EFFECTS OF SEVERE ENVIRONMENTAL EXPOSURE ON RC BEAMS STRENGTHENED WITH PRESTRESSED NSM-CFRP STRIPS

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Abstract

An experimental program is conducted to examine the effects of severe environmental 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. The program includes testing five large-scale (5.15m long) simply supported rectangular RC beams: one unstrengthened control beam and four NSM-CFRP strengthened beams prestressed with 0%, 20%, 40%, and 60% of the ultimate tensile strength of CFRP strip. After strengthening, each beam is loaded up to 20% above its analytical cracking load before being exposed to 500 freeze-thaw cycles; where each cycle is programmed between +34°C to −34°C with period of 8hrs and a relative humidity of 75% for temperature above +20°C. The beams are simply supported and tested under static monotonic loading in four-point bending configuration. Effects of environmental exposure are elaborated on the load-deflection curves, strain profiles along the length of the CFRP strips, ductility, and mode of failure by comparing the test results with those of identical beams tested without any environmental exposure.

Keywords: Carbon Fibre Reinforced Polymer, ductility, freeze-thaw, near-surface mounted, prestressing; strengthening; strip.

1. Introduction

In recent years, Fibre Reinforced Polymer (FRP) composites have been widely employed as an attractive alternative for strengthening of Reinforced Concrete (RC) members. Prestressed Near-Surface Mounted (NSM) Carbon FRP (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.

In earlier studies [1-3], applying prestressing in the NSM reinforcement was accomplished against both ends of the beam or against an independent steel reaction frame which limited the application of the prestressed NSM method to the laboratory projects. The practical issue of the prestressed NSM method was overcome with the development of an innovative mechanical anchorage system which allows prestressing the NSM CFRP strips and rebars against the concrete beam itself [4-5]. Although the static and fatigue performance of the NSM CFRP strengthened beams employing the practical prestressing system have been examined by a few researchers [4-6]; however, the long-term performance under freeze-thaw
exposures of strengthened beams with this system has not been investigated. In this context, the effects of freeze-thaw exposure on the behaviour of non-prestressed NSM CFRP strengthened RC beams were investigated by Derias [7] and Mitchell [8].

The objective of this paper is to investigate the effects of freeze-thaw cycling exposure on the performance of the RC beams strengthened with prestressed NSM CFRP strips in terms of load-deflection curve, strain profile in CFRP strip, 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. Hence, the results of five exposed beams tested in this research are compared with those of identical unexposed beams tested by Gaafar [4].

2. Experimental program

2.1 Test beams

Five large-scale RC beams, 5.15 m long, with a rectangular cross-section (200×400 mm), and simply supported were subjected to 500 freeze-thaw cycles and statically tested at room temperature up to failure under four-point bending configuration. One beam was considered as unstrengthened control beam, and four beams were strengthened using NSM CFRP strips (with 0%, 20%, 40%, and 60% prestressing levels based on the manufacturer’s reported ultimate tensile strength of CFRP strips). The test setup and geometry of the beams are depicted in Figure 1.

![Test setup and geometry of the beams.](image1.png)

**Figure 1.** Test setup and geometry of the beams.

![Cross-section of the beams and end anchor details.](image2.png)

**Figure 2.** Cross-section of the beams and end anchor details.
The compression steel reinforcement consisted of 2-10M deformed steel bars with a total area of 200 mm$^2$ while the tension steel reinforcement consisted of 3-15M deformed steel bars with a total area of 600 mm$^2$. The stirrups consisted of 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 as shown in Figure 2a. The CFRP strips were prestressed using the anchorage system developed by Gaafar [4] which can be accomplished against the beam itself with temporary brackets bolted to the side of the beam and steel end anchors bonded to the CFRP strips as depicted in Figure 2b. The prestressing procedure is illustrated in El-Hacha and Gaafar [5].

Although under service load, flexural cracks in concrete beams internally reinforced with prestressed tendons should be avoided and the member is to be considered as uncracked section, in this research the applied prestressing method is to strengthen the cracked concrete beams. Therefore, investigating the long-term behaviour of uncracked concrete beams strengthened with prestressed CFRP is unrealistic. For this reason, all five beams were strengthened using prestressed CFRP after being cracked up to 1.2 times the analytical cracking load for each beam to also accelerate the effects of freeze-thaw exposure on the specimens.

2.2 Material Properties

Material properties of the CFRP strips are presented in Table 1. The tension and compression steel bars (3-15M and 2-10M) possessed yield strength of 438 MPa and 457 MPa, respectively, obtained from tension tests. All five beams were cast from one concrete batch; the compressive strengths of unexposed and exposed concrete cylinders were 41.5±6.2 MPa and 32.1±10.8 MPa at the time of testing the beams to failure. The exposed concrete cylinders were subjected to the same environmental conditioning as the beams. Two types of epoxy adhesives were used: Sikadure® 330 with an ultimate tensile strength of 30 MPa was used inside the end anchors while Sikadure® 30 with an ultimate tensile strength of 24.8 MPa was used to fill in the groove between the end anchors [9]. To investigate the freeze-thaw exposure effects, the results of the exposed tested beams in this research are compared with identical unexposed RC beams tested by Gaafar [4]. For the unexposed beams; material properties of the employed CFRP strips are presented in Table 1; the tension and compression steel bars (3-15M and 2-10M) possessed yield strength of 475 MPa and 500 MPa, respectively; and the concrete had an average compressive strength of 40 MPa [4].

Table 1. Material properties of CFRP strip reported by manufacturer and obtained from tension test.

<table>
<thead>
<tr>
<th>CFRP products (Manufacturer)</th>
<th>Type of test</th>
<th>Dimensions (mm)</th>
<th>$A_{\text{CFRP}}$ (mm$^2$)</th>
<th>Manufacturer Tension test</th>
<th>Tension test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$f_{\text{UCFRP}}$ (MPa)</td>
<td>$E_{\text{CFRP}}$ (GPa)</td>
</tr>
<tr>
<td>Aslan 500 CFRP tape (Hughes Brothers Inc [10])</td>
<td>F</td>
<td>2×16</td>
<td>31.2</td>
<td>2068</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>2×16</td>
<td>31.2</td>
<td>2068</td>
<td>124</td>
</tr>
</tbody>
</table>

F= beams subjected to freeze-thaw exposure, R= beams kept at room temperature, Gaafar [4]

2.3 Freeze-thaw exposure

The applied freeze-thaw cycling exposure is selected based on the maximum and minimum mean daily temperatures and the annual mean relative humidity in Canada [11]. The five cracked beams were subjected to 500 freeze-thaw cycles inside an environmental facility chamber which was programmed to accomplish three cycles per day between +34°C to −34°C with a relative humidity of 75% for temperature above +20°C. The accelerated 500 cycles used in this study is equivalent to at least 12.8 years, considering an average freeze-thaw frequency of 39 cycles per year for Canada [12].
3. Test results and discussions

3.1 Load-deflection curve

The results of the exposed (set B) and unexposed (set A, tested by Gaafar [4]) beams are presented in Figure 3 and Table 2. The exposed curves are plotted with considering the permanent deflections due to cracking of the beams after strengthening. The load-deflection curves include the negative camber due to prestressing, initiation of flexural cracks, yielding of tensile steel rebar, CFRP rupture or concrete crushing which causes a large drop in load at ultimate stage, and post failure behaviour. One week after prestressing, an upward camber ranging between 0.49-1.7 mm for beams from set B and between 0.47-1.6 mm for beams from set A were recorded. The values of the initial and effective pre-strain in the CFRP strip, computed by taking the average of the strain values at the constant moment region of the beams, are presented in Table 2 showing an average prestressing loss of 1.7±1.1% one week after prestressing. The beams were cracked after strengthening; the obtained cracking loads show significant increase due to prestressing (up to 153% for set B and up to 151% for set A) with respect to the non-prestressed strengthened beam of each set. The unstrengthened control beams showed a low cracking load which is due to presence of the micro cracks in the large-scale beams before testing, mainly caused from moving the beams during the testing process. In fact, the cracking load of the unstrengthened control beam should have been close to that of non-prestressed strengthened beam.

![Figure 3. Load-deflection curves of the beams.](image)

Comparing beam B0-F with beam BS-NP-F shows similar flexural behaviour of the two beams prior to yielding of the unstrengthened control beam. In fact, strengthening using non-prestressed NSM CFRP strips has insignificant effect on the flexural behaviour in the elastic range; on the other hand, it enhances the flexural behaviour (stiffness, yield and ultimate loads) in the plastic range. Besides, comparing the results of beams BS-P1-F, BS-P2-F, and
BS-P3-F with beam BS-NP-F reveals enhancement of the flexural behaviour at the elastic and plastic ranges due to strengthening using the prestressed NSM CFRP strips; this enhancement causes delaying in the crack formation and reducing the crack width which leads to better serviceability performance in addition to the improvement in yielding and ultimate strengths, and stiffness of the beam.

Up to 64% increase in the yielding load of the strengthened beams in set B and up to 56% increase in the yielding load of the strengthened beams in set A were observed with respect to the corresponding unstrengthened control beam of each set. Enhancements of 22% out of 64% and 15% out of 56% are related to increase due to CFRP strengthening and the rests (which are 42% and 41%, respectively) are due to prestressing effect. Besides, up to 53% increase in ultimate load of the strengthened beams in set B and up to 78% increase in ultimate load of the strengthened beams in set A were recorded with respect to the corresponding unstrengthened control beam of each set; 35% out of 53% and 61% out of 78% are reached by strengthening with non-prestressed CFRP strip and the remaining (which are 18% and 17%, respectively) are due to prestressing. In fact, strengthening has more contribution in enhancement of the ultimate load while prestressing has more contribution in enhancement of the yield load than the ultimate load.

All tested beams showed a typical failure mode, i.e., tension steel reinforcements yielding followed by CFRP rupture or concrete crushing. The failure modes are marked in Figure 3. Comparing the load-deflection curves of the exposed and unexposed beams reveals that freeze-thaw exposure has its major effects on the ultimate stage, particularly on failure mode; by shifting the mode of failure from CFRP rupture to concrete crushing as marked in Figure 3 for beams BS-NP-F and BS-P1-F in comparison with beams BS-NP-R and BS-P1-R, respectively. This shift resulted in 2.1% and 12.2% decrease in ultimate load and ultimate deflection of beam BS-NP-F in comparison with beam BS-NP-R, respectively; in addition it resulted in 9% and 20% decrease in ultimate load and ultimate deflection of beam BS-P1-F in comparison with beam BS-P1-R, respectively. For the beams with high prestressing level, BS-P2-F and BS-P3-F, the effect of freeze-thaw exposure is negligible. In fact, when the beam is highly prestressed the failure is governed by CFRP rupture while the concrete strain in extreme compression fibre is small. Hence, the damage done to the concrete due to freeze-

<table>
<thead>
<tr>
<th>Table 2. Summary of the test results.</th>
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<tbody>
<tr>
<td><strong>Set</strong></td>
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<td>---------</td>
</tr>
<tr>
<td><strong>set A unstrengthened</strong></td>
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<td></td>
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<tr>
<td><strong>set B</strong></td>
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</table>

F = the beam under freeze-thaw exposure
R = the beam under room temperature
P_i and P_u = load and deflection at cracking
P_eff and w_eff = effective prestress and camber after 7 days of prestressing
P_y and γ = load and deflection at yielding
Freff = maximum CFRP strain at failure
Φ = area under P- curve
Δ_y and Δ_u = permanent deflection due to cracking after strengthening
CC = concrete crushing
CCS = concrete cover spalling
FR = CFRP rupture

† calculated based on concrete strain 0.004125 to be consistent with the other beams failed by crushing.
thaw exposure should be extremely high to result in a major decrease in concrete crushing strain and leads to changing the mode of failure from CFRP rupture to concrete crushing at small strain; this behaviour has not experienced in the cases of beams BS-P2-F and BS-P3-F.

### 3.2 Strain profile

The strain profiles along the length of the NSM CFRP strip for beam BS-P1-R versus BS-P1-F and for beam BS-P3-R versus BS-P3-F are presented in Figure 4, at cracking, yielding, and ultimate loads. The profiles are plotted based on the reading of strain from the installed strain gauges at specified locations. A very good correlation at cracking and yielding is observed which reveals the negligible effect of freeze-thaw exposure up to yielding. In Figure 4a, at ultimate load, the strain values of beam BS-P1-R are smaller than those from beam BS-P1-F. Because, beam BS-P1-R failed due to CFRP rupture while beam BS-P1-F failed due to concrete crushing due to the freeze-thaw exposure on this beam which resulted in lower ultimate loads and not fully utilization of capacity of the CFRP strips. For beam BS-P1-F, a 15.5% decrease in maximum CFRP strain at failure occurred with respect to unexposed beam. For beams BS-P3-R and BS-P3-F shown in Figure 4b, the type of failure is the same (CFRP rupture) and is not affected by the freeze-thaw exposure, and much lower difference in maximum CFRP strain at ultimate is observed. In Figure 4b, the drop in strain at length 4350 mm is a result of small slippage after transferring the prestressing force to the steel end anchor.

![Figure 4. Strain profile along the CFRP strip.](image)

![Figure 5. Energy absorption and ductility index versus prestrain in CFRP strip.](image)
3.3 Ductility

The ductility index (the ratio of the ultimate deflection to the deflection at yielding) and energy absorption (the area under load deflection curve up to the peak load) for each beam are presented in Table 2 and the trends of the exposed and unexposed beams with respect to prestrain value are plotted in Figure 5. A decrease of 13.8% and 26.7% in energy absorption of beams BS-NP-F and BS-P1-F occurred with respect to the corresponding unexposed beams. The reason is that the freeze-thaw exposed beams showed different mode of failure than the unexposed beams causing smaller ultimate deflection and peak load. The effect of freeze-thaw on the energy absorption of beam BS-P3-F is negligible; on the other hand, the difference in energy absorption of beam BS-P2-F is not caused by freeze-thaw exposure since the mode of failure of the exposed and unexposed beam is the same and is due to different CFRP rupture strain at ultimate. In addition, the ductility index decreases as the prestressing level increases; a maximum of 51% decrease in both sets of the beams occurred with respect to the corresponding non-prestressed strengthened beam of each set. According to results of the tested beams, it can be concluded that at low prestressing level (less than 26% of the ultimate tensile strain of the CFRP strips) the ductility index and the energy absorption of the exposed beams are smaller than the unexposed beams mainly caused by shifting the mode of failure from CFRP rupture to concrete crushing.

4. Conclusions

The effects of freeze-thaw cycling exposure on the flexural performance of RC beams strengthened with prestressed NSM-CFRP strips were investigated. The following conclusions can be drawn:

- The freeze-thaw exposure mainly affects the ultimate stage, and particularly the failure mode of the beams, by shifting the mode of failure from CFRP rupture to concrete crushing.
- A 12.2-20% decrease in ultimate deflection and a 2.1-9% decrease in ultimate load of the exposed beams were observed in comparison with the identical unexposed beams.
- The effects of freeze-thaw exposure on the flexural behaviour of the beams strengthened with high prestressing levels of NSM CFRP strip, in which the failure is governed by CFRP rupture while the concrete strain in extreme compression fibre is small, are negligible. The damage done to the concrete caused by the freeze-thaw exposure on the beams with such behaviour must be extremely high to affect the flexural performance.
- The ductility index and energy absorption of the exposed beams are smaller than those from the unexposed beams at low prestressing levels (less than 26% of the ultimate strain of the CFRP strips). A 13.8-26.7% decrease in energy absorption of the exposed beams occurred in comparison with the identical unexposed beams.
- Strengthening with non-prestressed NSM CFRP strips has significant effects in the plastic range of a load-deflection curve while strengthening using prestressed NSM CFRP strips has significant effects in both the elastic and plastic ranges.

The findings of this experimental investigation reveal the minor effects of the freeze-thaw cycling exposure on the flexural behaviour of RC beams strengthened using prestressed NSM-CFRP strips and cover the gaps in this field. The study provides evidence that this practical prestressed strengthening system can be implemented in field applications with confidence to improve the flexural performance of deficient RC members.
5. Acknowledgement

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6. References


