Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24July 2008, Zurich, Switzerland

Performance of NSM FRP strengthened concrete slabs at low temperatures

P. Burke, L.A. Bisby & M.F. Green
Department of Civil Engineering, Queen's University, Kingston, Ontario, Canada

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 able to more fully exploit the strength of FRP materials because of generally superior anchorage performance. Research to date has focused primarily on overall member behaviour and/or the various parameters that affect the bond of either rectangular NSM strips or round NSM bars. Little information is available on the cold-regions durability of these systems, in particular with respect to their performance at low temperatures as might be experienced in bridge, parking, and some industrial applications. Available research studying the performance of externally bonded FRP strengthening systems at low temperatures has shown few negative effects. Nevertheless, with the increased volumes of adhesive required for NSM applications and the associated differential thermal expansion between the FRP, adhesive, and substrate concrete, damage due to differential thermal expansion and epoxy embrittlement at low temperature could become important. This paper presents the results of an experimental program investigating the low temperature flexural performance of NSM carbon/vinylester FRP tape strengthened concrete slabs. The effects of adhesive type (cementitious or epoxy) and groove width are discussed at both room (21˚C) and low (-26˚C) temperature. The results show no discernable negative impacts on the performance of any of the strengthened members at low temperature.

1 INTRODUCTION AND OBJECTIVES

This paper deals with the low temperature performance of near surface mounted (NSM) FRP systems for flexural strengthening of reinforced concrete (RC) members. Research performed over the past two decades has clearly shown that existing RC members can be strengthened by externally bonding FRP sheets (typically unidirectional) to the beams' tensile face(s) with an epoxy adhesive to increase their flexural strength and stiffness. Despite the popularity of these externally-bonded (EB) systems, in practice they have a number of limitations. A primary limitation is that the bond between the concrete and the FRP, which is critical for adequate performance in most cases, is often unable to develop the full tensile strength of the FRP sheet, resulting in undesirable debonding failures. The resulting design procedures for these systems often impose severe strain limits making them less economical, and hence less competitive then if the full strength were used. Furthermore, because these systems are located on the external faces of the member, the FRP and adhesive are directly exposed to the environment, fire, and vandalism.

The aforementioned drawbacks of EB FRP strengthening systems have led to the development of NSM FRP strengthening techniques. In these techniques, slots are cut into the surface(s) of structural members and FRP reinforcement is bonded into the grooves with an adhesive (typically an epoxy resin). This technique is often able to mobilize a greater proportion of the strength of the FRP because of superior bond characteristics that help to prevent debonding failures. Furthermore, because NSM FRP strengthening systems are located slightly within the member, they are somewhat protected from damage, environmental effects, fire, and vandalism.

While both research and field applications of NSM FRP systems have been promising (De Lorenzis and Teng 2006), little research has been reported on durability related issues with respect to NSM FRP strengthening techniques for concrete. In particular, apparently only one study is available on the performance of NSM FRP strengthening systems at low temperature (Taljsten et al. 2003). As such, a research project was undertaken to:

1. experimentally investigate the performance of flexural NSM FRP strengthening systems for RC slabs at temperatures as low as -26°C; temperatures that might realistically be experienced in bridge or parking garage slab strengthening applications in Canada;
2. experimentally investigate the relative performance of both epoxy and cementitious adhesives for NSM FRP applications for RC members at room and low temperatures, with a view to reducing installation costs for NSM systems by using lower cost adhesives; and
3. experimentally investigate the effects of groove width on the performance of NSM FRP strengthening systems, again with a view to reducing the costs of these systems by reducing the required volume of adhesives.

2 EXPERIMENTAL PROGRAM

The experimental program consisted of tests on 16 RC slab strips each strengthened in flexure with a single strip of a commercially available carbon FRP tape NSM system and tested at a uniform temperature of either 21˚C or -26˚C. Figure 1 shows dimensions and reinforcement details of the RC specimens. The slab strip specimens were designed to simulate a scaled down one-way RC slab strengthened with an NSM FRP system. The goal of the slab design was to avoid crushing of the concrete or shear failure of the NSM strengthened specimens, such that the NSM system would reach levels of strain sufficient to cause bond failure prior to overall failure of the member. The dimensions of the slab strips and the NSM groove were chosen to meet the edge distances and groove dimensions recommended by ACI 440.2R-07-Draft (ACI 2007), with the exception of beams with a 3.2 mm wide groove which violated the minimum groove width requirement. Grooves were cut by hand using a tuckpoint grinder with a diamond concrete cutting disc. All beams had a small notch at midspan to act as a crack initiator and to allow for installation of a conventional foil strain gauge on the FRP strip within the constant moment region.

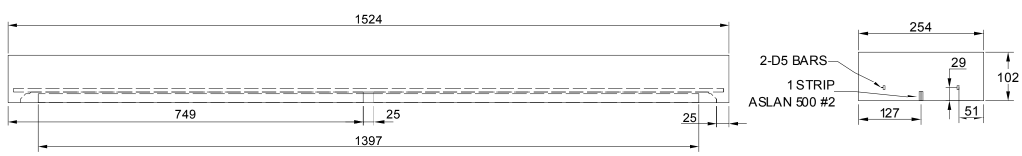


Figure 1. Details and dimensions (in mm) of NSM FRP strengthened RC slab strips.

Table 1 provides details of the specific materials used and parameters varied during testing. The variables of interest were: i) the effect of NSM strengthening, ii) the thermal exposure condition at the time of testing (21˚C or -26˚C), iii) the type of adhesive system (epoxy or cementitious grout), and iv) the width of the NSM groove (3.2 mm or 6.4 mm nominal).

The compressive strength of the concrete at the time of testing, f_c', was 46.3 ± 1.6 MPa at 21˚C and 50.1 ± 0.8 MPa at -26˚C, as determined from three standard cylinder tests in each case. The average properties of the CFRP strip were determined from six coupon tests in accordance with ACI 440.3R-04 (ACI 2004) as ultimate strength, f_{fu} = 2780 ± 140 MPa, elastic modulus, E_f = 141 ± 4 GPa, and strain at failure, ε_{fu} = 2.0 ± 0.1 %. The manufacturer specified properties of the FRP strips were f_{fu}^* = 2068 MPa, E_f = 124 GPa, and ε_{fu}^* = 1.7 %.

All beams were tested upside down in four-point bending (see Fig. 2) to enable monitoring of the bond performance using digital image correlation (details of this are not presented in the current paper). Conventional instrumentation was used to collect data on load, crosshead stroke, vertical displacements, strain over the cross-section at midspan, and strain in the NSM FRP strip at midspan (Fig. 2).

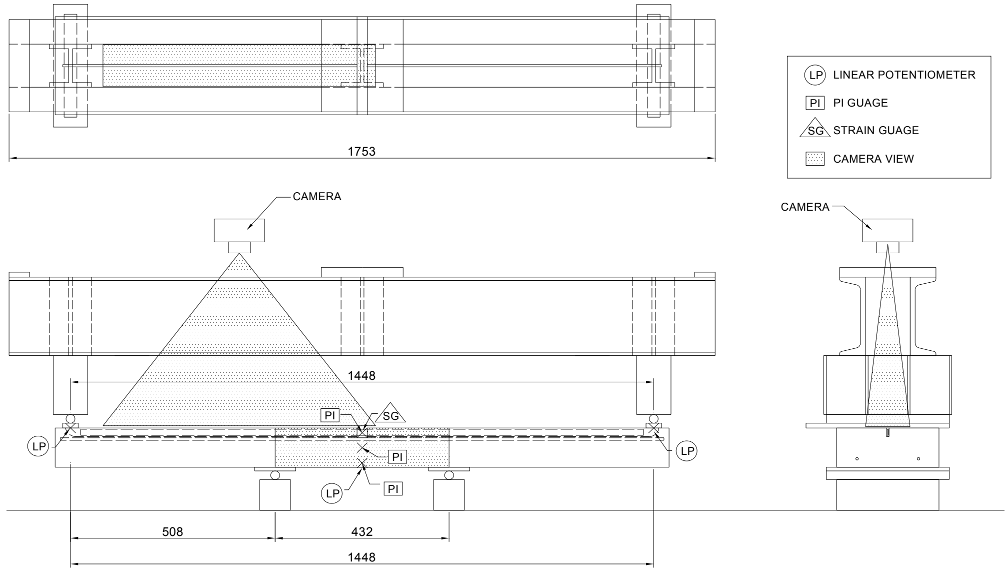


Figure 2. Details of test setup and instrumentation (all dimensions in mm).

Table 1. Details and selected results of the experimental program

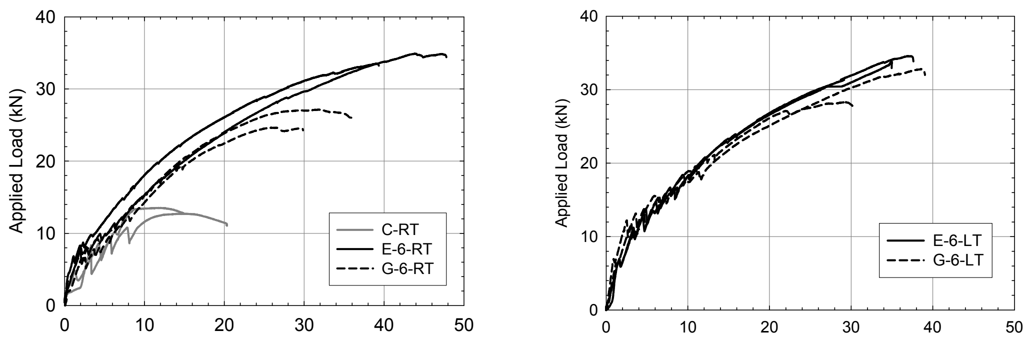
Specimen name[a]	Study variable	Groove width (mm)	Adhesive type	Test temp. (°C)	Norma-lized ult. load[e]	Normalized FRP strain at failure[f]	Failure mode[g]
C-RT-1	Control	--	--	21	1.05	--	CC
C-RT-2	Control	--	--	21	0.95	--	CC
E-6-RT-1	NSM[b]	6.4	Epoxy[c]	21	2.78	0.74	SC
E-6-RT-2	NSM	6.4	Epoxy	21	2.90	0.83	DEC
E-3-RT-1	Groove width	3.2	Epoxy	21	2.60	0.66	DEC
E-3-RT-2	Groove width	3.2	Epoxy	21	2.77	0.71	DEC
G-6-RT-1	Adhesive type	6.4	Grout[d]	21	2.04	0.50	DGS
G-6-RT-2	Adhesive type	6.4	Grout	21	2.25	0.56	DGS
C-LT-1	Low temp. control	--	--	-26	1.12	--	CC
C-LT-2	Low temp. control	--	--	-26	1.15	--	CC
E-6-LT-1	Low temp. NSM	6.4	Epoxy	-26	2.80	0.71	SC
E-6-LT-2	Low temp. NSM	6.4	Epoxy	-26	2.87	0.70	SC
E-3-LT-1	Groove width	3.2	Epoxy	-26	2.89	0.83	DEC
E-3-LT-2	Groove width	3.2	Epoxy	-26	3.05	0.80	SC/DEC
G-6-LT-1	Adhesive type	6.4	Grout	-26	2.35	0.52	DGS
G-6-LT-2	Adhesive type	6.4	Grout	-26	2.72	0.70	DGS

[a] Adhesive-Groove width-Testing temperature-Test number: C – control, E – epoxy adhesive, G – grout adhesive, 6 – 6.4 mm groove width, 3 – 3.2 mm groove width, RT – room temp., LT – low temp.
[b] Aslan™ 500 #2 CFRP tape (www.hughesbros.com).
[c] KEMKO® 038 Crack Injection Epoxy (www.chemcosystems.com).
[d] Target® 1118 Grout (www.targetproducts.com).
[e] Normalized against the average strength of the unstrengthened slab strips tested at room temperature..
[f] Normalized against the manufacturer specified ultimate strain value of $\varepsilon_{fu}* = 0.017$.
[g] CC – concrete crushing, SC – shear crack induced debonding, DEC – debonding at the epoxy-concrete interface, DGS – debonding at the grout-strip interface.

3 RESULTS AND DISCUSSION

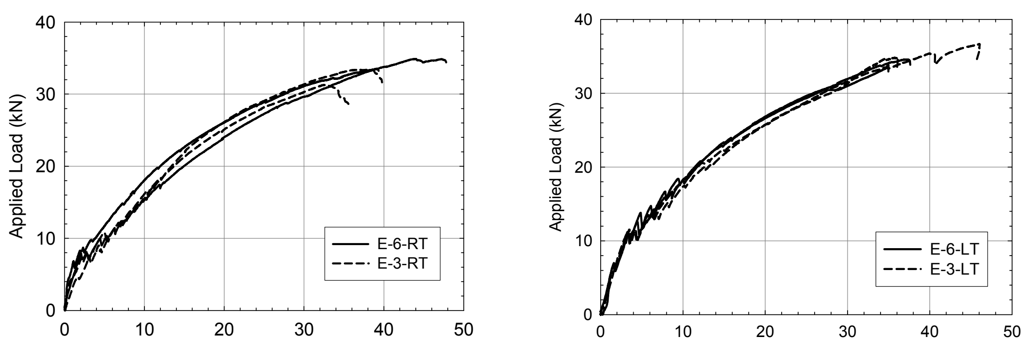
Table 1 and Figures 3 through 6 provide selected results of the experimental program. The behaviour of the various NSM FRP strengthened slab strip specimens subject to each of the parameters is compared based on their observed load versus midspan deflection response. In addition, the specific performance of the NSM systems is compared (Fig. 6b) on the basis of strain in the FRP strip at midspan at failure. The reader will note that ACI 440.2R-07-DRAFT (ACI 2007) suggests an FRP strain limit of $0.7\varepsilon_{fu}$ to prevent debonding failures of NSM systems.

Figure 3 isolates the effects of adhesive type on the applied load versus midspan deflection response of slab strips with a nominal groove width of 6.4 mm tested at both room temperature and low temperature. Unfortunately, an instrumentation malfunction led to the loss of deflection data for the control beams tested at low temperature. Keeping in mind that only two specimens of each type were tested in the current study, and thus the observed trends discussed below must be viewed with caution in terms of their statistical significance, Figures 3a and 6 show that the effect of the addition of the NSM reinforcement was pronounced for all adhesive systems and groove widths, with strength increases ranging from a minimum of 104% for the grout adhesive to 190% for the epoxy adhesive and significant midspan deflection increases at failure. Figure 3 also suggests that the grout adhesive system may be somewhat less effective than the epoxy adhesive system, with the difference between systems being more pronounced at 21˚C (about 24% lower strength on average for the grout adhesive) than at -26˚C (about 11% lower strength on average).



(a) (b)

Figure 3. Effect of adhesive type on applied load versus midspan deflection response of slab strips tested at (a) room temperature and (b) low temperature.



(a) (b)

Figure 4. Effect of NSM groove width on applied load versus midspan deflection response of slabs strips tested at (a) room temperature and (b) low temperature.

Figures 4 and 6a show the effects of NSM groove width on the response of slabs strips tested at both room and low temperature (for the epoxy adhesive system only). These figures suggest that, for the systems tested herein, there is no discernable effect of groove width on the performance of the slab strips at either room or low temperature (about ±6% variation in strength for different groove widths).

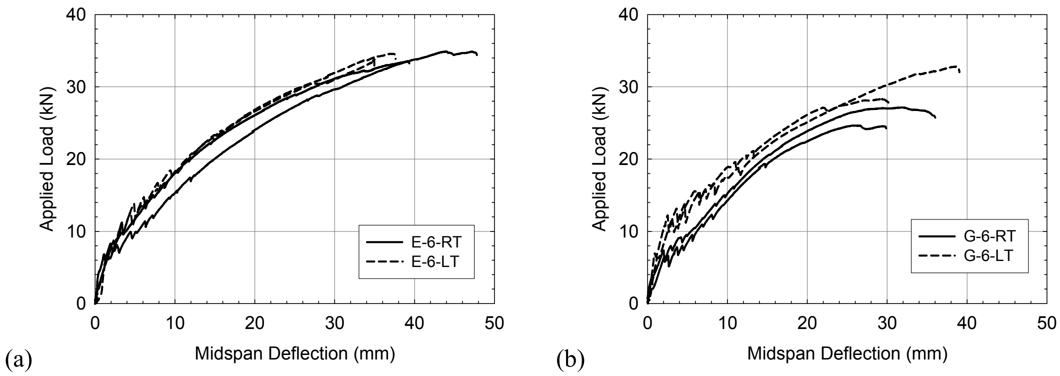


Figure 5. Effect of low temperature on slabs strips with (a) epoxy and (b) cementitious grout adhesive.

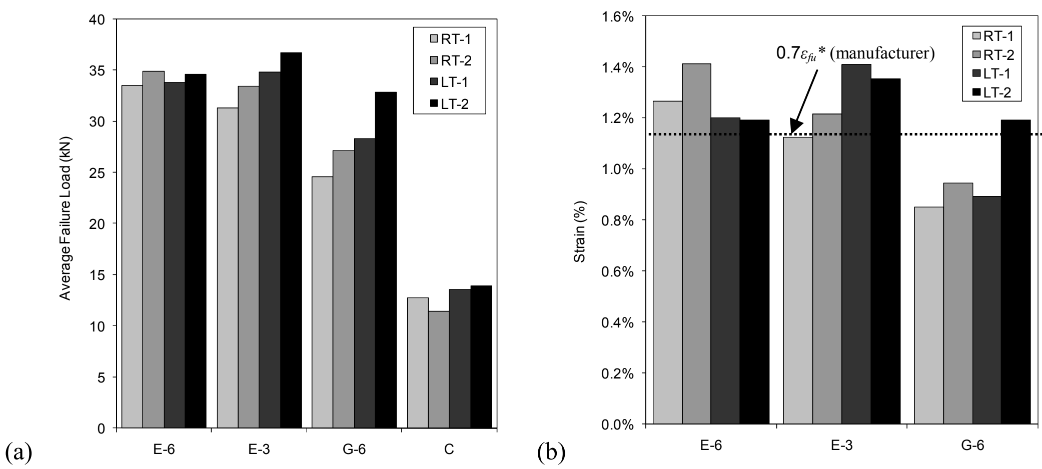


Figure 6. Performance of slab strips with respect to (a) load capacity and (b) strain in the FRP at failure.

Figure 5 isolates the effect of low temperature on slabs strips with both epoxy and grout adhesive systems. In general, epoxy adhesive strengthened slab strips (Figs. 5a and 6a) tended to be unaffected (6.4 mm groove width) or to have very slightly increased load capacity (3.2 mm groove width) by exposure to low temperature. This is as expected given the observed failure modes discussed below and the well known beneficial effects of low temperatures (-26˚C) on the strength and stiffness properties of concrete. The increase in concrete and grout strength at low temperature is also demonstrated by the slight (14% on average) improvement in the strength of the unstrengthened control slabs at low temperature as compared with the room temperature control slabs (Fig. 6a). Figure 5b shows an increase in the cracking strength and load capacity at low temperature for grout adhesive strengthened slab strips (average strength increases of about 18%). Again, this can be attributed to the improved properties of the concrete (and presumably the cementitious grout adhesive) at low temperature.

Figure 6b shows the relative performance of the respective slab strips with respect to an important parameter in the design of these types of strengthening systems: the tensile strain in the FRP strip at failure. Also included in this figure is the strain limit currently being proposed by ACI 440.2R-07-DRAFT (ACI 2007) for design of these systems (ignoring environmental effects). It is important to note that the FRP strain was measured only at midspan in tests described herein, such that the actual strain in the FRP strip at the location of failure is not known. However, because the slabs were tested in third-point loading, it is reasonable to assume that the FRP strain was more or less constant within the constant moment region, in which failure initiated for most members. This figure shows that the proposed strain limit accurately captures the FRP strains at failure for the epoxy adhesive strengthened slabs tested herein. Clearly, it is likely that localized FRP strain increases were acting near flexural cracks in the constant moment region, but from a design perspective the strain limit seems to perform well. Slabs strengthened using the grout adhesive were less able to develop strain in the FRP prior to failure, showing a 33% failure strain reduction (on average) at room temperature, and a 13% reduction at low temperature, as compared against the epoxy adhesive system.

Table 1 provides a summary of the failure modes experienced by each of the slab strips tested in the current study. All unstrengthened slabs failed by concrete crushing in the constant moment region after yielding of the internal steel reinforcement, as expected. In general, The NSM FRP strengthened slab strips failed by sudden and violent debonding of the FRP strengthening system. In all cases, the FRP debonding initiated near one of the loading points (i.e., at the location of maximum combined bending moment and shear), with the failure initiating at the location of a large flexural or flexural-shear crack. It is noteworthy that, where bond failure occurred, the failure was in the concrete directly adjacent to the epoxy-concrete interface for the epoxy adhesive slabs but in the grout adhesive adjacent to the FRP-grout interface for the grout adhesive slabs. This observation may partly explain the lower observed FRP strains at failure for the grout adhesive strengthened beams in the current study, since available NSM debonding models predict superior bond performance for NSM strengthening systems with a larger perimeter at the adhesive (polymer)-concrete interface (Seracino et al. 2007). For the grout adhesive strengthened beams in the current study, the polymer-concrete interface can be taken as the strip-grout interface, and the perimeter can be based on the FRP strip's dimensions, rather than on the groove dimensions as would typically be the case. Finally, under likely service load levels, all of the NSM FRP strengthened slabs performed in a similar manner to each other.

4 CONCLUSIONS

This paper has presented the results of a series of tests designed to investigate the performance of RC slab strips strengthened in flexure with NSM carbon FRP tapes with varying adhesive type, groove width, and temperature (room or low temperature). Based on these preliminary results:

- epoxy adhesives provide superior performance as compared with cementitious grout adhesives for NSM FRP strengthening systems for RC members, although grout adhesives can be used effectively;
- there is no discernable impact of groove width on the performance of epoxy adhesive strengthened members at either room or low temperatures; and
- there are no discernable negative effects of low temperature on the performance of NSM FRP strengthened RC slabs using either epoxy or cementitious grout adhesives.

5 ACKNOWLEDGEMENTS

The authors are members of ISIS Canada and wish to acknowledge the support of the Networks of Centres of Excellence Program of the Government of Canada and the Natural Sciences and Engineering Research Council of Canada, Vector Construction, and Hughes Bros. Inc.

6 REFERENCES

ACI 2007. *ACI 440.2: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. Farmington Hills, MI: American Concrete Institute.

ACI 2004, *ACI 440.3: Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures*. Farmington Hills, MI: American Concrete Institute.

De Lorenzis, L., Teng, J.G. 2006. Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures. *Composites Part B: Engineering* 38: 119-143.

Seracino, R, Raizal Saifulnaz, M.R. Oehlers, D.J. 2007. Generic Debonding Resistance of EB and NSM Plate-to-Concrete Joints. *Journal of Composites for Construction* 11(1): 62-70.

Täljsten, B., Carolin, A., Nordin, H. 2003. Concrete Structures Strengthened with Near Surface Mounted Reinforcement of CFRP. *Advances in Structural Engineering* 6(3): 201-213.