EFFECTS OF SUSTAINED LOAD AND FREEZE-THAW EXPOSURE ON RC BEAMS STRENGTHENED WITH PRESTRESSED NSM-CFRP STRIPS

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ABSTRACT
An experimental program was conducted to investigate the combined effects of sustained load and freeze-thaw cycling exposure on the flexural behaviour of reinforced concrete (RC) beams strengthened in flexure using prestressed Near-Surface Mounted (NSM) Carbon Fibre Reinforced Polymer (CFRP) strips. Two sets of three large-scale rectangular RC beams (sets BS-F and BS-FS) were tested. Each set consisted of one unstrengthened control beam, one strengthened beam with non-prestressed NSM-CFRP strips, and one strengthened beam using prestressed NSM-CFRP strips with 60% of the ultimate tensile strength of the CFRP strips. After strengthening, three beams from set BS-F were exposed to 500 freeze-thaw cycles (three cycles per day between +34°C to −34°C with a relative humidity of 75% for temperatures above +20°C). Also, the beams from set BS-FS were exposed to 500 freeze-thaw cycles (three cycles per day between +34°C to −34°C with fresh water spray for 10 minutes at a rate of 18 L/min at a temperature of +20°C while being subjected to a sustained load equal to 47% of the theoretical ultimate capacity of the non-prestressed NSM-CFRP strengthened beam. The beams were simply supported and tested under static monotonic loading in four-point bending configuration until failure. The damage done to the beams due to exposure was evaluated, and furthermore, the effects of sustained load and freeze-thaw exposure were elaborated on the load-deflection response, type of failure, ductility, and energy absorption. Analysis of the results revealed the significant effects of the sustained load and freeze-thaw cycling exposure on the flexural performance of RC beams strengthened with prestressed and non-prestressed NSM-CFRP strips.

KEYWORDS
CFRP, ductility, freeze-thaw, sustained load, near-surface mounted, prestressing, strengthening, temperature.

INTRODUCTION
Deterioration of RC structures due to severe weather conditions is a common problem in many countries. Identification of a proper upgrading method for damaged structure by considering its performance under severe weather conditions is vital. Prestressed Near-Surface Mounted (NSM) Carbon Fibre Reinforced Polymer (CFRP) is one of the latest developed strengthening methods in which a prestressed CFRP reinforcement is mounted into a pre-cut groove on tension face of a RC member. Several researchers performed experimental and analytical studies on using prestressed NSM-CFRP reinforcements for flexural strengthening of RC members (Nordin and Täljsten 2006; De Lorenzis and Teng 2007; Gaafar 2007; Badawi and Soudki 2009; Omran and El-Hacha 2010, 2012a, 2012b, 2012c, 2012d; El-Hacha and Gaafar 2011; Oudah 2011; Oudah and El-Hacha 2011, 2012a, 2012b, 2012c, 2012d; El-Hacha and Oudah 2013). In earlier studies, the prestressing was applied against both ends of the RC beam or against an independent steel reaction frame that made this method impractical for field applications. The practical issue of the prestressed NSM method was solved with the development of an innovative mechanical anchorage system enabling prestressing the NSM-CFRP strips or rebars against the concrete beam itself (Gaafar 2007; El-Hacha and Gaafar 2011). So far, the performance of the NSM-CFRP strengthened beams employing the practical prestressing system have been studied under static and fatigue loading, and freeze-thaw cycling exposure (Gaafar 2007; Omran and El-Hacha 2010, 2012a, 2012b, 2012c, 2012d; El-Hacha and Gaafar 2011; Oudah 2011; Oudah and El-Hacha 2011, 2012a, 2012b, 2012c, 2012d; El-Hacha and Oudah 2013). No studies have considered the effects of combined freeze-thaw exposure and sustained load on the behaviour of prestressed NSM-CFRP strengthened RC beams. In this context, only the combined effects of freeze-thaw exposure and sustained load on the behaviour of non-prestressed NSM-CFRP strengthened RC beams were investigated by Derias (2008) and Mitchell (2010).

The objectives of this paper are to investigate the effects of freeze-thaw exposure and also the effects of combined freeze-thaw exposure and sustained load on the performance of RC beams strengthened with
prestressed and non-prestressed NSM-CFRP strips in terms of load-deflection response, ductility index (ratio of deflection at ultimate to deflection at yielding), energy absorption (area under load-deflection curve up to yielding and peak loads), and failure mode.

EXPERIMENTAL PROGRAM

Test Beams

The test matrix consisted of two sets: BS-F and BS-FS. Each set consisted of three large-scale RC beams, 5.15 m long, simply supported, with a rectangular cross-section (200×400 mm): one un-strengthened control beam (B0), one beam strengthened using non-prestressed NSM-CFRP strips (BS-NP), and one beam (BS-P3) strengthened using prestressed NSM-CFRP strips with 60% of the ultimate tensile strain of CFRP strips. Each beam from set BS-F was initially loaded after strengthening up to 1.2 times its cracking load, and then, subjected to 500 freeze-thaw cycles. On the other hand, each beam from set BS-FS was subjected to a load of approximately 62 kN (47% of the theoretical ultimate load of the non-prestressed NSM-CFRP strengthened RC beam) and 500 freeze-thaw cycles. Thereafter, each beam was tested under static monotonic loading up to failure in four-point bending configuration. Test setup, details and geometry of the beams are presented in Figure 1.

The tension steel reinforcement consisted of 3-15M deformed steel bars with a total area of 600 mm², and the compression steel reinforcement consisted of 2-10M deformed steel bars with a total area of 200 mm². The stirrups consisted of 25-10M deformed steel bars. Each beam was strengthened using two 2×16 mm rough textured CFRP strips glued together from the width and mounted in one groove cut on the tension face of the beam (shown in Figure 1b). The CFRP strips were prestressed using the anchorage system developed by Gaafar (2007) which can be accomplished against the beam itself with temporary brackets bolted to the side of the beam and end anchors bonded to the CFRP strips as depicted in Figure 1c. More details about the prestressing procedure can be found in Gaafar (2007) and El-Hacha and Gaafar (2011).

Material Properties

![Figure 1. Details of the beams](image-url)
The tension, compression, and shear reinforcements possessed specified yield strength of 440 MPa and a specified modulus of elasticity of 200 GPa. The specified 28 days concrete compressive strength was 40 MPa having a maximum aggregate size of 20 mm and an air content of 1%. The CFRP strips (Aslan 500 Tape) had a tensile strength, a modulus of elasticity, and an ultimate tensile strain of 2068 MPa, 124 GPa, and 0.017, respectively, as reported by the manufacturer (Hughes Brothers Inc.).

Freeze-Thaw Exposure and Sustained Loading

The applied freeze-thaw cycling exposure was selected based on the maximum and minimum mean daily temperatures and the annual mean relative humidity in Canada (CAN/CSA-S6-06, 2011). The three cracked beams from set BS-F were subjected to 500 freeze-thaw cycles inside an environmental chamber, which was programmed to accomplish three cycles per day between +34°C to −34°C with a relative humidity of 75% for temperatures above +20°C. The beams from set BS-FS were subjected to similar freeze-thaw cycle applied to set BS-F except that the 75% relative humidity at temperatures above +20°C was replaced with fresh water spray (at a rate of 18 L/min for a time period of 10 min) at a temperature of +20°C to increase the severity of the applied exposure. Three beams from set BS-FS were loaded inside the environmental chamber using a self-reacting loading system. The applied loads were: 60.1 kN for B0-FS, 62.5 kN for BS-NP-FS, and 63.3 kN for BS-P3-FS representing 47±1% of the theoretical ultimate load of the non-prestressed strengthened beam, BS-NP.

RESULTS AND DISCUSSIONS

Photos of the beams after being subjected to the freeze-thaw exposure (for set BS-F) and the combined exposure and sustained load (for set BS-FS) are presented in Figure 2, showing the damages and cracks occurred in the beams. After removing from the environmental chamber, the beams were kept at least three days at room temperature, and then, were tested under four-point static monotonic loading to failure. The results are presented in Figure 3 and Table 1.

Comparison between the two exposed sets, as shown in Figure 2, revealed that the effects of the applied exposure on set BS-FS were significantly severe. However, minor thermal cracks (due to freeze-thaw exposure) were observed in set BS-F resulting insignificant damage to the concrete and the concrete-epoxy interface, while extensive thermal and flexural cracks (due to combined freeze-thaw exposure and sustained load) were observed in set BS-FS resulting in significant damage to the concrete and the concrete-epoxy interface. The flexural cracks (due to sustained load) occurred in the beam strengthened with prestressed NSM-CFRP strips (BS-P3-FS shown in Figure 2f) were less than that in the beam strengthened with non-prestressed NSM-CFRP strips (BS-NP-FS).
shown in Figure 2d), while the beams almost had similar amount of the thermal cracks. It was observed that debonding occurred at the end regions of the NSM-CFRP strips at the concrete-epoxy interface for beam BS-P3-FS (shown in Figure 2f) up to 65% of the total prestressing length (665 mm from fixed end anchor towards mid-span and 1865 mm from the jacking end anchor towards mid-span, the jacking end and fixed end are shown in Figure 1a). On the other hand, no sign of debonding was observed in the non-prestressed NSM-CFRP strengthened RC beam, BS-NP-FS. In fact, the beam strengthened with prestressed NSM-CFRP strips is susceptible to debonding under freeze-thaw exposure and sustained load while the beam strengthened with non-prestressed NSM-CFRP strips is not. The reason is that the concrete surrounding the prestressed NSM-CFRP strips is under shear stress and due to its degradation under freeze-thaw exposure the bond capacity at the concrete-epoxy interface gradually decreases and leads to debonding. Also, the debonded length at the jacking end of the NSM-CFRP is higher than that at the fixed end. The reason is that the concrete-epoxy interface is under more shear stress at the jacking end than the fixed end, since the steel anchor at jacking end was bolted after adhesive cured (24hrs after prestressing) and then the jacks used for prestressing were released (more details about the prestressing procedure can be found in Gaafar 2007; El-Hacha and Gaafar 2011). This procedure applies more shear stress at the concrete-epoxy interface at the jacking end. The applied freeze-thaw exposure combined with sustained load resulted in permanent deflections at mid-span of 15.6 mm, 13.7 mm, and 8 mm for beams B0-FS, BS-NP-FS, and BS-P3-FS, respectively, as presented in Table 1.

The post-exposure load-deflection responses of the beams are presented in Figure 3 and a summary of the test results is presented in Table 1. For set BS-F, the load-deflection curves include the negative camber due to prestressing, yielding of tension steel rebar (at the points on the curves where there is the significant change in the slope of the load-deflection response due to the decrease in stiffness of the beam), CFRP rupture or concrete crushing which causes a large drop in the load at ultimate, and the post failure behaviour. On the other hand, for set BS-FS, the load-deflection curves comprise the negative camber due to prestressing, yielding of the tension steel rebar, concrete crushing or NSM-CFRP debonding, and post failure. A similar camber of 1.7 mm for beams BS-P3-F and BS-P3-FS was recorded one week after prestressing. The values of the initial and effective pre-strain in the CFRP strips, computed by taking the average of the strain values at the constant moment region of the beams, are presented in Table 1 showing an average prestress loss of 2.25% and 2.02% for beams BS-P3-F and BS-P3-FS, respectively, one week after prestressing. These prestress losses occurred due to seating losses (small anchorage slip due to removing the temporary brackets) and elastic shortening of concrete.

![Figure 3](image-url)  
**Figure 3.** Comparison between load-deflection responses of the beams (freeze-thaw exposure versus combined sustained load and freeze-thaw exposure)
Pcr and DB-CC failure initiated by the NSM-CFRP debonding and concrete crushing almost simultaneously, followed by the concrete crushing 

The obtained cracking load of the prestressed strengthened beam shows significant increase due to prestressing (up to 154% for set BS-F) with respect to the non-prestressed strengthened beam. The un-strengthened control beams showed a low cracking load which is due to the presence of the micro-cracks in the large-scale beams before testing, mainly caused from moving the beams during the testing process. Comparison between the yield loads shows an average decrease of 18.4±1% and 28.5±3.1% in the load and the deflection at yielding of the beams in set BS-FS with respect to the corresponding beams in set BS-F, respectively. Besides, an average decrease of 23.6±2.8% was observed in the ultimate load of the beams in set BS-FS in comparison to set BS-F. Furthermore, the deflection at ultimate for the beams in set BS-FS shows an average decrease of 41.8±3.9% in comparison with the beams from set BS-F. These significant reductions are the results of the damage done to the concrete and concrete-epoxy interface of the beams in set BS-FS due to combined freeze-thaw exposure and sustained load.

The failure modes of the beams are marked in Figure 3. Three exposed beams in set BS-F showed a typical failure mode, i.e., tension steel yielding followed by CFRP rupture or concrete crushing, while the exposed beams in set BS-FS failed at early stages after yielding due to concrete crushing or an initial NSM-CFRP debonding and concrete crushing, almost simultaneously, followed by the concrete crushing (for beam BS-P3-FS). Comparing the load-deflection curves of sets BS-FS and BS-F reveals that in set BS-FS the concrete was significantly affected and was damaged more than that beams in set BS-F. This damage caused an early concrete crushing failure or a combination of the NSM-CFRP debonding and concrete crushing (for beam BS-P3-FS). The energy absorptions (Φ) of the beams (defined as the area under the load-deflection curve up to the peak load) are presented in Table 1. It is clear that the beams from set BS-FS showed a significant reduction in energy absorption in comparison with set BS-F. An average of 54±3.4% decrease in energy absorption was observed for set BS-FS in comparison with set BS-F. Besides, the results presented in Table 1 show an average decrease of 18.9±1.3% in ductility indices (defined as the ratio of the deflection at ultimate to the deflection at yielding) of the set BS-FS in comparison with set BS-F.

<table>
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<th>Set</th>
<th>Beam ID</th>
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<th>Δm (mm)</th>
<th>Pcr (kN)</th>
<th>Δu (mm)</th>
<th>Frp@u (µ)</th>
<th>Δcr (mm)</th>
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Φ = energy absorption (area under P-A curve)  
CC and FR = concrete crushing and CFRP rupture  
µ = ductility index = Δu / Δcr  
DB-CC = failure initiated by the NSM-CFRP debonding and concrete crushing almost simultaneously, followed by the concrete crushing

The effects of freeze-thaw exposure and combined freeze-thaw exposure and sustained load on the flexural performance of RC beams strengthened with prestressed and non-prestressed NSM-CFRP strips were investigated. Based on this experimental research, the following conclusions can be drawn:

- For the environmental exposure and long-term loading conditions used in this study, it was found that the freeze-thaw exposure had insignificant effects on the concrete and the concrete-epoxy interface of the beams strengthened using prestressed and non-prestressed NSM-CFRP strips. On the other hand, the combined freeze-thaw exposure and sustained load had significant effects on the concrete and the concrete-epoxy interface. For the latter condition, on average, the beams exhibited about 18% decrease in the yield load, 24% decrease in the ultimate load, 19% decrease in the ductility, and 54% decrease in the energy absorption.
- Under freeze-thaw exposure and sustained load, the beam strengthened with prestressed NSM-CFRP strips was susceptible to debonding at the end regions of the NSM-CFRP strips while such negative effect was not observed in the beam strengthened with non-prestressed NSM-CFRP strips.
- Under freeze-thaw exposure and sustained load, the beam strengthened with prestressed NSM-CFRP strips exhibited less flexural cracks than the non-prestressed strengthened beam while the amount of thermal cracks was similar for both types of the beams.

The overall comparison of the beams tested in this research reveals that the beams strengthened with the prestressed NSM-CFRP strips subjected to combined severe environmental exposure and sustained loading, tested to failure in flexure under static monotonic loading, do not perform well especially after yielding of
tension steel. In particular, the NSM-CFRP debonding at the end regions of the prestressed strengthened beams and the low ductility and energy absorption resulted from the severe damage to the concrete material are the issues that should be considered in long-term performance of the prestressed NSM-CFRP strengthened RC beams under freeze-thaw exposure and sustained loading.

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REFERENCES