^c determined by the authors as an average of three tests using differential scanning calorimetry (DSC) with T_g taken on the second heating cycle
^d it was not possible to determine the T_g value for the NSM tape's matrix using DSC

All elevated temperature tests terminated due to bond failure in either the vinylester matrix of the NSM tape or in the epoxy adhesive. Epoxy 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 minutes, 11 minutes, and 12 minutes of heating, respectively. Bond failure initiated at the epoxy-concrete interface with a smooth and distinct failure plane. Room temperature bond failures in beams strengthened with this system and adhesive typically occurred about 1 mm into the substrate concrete from the epoxy-concrete interface. This change in failure plane is a clear indication of deteriorating mechanical properties of the epoxy adhesive at elevated temperatures. Interestingly, while the surface temperature was well above the epoxy adhesive's T_g (measured as 51°C) at the instant of failure, the base of the NSM groove was somewhat below T_g in all cases.

Grout specimens G-200-1 and G-200-2 displayed superior performance as compared with all epoxy-bonded specimens, and failed under the 20 kN load after 73 and 76 minutes of heating, respectively, by pullout at the NSM tape-grout interface. The enhanced performance of this adhesive system can be attributed to the fact that the weak link in this strengthening system, from a thermal point of view, was the vinylester matrix of the NSM tape, which had considerably better resistance to high temperature than the Kemko epoxy adhesive (as previously discussed). Specimen G-100-1 displayed (as did all other specimens) an increase in midspan deflection during the first hour of heating due to thermal bowing resulting from heating of its tensile face, but the deflection then levelled off and the slab strip 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. Thus, this specimen actually tested stronger than either of its room temperature equivalents, indicating that the heating to 100°C had no discernable negative impact on performance of the system.

Specimen E-200-3, which was the first specimen tested at elevated temperature, was anomalous and is worthy of mention. Due to an error in the testing procedures, this specimen was inadvertently tested with approximately 50 mm of the bond unheated at the unloaded end. As a result, this specimen was able to hold the sustained load for more than one hour (or approximately seven times the otherwise identical epoxy adhesive strengthened specimens). This result demonstrates the previously observed (Blontrock et al., 2000) result that only short lengths of unheated bonded regions are required to maintain the structural effectiveness of bond-critical FRP strengthening systems at high temperature. This further implies that it may not be necessary to insulate the full

length of an NSM FRP strengthening system to provide protection against fire, but that partial insulation may be sufficient in some cases. Clearly, additional research is required to support this concept.

CONCLUSIONS

Based on the initial testing presented in this paper, the following preliminary conclusions can be drawn:

1. The epoxy adhesive used herein provides superior bond performance as compared with the cementitious grout adhesive used for NSM FRP strengthening systems for RC members, although grout adhesives can apparently be used but with more stringent strain limits. Additional research is needed to better understand bond development for both types of adhesive.
2. If well insulated against the thermal impact 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 have sufficient strength to resist service loads. While additional research is needed to confirm this possibility, it appears that:
 - a. the epoxy adhesive NSM FRP strengthening system may be capable of withstanding up to 44 minutes of fire;
 - b. the performance at high temperature of NSM FRP strengthening systems can be improved considerably by using a cementitious grout adhesive; and
 - c. the grout adhesive NSM FRP strengthening system tested herein may be capable of withstanding more than 4 hours of fire.

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