FRPRCS-14, Belfast - June 2019

Cold Temperature Effects on the Impact Resistance of SFRC Panels Strengthened with FRP Straps

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Abstract

As part of a larger study, lightweight armour panels were designed using steel fibre reinforced concrete (SFRC) strengthened with fibre reinforced polymer (FRP) straps and experimental testing was conducted. These panels were designed to be a part of a modular protective system that could be used to protect key infrastructure and assets that may be exposed to extreme loading. Experimental quasi-static and dynamic tests were conducted and residual panel flexural strengths were determined after the panels were tested dynamically. All tests were conducted with panels at ambient laboratory temperatures and extreme cold temperatures to simulate Arctic conditions. This paper shows that the cold temperature panels that did not completely fail during dynamic testing maintained a residual flexural strength equal to their quasi-static flexural strength. This is in contrast with ambient temperature panels, which had varying residual flexural strengths with minimal correlation to the permanent deflection caused by the dynamic loading. The results show that the residual flexural strength of a panel exposed to an impact under extreme cold temperature conditions can be predicted based on its quasi-static flexural strength.

Keywords: Impact, cold temperature, protective structure, fibre reinforced polymer, panel

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Introduction

Structures with the ability to protect key infrastructure and personnel from the effects of an explosive blast, either accidental or targeted, are critical to the oil and gas and defence industries. In Canada, the majority of the oil and gas industry is located in northern climates and the Canadian Armed Forces has several installations in Arctic regions where extreme cold temperatures are typical during the winter months. Expeditionary forces that do not rely on a large logistical support framework are ideal for operations in extreme climates, such as the one in Canada's Arctic. These forces require lightweight, modular protective structures that can be installed with limited resources. Lightweight armoured panels made of advanced materials such as steel fibre reinforced concrete (SFRC) combined with fibre reinforced polymer (FRP) wraps could be suitable for this purpose. There has been significant research conducted in the fields of FRP strengthening of reinforced concrete (RC) structural components in cold temperatures [1] [2] and blast [3]. However, there is presently a dearth of published literature on the topic of FRP strengthened SFRC exposed to the combined effects of blast or impact loads and extreme cold temperatures.

Research Objectives and Scope

This paper is part of a larger research project that focused on the ability of two types of armour panels to resist impact loads at ambient and cold temperatures [4]. The specimens evaluated in this study were made of steel fibre reinforced concrete (SFRC) and they were strengthened with fibre reinforced polymer (FRP) straps. The panels were tested either quasi-statically, using a three-point flexural bending test, or dynamically, using a pendulum-type impact hammer. The impact-tested panels were tested for residual flexural strength using the same three-point flexural bending test that was used on the quasi-statically tested panels. This was done to enable a comparison of flexural strength between a damaged and undamaged panel. All tests were conducted on panels at ambient laboratory temperatures and extreme cold temperatures.

The scope of this paper has been limited to focus on the results of the residual flexural strength testing done on impact-tested panels at extreme cold temperatures. While the paper will compare the results of the cold temperature panels to the ambient temperature panels, the focus is on the effect of cold temperature on the panel's behaviour. Although these panels would be installed in a spaceframe-type structure to provide sufficient protection, the design and testing of this type of structure was beyond the scope of this research.

Experimental Program

Specimens

A total of eleven specimens were tested as part of this experimental program. Three of those specimens were tested in a quasi-static manner and the remaining eight specimens were tested dynamically using the impact hammer. All specimens have the same external dimensions; 1040 mm in length, 535 mm wide and 38 mm thick, as shown in Figure 1. Panel dimensions were selected to keep the total panel mass around 50 kg, which would allow them to be carried by two personnel.

Ready mix air-entrained concrete with a steel fibre content of 1% by volume was used in this study. The fibres used were Bekaert Dramix RC-65/60-BN fibres. These fibres are 60 mm in length with a diameter of 0.55 mm and a tensile strength of 1345 GPa [5]. Compression tests were carried out using cylinders with a 100 mm diameter and 200 mm height, and were conducted according to ASTM C39 [6]. Testing showed that the concrete provided had an average compressive strength of 40 MPa and an average modulus of elasticity of 22 GPa.

FRP straps with a width of 100 mm were added to the SFRC panels in order to increase their flexural strength. The FRP used in this study was BASF MBrace CF 130 [7]. This product is a unidirectional dry fabric constructed of high strength carbon fibres that is applied to a concrete surface using a two-part vinyl ester polymer. Manufacturer provided technical data lists the ultimate tensile strength of the FRP system as 3800 MPa and the tensile modulus as 227 GPa. Two straps were applied to each panel tested as part of this research project, with each strap having a width of 100 mm and consisting of two layers of CF 130.

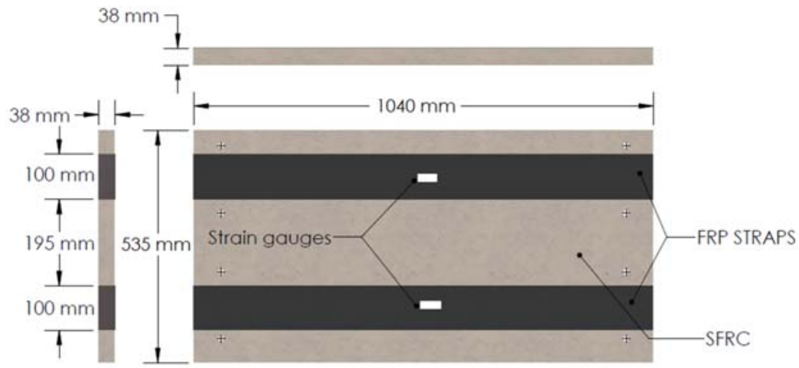

Figure 1: Panel dimensions

Test Setup, Instrumentation, Procedures
Quasi-static testing was conducted using a three-point flexural bending test on a MTS Model 322 machine. This machine was displacement-controlled and the head was set to displace at a rate of 2 mm/min. Panels were supported within the machine by triangular pins with bearing plates on top, which would allow translation in the horizontal direction and rotation. The load was applied to the panel at midspan to simulate the same loading conditions as those found in the dynamic test. Midspan displacement was monitored by a 300 mm LVDT.
Dynamic tests were conducted at varying hammer heights, which altered the impact energy of the system. The same impact energies were used for tests at each temperature, in order to have readily comparable data. Once an impact test was completed, the residual flexural strength of the panel was tested using the same three-point bending test setup that was used for the quasi-static testing. Cold temperature panels were placed in an industrial-sized freezer capable of reducing the panel's temperature to -70°C. For the residual strength tests, panels were returned to the freezer post-impact test until their temperature returned to -70°C. Once the panel had returned to this temperature, it was removed from the freezer and placed in the quasi-static testing frame. Due to the length of the residual flexural strength test, it was impossible to maintain the target temperature of -55°C for the entire duration. The testing was conducted such that the temperature at the beginning of the test was lower than the target value, and the temperature upon completion was higher than the target, leading to a mean testing temperature consistent with the target temperature. Temperature was monitored using a type T thermocouple, which was applied to the surface of each panel.

Test Results

Panel specimens were tested after 28 days of curing time. A summary of the results is shown in Table 1. The post-impact deflection listed in the table is the result of the impact test and was the initial deflection for the residual strength test. The residual flexural strength and residual maximum deflection values in the table are the results of the quasi-static residual flexural strength test.

Table 1: Summary of Testing Results

Specimen	Temperature	Drop height [mm]	Post-impact deflection [mm]	Residual flexural strength [kN]	Residual maximum deflection [mm]
SAI1	Ambient	500	1.4	15.0	115.1
SAI2	Ambient	750	3.9	13.4	106.5
SAI3	Ambient	1000	7.2	14.8	113.0
SAI4	Ambient	1500	6.8	12.0	121.1
SCI1	Cold	500	5.3	15.1	113.8
SCI2	Cold	750	6.0	15.1	95.4
SCI3	Cold	1000	8.0	15.7	110.8
SCI4[a]	Cold	1500	35.1	--	--

[a]Complete debonding of FRP straps and large cracking/spalling of concrete, no residual strength.

The load-deflection behaviour from the residual flexural strength tests done on the impact-tested panels can be found in Figure 2. As shown in the graphs, each impact-tested panel starts from the deflection caused by the impact test and then displays similar behaviour to the quasi-static panels, with fluctuations in the peak load due to the local fracture and debonding of the FRP. The cold temperature panels display more predictability than the ambient temperature panels, regardless of the magnitude of impact energy they were exposed to during the impact test. All cold temperature panels achieved a residual flexural strength of 15 kN and a maximum midspan deflection of 95 mm – 120 mm. This is likely due to the increased tensile strength in the concrete due to the cold temperature, which controls and limits the extent of debonding of the FRP. Furthermore, cold temperatures may cause the concrete to have increased bond strength on the steel fibres, increasing the overall tensile strength of the panel. The ambient temperature panels display a much less predictable load-deflection behaviour, with a general observation that panels with a higher post-impact deflection typically had a lower residual flexural strength.

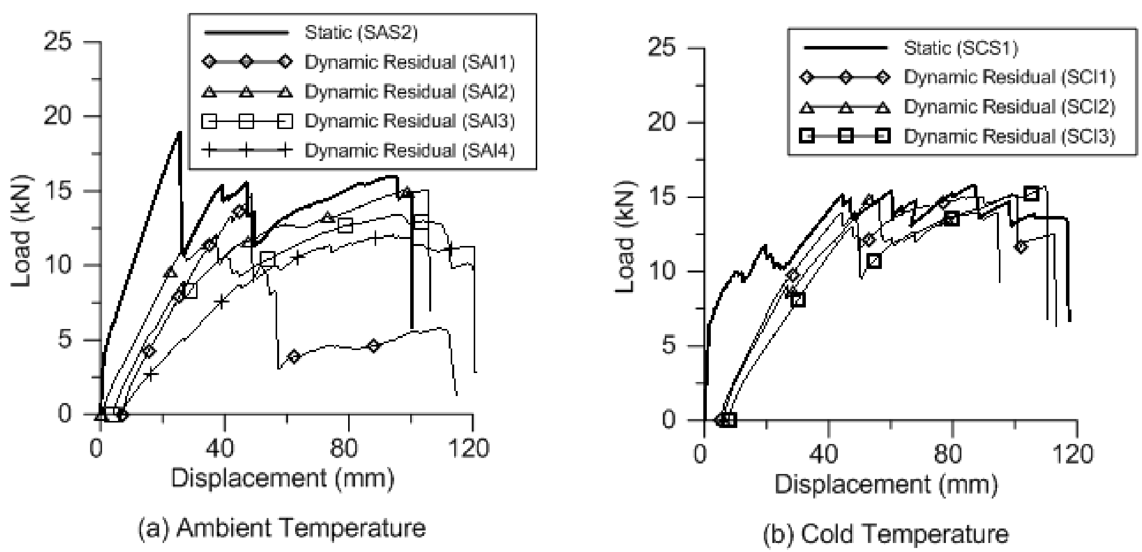

Figure 2: Load-deflection behaviour during residual flexural strength test

When tested for residual flexural strength, all panels failed in the same manner, regardless of the temperature at which they were tested. Failure of a panel progressed from debonding and fracturing of the FRP straps on the tension face, followed by debonding of FRP straps on the compression face, which ultimately led to complete fracturing of the tension face FRP straps. The cold temperature panel tested at a drop height of 1500 mm was the only panel to completely fail as a result of the impact test and was not tested for residual strength. Complete failure was assessed as debonding and fracturing of the FRP straps, which resulted in a very large permanent deflection and the inability to transport it to the residual strength testing apparatus. The cause of failure at this drop height for the cold temperature panel could be attributed to the increased stiffness and strength of the FRP straps under cold temperatures, which would have attracted more load to the straps and led to a more brittle failure.

Conclusions

The experimental program that was used in this research was created to design and test a lightweight armour panel made of SFRC that was strengthened with FRP straps. These panels could be utilized as part of a modular protective system by industry or military forces to form protective works that would protect personnel and critical assets from the effects of projectiles or an explosive blast. The following conclusions are based on the results outlined in this paper:

1. Cold temperature panels that did not completely fail under impact loading display similar residual flexural strengths, regardless of the amount of permanent deflection sustained from the impact test.
2. Ambient temperature panels appeared to have reduced residual flexural strength as the magnitude of permanent deflection from the impact test increased.
3. Cold temperature panels display increased residual flexural strength when compared to ambient temperature panels that were subjected to a similar impact load.

Acknowledgements

This research project was funded by the Natural Science and Engineering Research Council of Canada (NSERC) and the Canadian Defence Academy Research Program (CDARP).

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