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Effects of low temperature on the static behaviour of reinforced concrete beams with temperature differentials

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HIGHLIGHTS

- A thorough study on the static behaviour of reinforced concrete at low and room temperature.
- Application of DIC/PIV technique in measuring crack widths.
- Measurement of temperature-related strain errors in DIC camera system through calibration tests.
- Comparison of crack widths as well as crack distribution and pattern at room and low temperature.
- Crack widths relationship with temperature differentials.

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ABSTRACT

This paper investigates the static behaviour of reinforced concrete beams at low temperatures compared to similar beams tested at room temperature. Four large-scale beams were fabricated and tested. The testing program for the beams consisted of four stages: incrementally loading the beams to a service load of 90 kN, sustaining the load at 90 kN for 48 h, cycling the load between 50 kN and 90 kN for 10 cycles, and loading the beam to failure. All of the beams had temperature differentials over their depth to simulate solar radiation and in-service temperature of the bridges. The beams tested at low temperature (−25 °C) demonstrated an increase in strength and ductility up to 13% and 34% respectively compared to the beams tested at +15 °C. The results also show that the cracking load increased while the number and the depth of the cracks decreased at low temperature. In addition, the widths of the shear cracks were reduced at low temperature compared to their counterparts at room temperature. The load at which the stirrups contributed structurally also increased drastically at low temperature. In this research, DIC/PIV technique was used to measure the widths of the shear cracks, and the effect of low temperature on the camera system was investigated through calibration tests to ensure the accuracy of the measured crack widths.

1. Introduction

Bridges are primary links of land transportation throughout the world. For instance, over 55 million cars and 10 million trucks crossed the Canada-U.S. border in 2011 [1]. A large number of these cars and trucks passed over bridges to reach their destination. However, Canada's highway bridges, on average, have passed almost 60% of their useful life since they were built in the 1960s and 1970s [2]. Inspecting Quebec's bridges after the collapse of the Viaduc de la Concorde in 2006 in Laval, revealed that 135 bridges in the province posed a potential safety concern serving as a warning that a high number of the nation's bridges could be in a similar condition [3]. In the United States, 25% of the nation's 607,380 bridges are classified as structurally deficient or functionally obsolete. In spite of the condition of these bridges, approximately 210 million daily trips in the U.S. are taken across them [4].

Bridges experience a number of deterioration mechanisms during their service life, predominantly caused by environmental conditions and traffic volume. Many concrete bridges are located in cold regions with prolonged freezing seasons, e.g. Canada and northern U.S. As these structures approach the end of their service life, and need to be repaired, retrofitted or even destroyed and reconstructed, the importance of research on structures in cold regions is increasing.

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Much research has been conducted on the effects of extreme environmental conditions, i.e. temperature, moisture, etc., on curing and pouring, behaviour and mechanical properties of concrete as well as on the behaviour and mechanical properties of reinforcing steel. In fact, most of the past research focused on the material level [5–8] rather than on structural behaviour of reinforced concrete members. Limited research is available describing the structural response of reinforced concrete members subjected to various types of loading conditions e.g. [9–13].

Montejo et al. [10–12] studied the effect of low temperature on the seismic behaviour of reinforced concrete columns. Ten specimens including six flexural dominated and four shear dominated circular columns were tested under reversed cyclic loading at +22 °C and −36 °C, respectively. The flexural dominated columns comprises two ordinary reinforced concrete and four reinforced concrete filled steel tube (RCFST) with a cantilever length of 1651 mm and diameter of 457 mm. The columns were transversely reinforced using spirals spaced at 60 mm to ensure a flexural failure. The shear dominated columns consisted of four circular reinforced concrete columns with a cantilever length of 762 mm and diameter of 419 mm. The longitudinal and transverse reinforcements were designed to ensure either ductile or brittle shear failure. The ductile shear design consisted of eight No.7 (D = 22 mm) bars and a No.3 (D = 10 mm) spiral spaced at 102 mm, and the brittle shear design consisted of eight No.9 (D = 29 mm) bars and a No.3 (D = 10 mm) spiral spaced at 145 mm. This research showed that, at low temperature, the strength of the flexural dominated columns increased by 16%, and this increase was accompanied by a reduction in the displacement capacity of these columns. However, the displacement capacity of the shear dominated columns increased at low temperature. This study also demonstrated that the shear strength of the cold ductile and brittle shear dominated columns respectively increased by 20% and 32%, and the increase in the shear capacity of the cold columns was at a higher rate than the flexural strength since the onset of shear failure delayed in the cold shear dominated specimens even though higher flexural strength at low temperature caused shear demand to increase. The elastic stiffness (defined as the load level required for first yield of the room temperature specimen) of the cold flexural dominated specimens as well as ductile and brittle shear dominated specimens increased by 27%, 56% and 35%, respectively, and initial stiffness (slope of load–deflection curve) of the cold columns increased at low temperature as well.

DeRosa et al. [13] studied the static behaviour of large-scale reinforced concrete beams at −20 °C and room temperature. Two beams were loaded and tested at room temperature while the other two beams were exposed to a temperature of −20 °C during the sustained and the following loading stages. The results of that study suggested that the cracks that formed in the two beams that were exposed to −20 °C temperature conditions closed up after the 48 h constant load period, and that the percentage increases in crack widths close to the failure load were smaller than those in similar beams tested at room temperature. In addition, the failure load for the beam tested at −20 °C was approximately 20% higher than its counterpart at room temperature. This study concluded that temperature had an impact on crack widths at ultimate loads, and that cracks in reinforced concrete specimens decreased in size at lower temperatures, which could potentially increase the overall shear capacity of the member during colder times of the year.

This paper presents an investigation of the effect of low temperature on the static behaviour of reinforced concrete beams. The results of static tests on four large-scale beams with temperature gradients that have a loading history of 48 h sustained load and 10 load cycles at room temperature and at −25 °C are discussed in this paper. It should be noted that the reinforcements and the dimensions of the beams used in this study were as same as the beams tested by DeRosa et al. (2012) [13]; however, these beams had a temperature differential over their depth, and their material properties as well as the testing condition were different, i.e. higher incremental and sustained load, the higher number of load cycles, and −25 °C constant ambient temperature from the first stage of the low temperature tests. This study is of particular importance to cold regions with prolonged freezing seasons.

2. Experimental program

2.1. Material tests

2.1.1. Concrete cylinder test

To determine the compressive and tensile strength of the concrete, concrete cylinders were cast together with the beams. The concrete mix included a maximum aggregate size of 10 mm, 7% air entrainment and 200 mm slump (with super plasticizer). Three compressive and three splitting tensile tests were conducted on concrete cylinders (150 mm × 300 mm) that had attained their minimum specified 28-day strength. The compressive and splitting tensile tests were performed in accordance with American Society for Testing and Materials (ASTM) C39M-12a and C496M-11, respectively.

The mean compressive and splitting tensile strengths of the concrete from the cylinder tests were 43.0 MPa and 3.6 MPa, respectively. The compressive strengths of the concrete at the time of the static tests are shown in Table 1.

2.1.2. Deformed bar tensile test

Hot rolled bars, 10M (11.3 mm diameter) and 20M (19.5 mm diameter), from a single batch of 400 Grade steel (HR G30.18 400W) were used in the beams as compression, shear and tension reinforcement. Samples of the 10M and 20M bars from the same batch were cut and tested in tension. In total, six tensile tests were conducted on the deformed steel bars, three tests on 10M bars and three tests on 20M bars in accordance with ASTM A370-12a and A615M-12. The uniaxial tensile tests on the 10M bars resulted in mean yield and mean ultimate strengths of 481 MPa and 669 MPa, respectively. Similarly, for 20M bars, mean yield and mean ultimate strengths were 421 MPa and 531 MPa, respectively.

2.2. Beam tests

Four reinforced concrete beams, 200 mm × 400 mm × 4200 mm were constructed with two 20M bar (300 mm^2) and two 10M bar (100 mm^2) as tension and compression reinforcement, respectively. Fig. 1 shows the cross-section and details of the internal reinforcement of NSR and NSL beams on the left as well as WSR and WSL beams on the right. The WS and NS designations stand for With Shear reinforcement and No Shear reinforcement, and R and L stands for the temperatures at which the beams were tested, R for room temperature (+15 °C) and L for low temperature (−25 °C). Shear reinforcement was provided for two beams (WSR and WSL) using 10M stirrups at 175 mm spacing. The other two beams (NSR and NSL) had no shear reinforcement, although individual 10M stirrups were provided at the centre and ends of the beams for constructability purposes.

Fig. 2 shows the reinforcement and internal instrumentation details as well as test configuration of the beams. Prior to casting the beams, 5 mm electric resistance strain gauges and type T thermocouples were attached to the reinforcing steel. The WSR and WSL beams had ten strain gauges: three on the tensile reinforcement, three on the compressive reinforcement and four on the stirrups in the middle of the shear spans. The beams without stirrups only had the first six strain gauges on their tensile and compressive reinforcements. All of the beams were instrumented with nine type T thermocouples, at midspan and near the ends at three levels.

To simulate solar radiation, heating pads and insulation were placed on the top surface of the beams prior to the start of each test to create a temperature gradient over the depth of the beams during the tests. The averages of the temperatures, read by the thermocouples, at three levels of the beams at the time of testing are shown in Fig. 3.

Two of the simply-supported beams were tested at +15 °C using an electric 900 kN Riehle testing machine and the other two beams were tested using a 500 kN servo-hydraulic actuator in a cold room equipped with a refrigeration system able to maintain a constant room temperature at −25 ± 2 °C. To protect the

Table 1
Compressive strengths of the concrete.

Beam description	Beam ID	Compressive strength (MPa)	Age (day)
No Shear Reinf.-Room Temp.	NSR	47.0	115
With Shear Reinf.-Room Temp.	WSR	43.0	130
No Shear Reinf.-Low Temp	NSL	45.0	255
With Shear Reinf.-Low Temp	WSL	43.0	288