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Bond Performance of CFRP-Concrete Joints Subjected to Freeze-Thaw Cycles: Experimental Study and Analytical Analysis

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Outline of presentation

- **Introduction and objectives,**
- **Experimental program,**
- **Test results,**
- **Discussions,**
- **Conclusions.**

Introduction

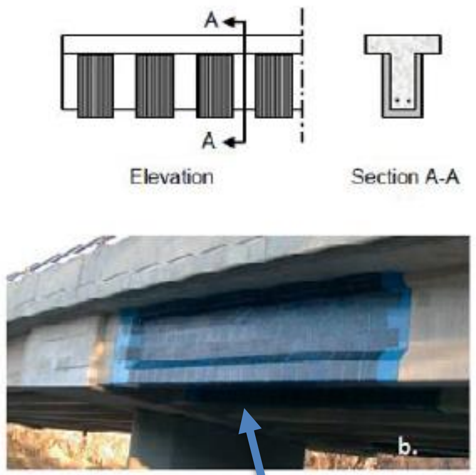
- **External reinforcement with CFRP sheets**

  - The use of Carbon Fiber Reinforced Polymer (CFRP) is becoming increasingly recognized for the rehabilitation and strengthening of concrete structures in service.
  - This technique comes to solve various problems and increase the life-span for concrete structures.

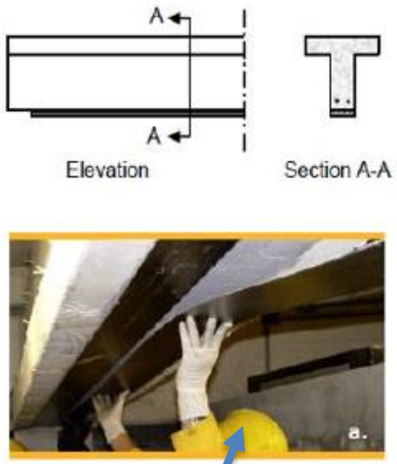


Introduction

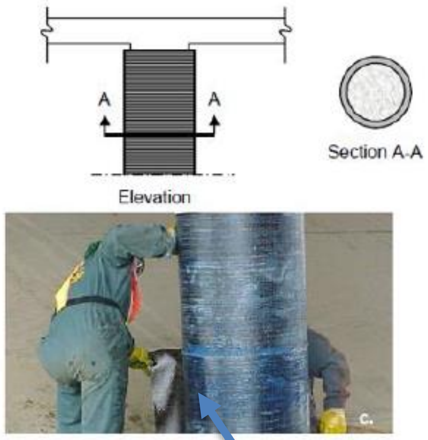
- **External reinforcement with CFRP sheets**
  - The technique of externally bonded CFRP composites have been used to increase both **flexural** and **shear capacity** of concrete elements, including girders and slabs. In addition, **axial capacity** of columns can be increased with CFRP wrapping.



Shear strengthening

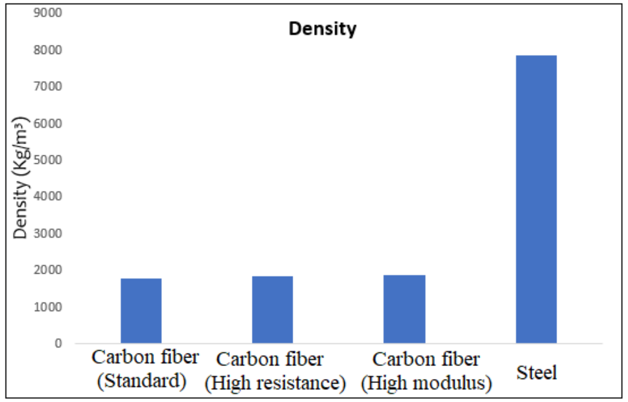


Flexural strengthening

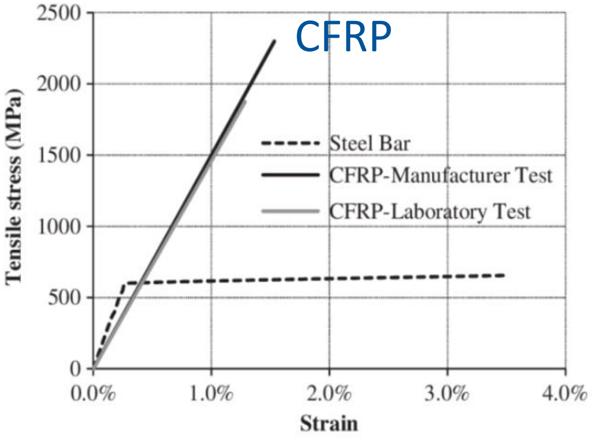


Column-confinement

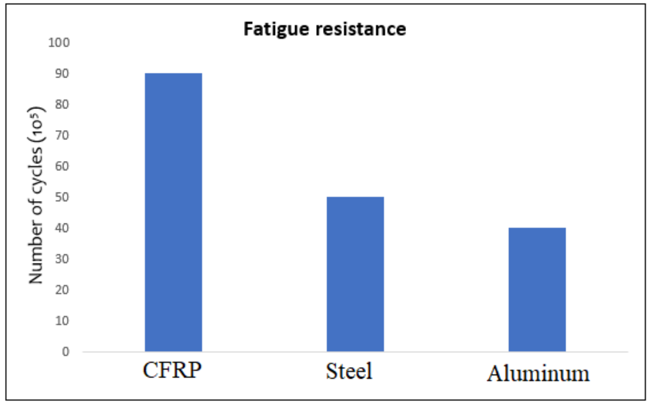
- **Why Carbon Fiber Reinforced Polymer (CFRP)?**
  - The choice of the CFRP is based on several advantages:



Lightweight material



High tensile capacity/weight ratio



Fatigue resistance

Ease of installation of CFRP sheets

Introduction

- **Problematic of bond between CFRP and concrete :**
  - However, this technique still has limitations such as the durability of the bond between CFRP and concrete which is caused by *environmental exposure*, *existing structural conditions* and *fatigue loads*.



CFRP debonding problem

Introduction

- **Effect of Freeze Thaw (F-T) cycles on the bond performance between CFRP and concrete interface :**

The findings of previous research:

- Some studies in the literature have shown **an improvement** of **bond properties** after **F-T cycles**.
- Other studies have shown **opposite results**, with **a negative effect** of **F-T cycles** on the **bond** behavior between CFRP and concrete.

Research	FT cycles; conditions	Results
(liu et al. 2019)	270; in air	Increase of fracture energy by 20%
	270; in water	Decrease of fracture energy by 41 %
(Mark F. Green et al. 2000)	300; Freeze in air and thaw in water	Increase of the bond capacity by 54 %
(Al-Mahmoud et al. 2014)	300; in salt water	Decrease of the bond capacity by 25.6 %
(Kolluru V. Subramaniam et al. 2008)	300; Wet surface	Decrease of the load capacity by 18 %

The project's objectives

- **Objectives**

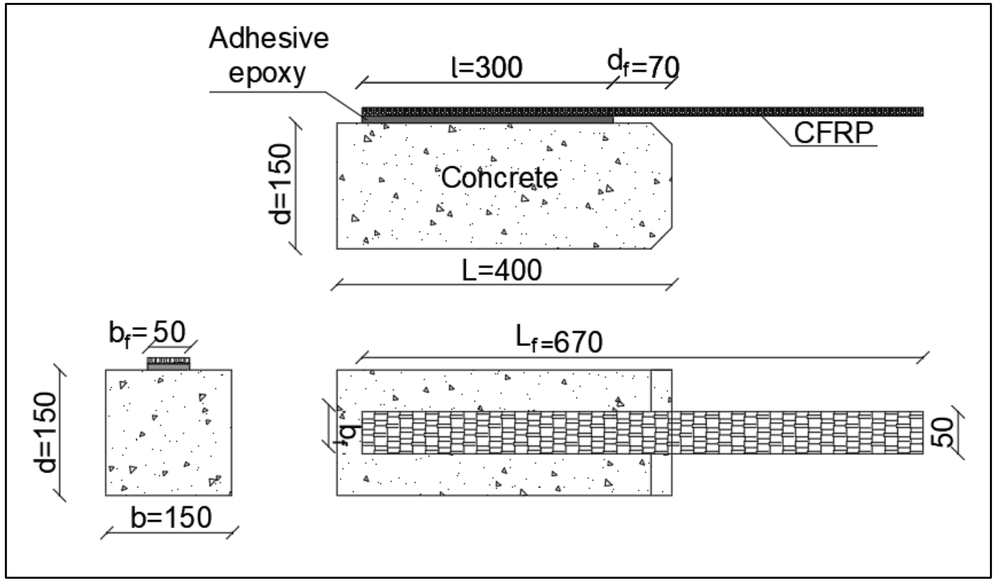
Given the contradictory results found in the literature review on the effects of freeze-thaw cycles on the bond behavior between CFRP and concrete, this paper aims to confirm one of the two existing results by :

Investigating the bond behavior of CFRP sheets/concrete joints under static loading after undergoing 100, 200 and 300 cycles of F-T under humid conditions.

➡ The aim of this research is to simulate the service life condition of bridge structural elements strengthened with CFRP fabrics by exposing them to F-T cycles in the presence of moisture on the surface.

Experimental program

- Single-lap shear test
  - The single lap shear test was used in this experimental program to evaluate the bond performance between CFRP and concrete;
  - The details of the specimen are obtained from ASTM standard (ASTM D8337/8337M, 2021).



Specimen details (ASTM D8337)

$$l = \sqrt{\frac{n t_f E_f}{\sqrt{f_c'}}}$$

Bond length, ACI 440.2R-17

Experimental program

- **Test parameters**
  - 4 control specimens were tested under static load until failure without conditioning.
  - 3 series, with four samples each, were tested after 100, 200 and 300 freeze-thaw cycles.
  - 3 concrete cylinders were tested in compression for each FT cycles.

Test parameters

Serie	Conditions	F-T samples	Cylinders
# 1	**0 F-T cycles (control samples)**	4	3
# 2	**100 F-T cycles**	4	3
# 3	**200 F-T cycles**	4	3
# 4	**300 F-T cycles**	4	3

Experimental program

- **Application of CFRP on concrete using the wet layup procedure**

The steps for preparing and applying CFRP to concrete blocks are:

Step # 1 : Preparation of the concrete surface

- According to the CFRP supplier's recommendations, a CSP3 to CSP5 (ICRI 2013) surface profiles should be obtained prior to apply the CFRP.
- The International Concrete Repair Institute (ICRI), indicates that the sandblasting method is one of the most effective methods to achieve a CSP3 to CSP5 surface profile.

1. Sandblasting method

Experimental program

- **Application of CFRP on concrete using the wet layup procedure**

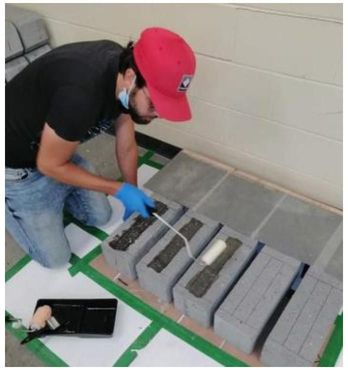
Step # 2. Applying primer epoxy *(MapeWrap Primer 1)*;

Step # 3. Applying the adhesive layer *(MapeWrap 11)*;

Step # 4. Saturation of the unidirectional carbon fiber sheets *(C Uni-Ax Uni-Ax 1200)* with epoxy resin *(MapeWrap 21)*;

Step # 5. Impregnation the sheets on the substrate

Step # 6. Applying a pressure with a roller.



2. Applying of the primer epoxy resin ‘’Primer layer’’.

3. Applying the adhesive layer (epoxy paste).

4. Impregnation of the carbon fiber fabric strip with epoxy resin.

5. Installation of CFRP strips.

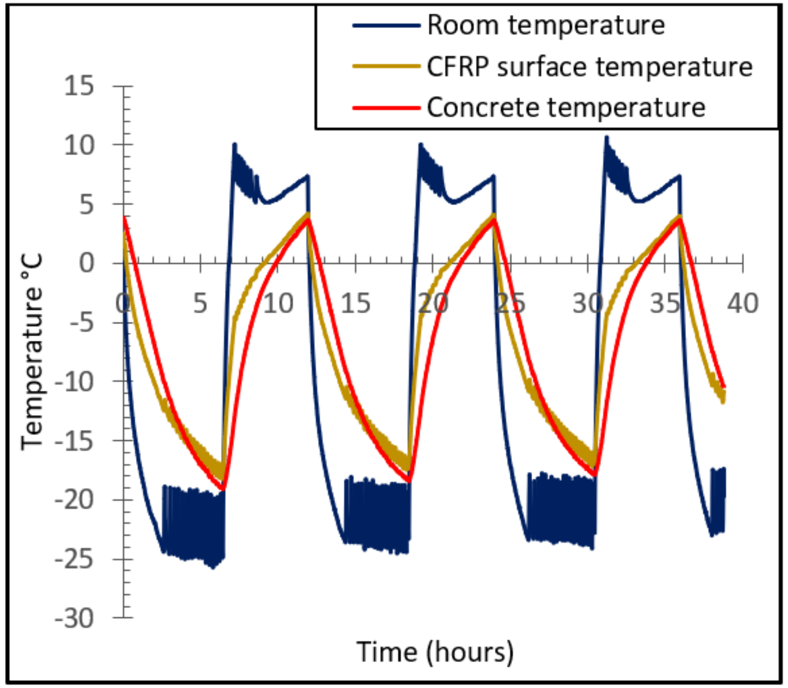
6. Applying a pressure with a roller the roller.

Experimental program

- **Freeze-Thaw (FT) Exposure**
  - Room temperature: -25 °C to +10 °C
  - Concrete temperature: -18 °C to +4 °C (ASTM C666, 2015)
  - Relative humidity: 73 %
  - Two cycles per 24 hours

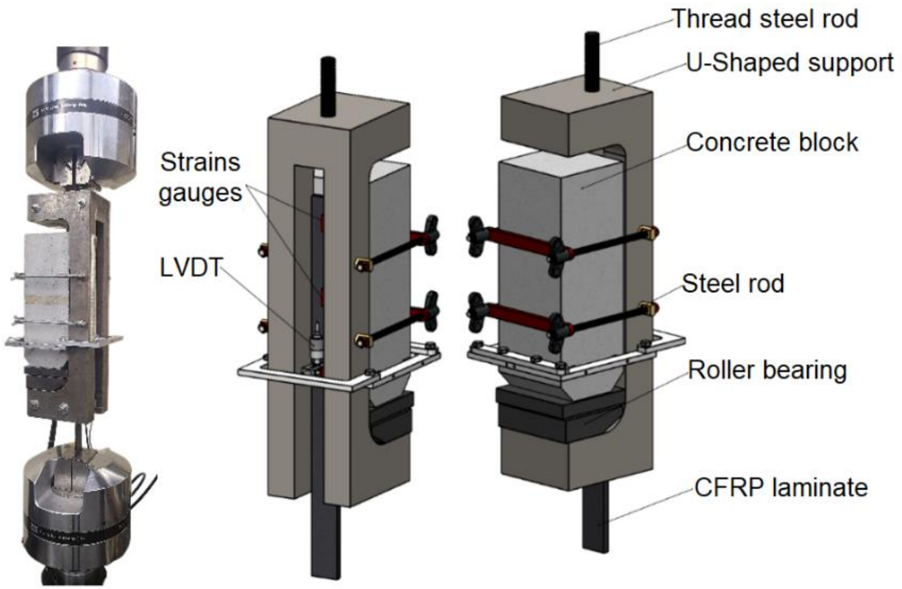
Freezing phase

Thawing phase

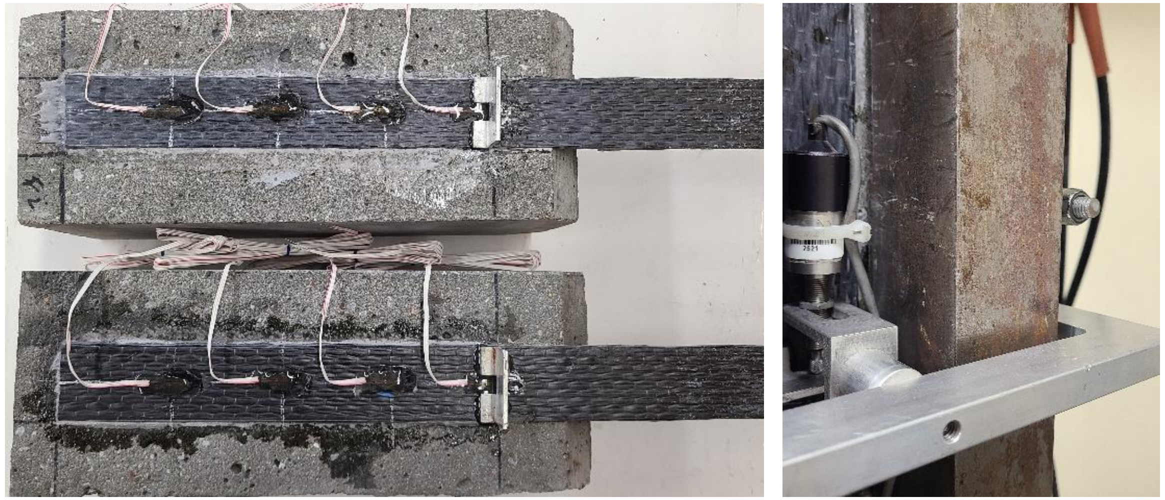


Freeze thaw cycles

- **Test set-up**
  - Four strain gauges (G1, G2, G3 and G4) of 6 mm length were placed on the CFRP strip in the bond length;
  - LVDT was installed at the beginning of the interface zone;
  - The specimen is inserted into a conventional tensile load frame, so that a direct shear can be applied on the CFRP-concrete interface;
  - The tensile load was applied with a loading rate of 0.3 mm/min until failure.



3D view of the test set-up



Strain gauges and the LVDT placement on the specimen

Test results

- **Failure modes:**

Serie 1

Cohesive failure in concrete with 2mm **(Control samples)**

Serie 2

Cohesive failure in concrete with 1 mm **(100 cycles)**

Serie 3

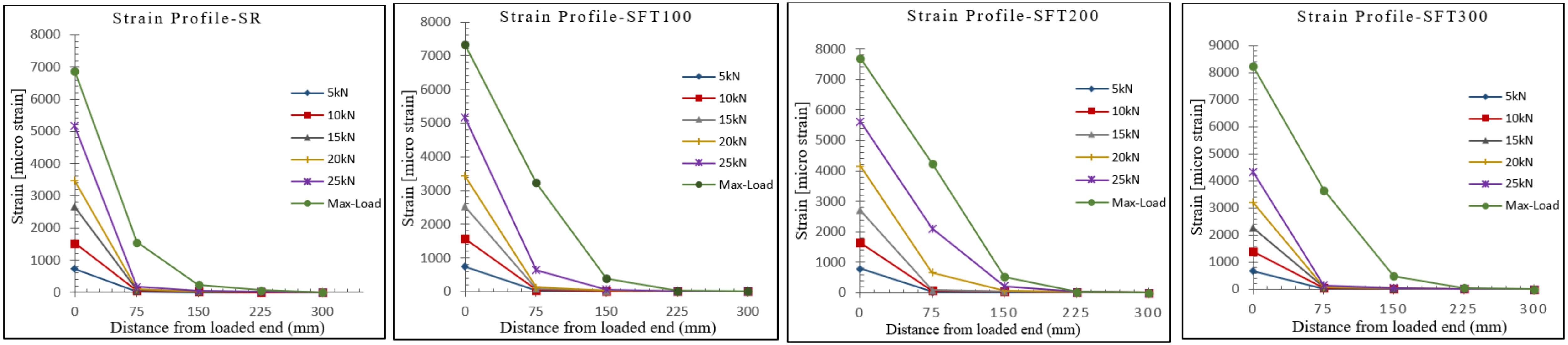
Mixed failure in concrete and adhesive/concrete interface **(200 cycles)**

Serie 4

Adhesive failure in the adhesive/concrete interface **(300 cycles)**

Test results

- **Strain profile**
  - The strain profiles of CFRP-concrete joints were plotted at 5 kN, 10 kN, 15 kN, 20 kN, 25 kN and at the maximum load.



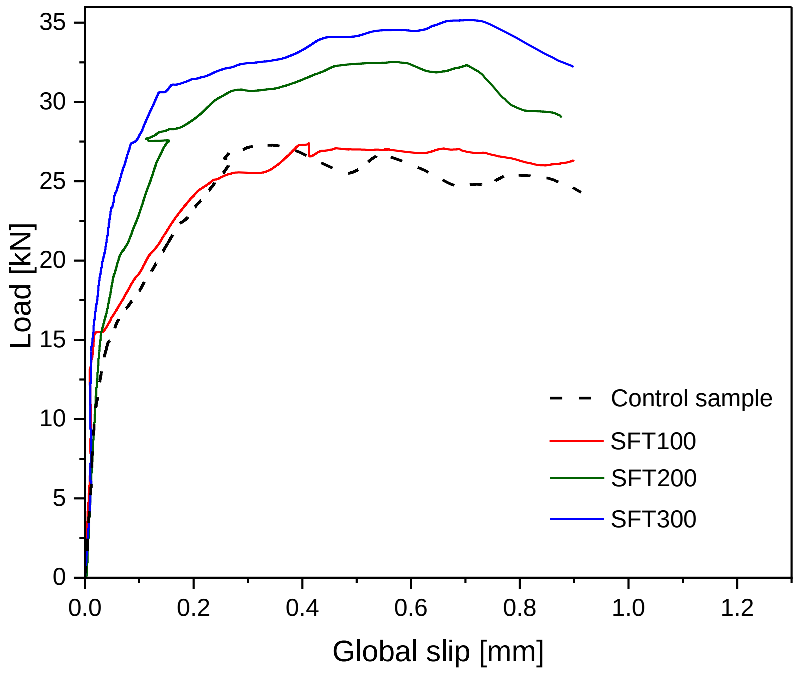
Strain profile

- **75 mm** damaged bond length at 25 kN for Control samples.
- **150 mm** damaged bond length at 25 kN for 100 F-T cycles samples.
- **225 mm** damaged bond length at 25 kN for 200 F-T cycles samples.
- **75 mm** damaged bond length at 25 kN for 300 F-T cycles samples.

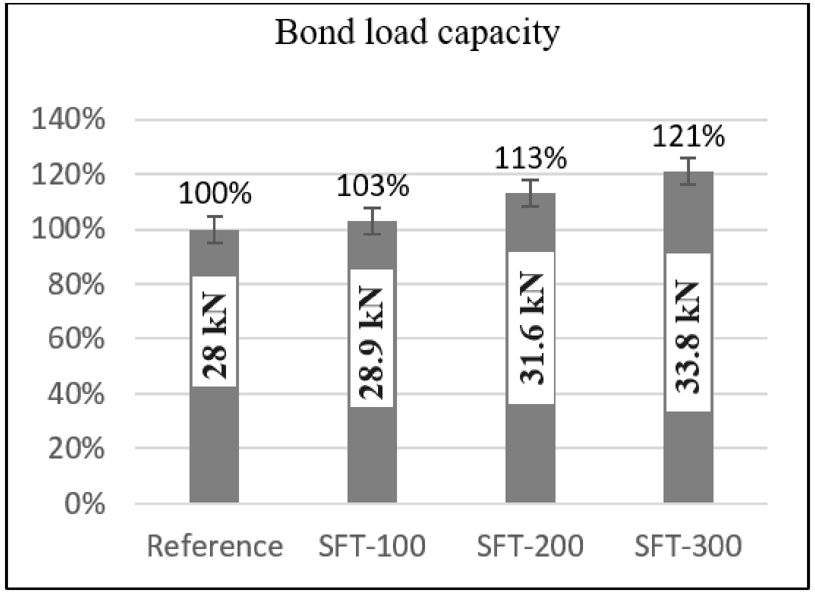
Test results

- **Bond capacity**

The peak load was increased by 3 %, 13 % and 21 % after the (CFRP-Concrete) joints were exposed to 100, 200 and 300 cycles of F-T, respectively.



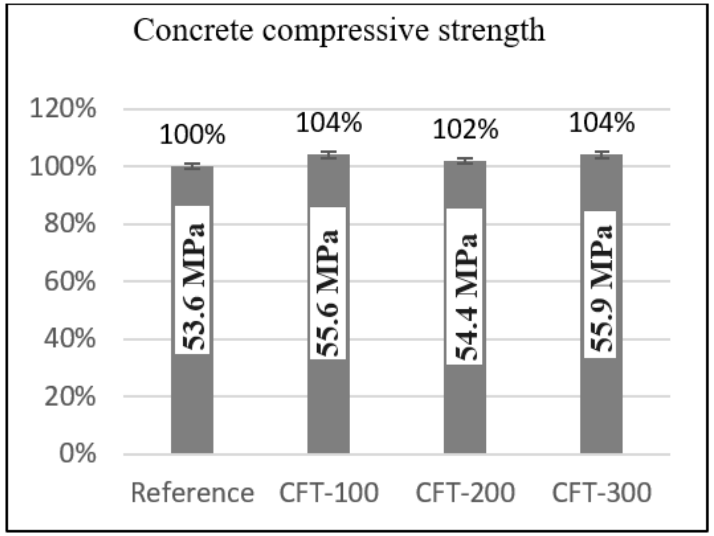
Load vs. global slip curves.



Effect of F-T cycles on the bond capacity.

Test results

- **Bond capacity**



Effect of FT cycles on the concrete compressive strength f'c

- F-T cycles led to a slight increasing in concrete compressive strength (f'_c), of about 2-4%.

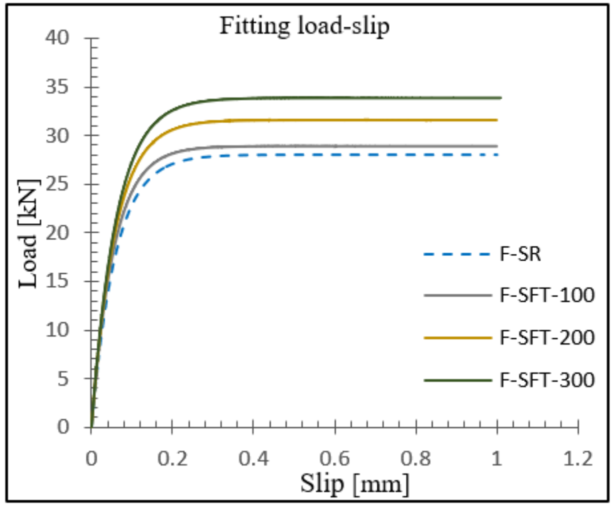
&

- Considering the failure mode of each test series

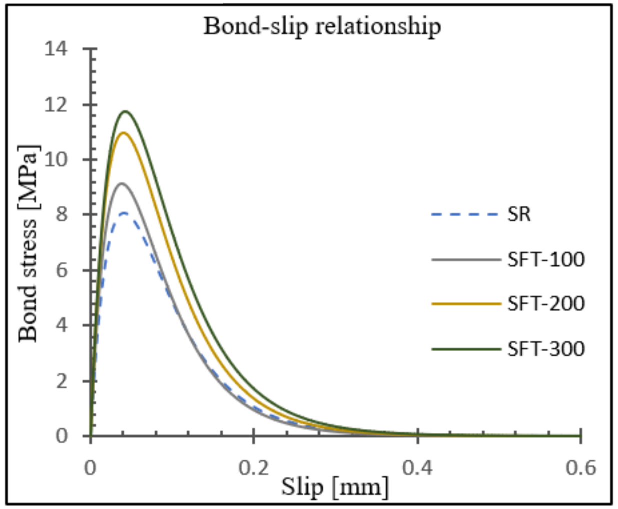
- The increase in bond capacity for samples tested after 100 cycles can be explained by the increase in concrete compressive strength.
- The increase in bond capacity of the samples tested after 200 and 300 FT cycles can be related to the change in the mechanical properties of the adhesive layer due to F-T cycles.

Test results

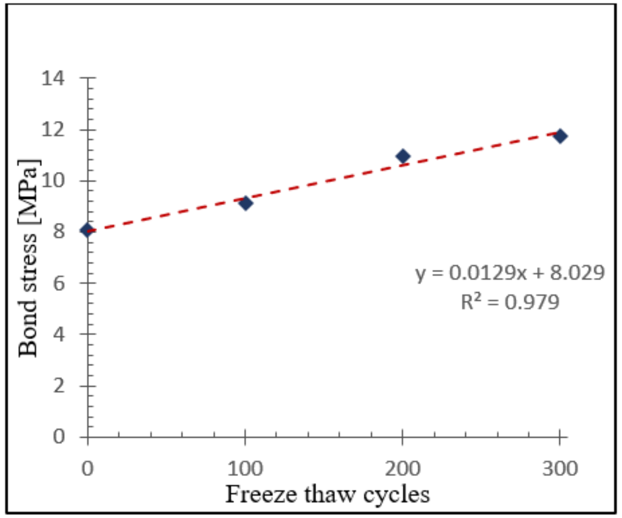
- **Bond strength**
  - The fitting parameters of the experimental curves of the applied load vs. slip were introduced in (Dai et al., 2005) model to construct the exponential form of the bond stress versus slip.
    - Bond slip relationship: $\tau(s) = 2BG_f(e^{-Bs} - e^{-2Bs})$ (1)
    - The interfacial fracture energy: $G_f = \frac{P_u^2}{2E_f t_f b_f^2}$ (2)



Fitting load-slip curves



Bond stress-slip curves



linear prediction model

The maximum bond strength increased by 13 %, 35 % and 46 % after exposing the CFRP-concrete joints to 100, 200 and 300 FT cycles, respectively.

Conclusion

The purpose of this study is to investigate the bond behavior between CFRP sheets and concrete after freeze thaw cycles in wet conditions. The following conclusions can be drawn.

1. Cohesive failure in the concrete substrate was observed for control samples as well as after 100 F-T cycles;
2. From 200 F-T cycles, the failure mode of the CFRP-concrete joints changed to adhesive failure at the CFRP-concrete interface. This change in failure mode allowed stating that the CFRP-concrete interface was affected by the increase of F-T cycles and by the presence of moisture during the F-T exposure.
3. The maximum bond stress increased by 13 %, 35 % and 46 % compared with reference results after exposing the CFRP-concrete joints to 100, 200 and 300 F-T cycles, respectively.
4. The improvement of the bond stress was related to the change in the mechanical proprieties of the adhesive layer.

We recommend to study the effect of F-T cycles on the adhesive properties in further research.

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