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Behaviours of reinforced concrete beams under low temperatures

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HIGHLIGHTS

- Low temperature increases yield and ultimate strength of steel reinforcement.
- Low temperature increase tensile and compressive strengths of the NWC.
- Low temperature improves resistance of RC beam.
- Developed FEM predicts well the behaviours of RC beams under low temperature.
- Developed analytical models predict well resistances of RC beam under low temperature.

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ABSTRACT

Reinforced concrete (RC) structure applied in the Arctic engineering and low temperature environment keeps increasing. This paper, experimentally, analytically, and numerically investigated the ultimate strength behaviour of the RC beams under different low temperatures. This paper firstly reported the experimental studies on mechanical properties of the steel reinforcements and normal weight concrete under different low temperatures. Empirical formulae were developed to incorporate the influences of the low temperature on the mechanical properties of the steel reinforcements and concretes. The ultimate strength behaviour of the RC beams under low temperature were studied through twelve quasi-static tests. The influences of the low temperatures and flexural reinforcing ratio on the ultimate strength behaviours of RC beams have been analysed and discussed. Analytical models were developed to predict the resistances corresponding to first crack, steel yielding, and ultimate resistances of the RC beams under low temperatures. Finite element model (FEM) was also developed to simulate the ultimate strength behaviour of the RC beams under low temperature. The accuracies of the analytical models and FEM simulations were checked through validations of the predictions by different models against the test results.

1. Introduction

The engineering activities in the cold regions, e.g., Tibet and Northern China, Arctic and Antarctic region, keep increasing. Recently, due to the Arctic region stores 13% of the world's undiscovered oil and 30% of the world's undiscovered gas, the explorations of the oil and gas have been extended to this region to meet the increasing demand of world's energy [1,2]. Thus, reinforced concrete (RC) platforms [3] or artificial island with reinforced concrete type of ice-resisting walls [4] have been built in the Arctic for the oil and gas explorations, e.g., the Tarsiut Caisson Retained Island (CRI) constructed in the Canadian Beaufort sea, the Molikpaq in the Canadian Beaufort sea, and the Concrete Island Drilling System (CIDS) in the Beaufort sea. Including the increasing constructions for the oil and gas explorations in the Arctic, the facilities and constructions for the liquid natural gas (LNG) also keep increasing all over the world [5]. In order to facilitate the transportation and storage of the LNG, LNG containers, usually made of RC structure, were built and put into use. Due to the fast developments of economy in Tibet and northern China, more infrastructures have been built in these cold regions, e.g., railway bridges, stations, and buildings. One common working scenario

Abbreviations: CDPM, concrete damage plasticity model; COV, coefficient of variation; FE, finite element; FEA, finite element analysis; FEM, finite element model; LNG, liquid natural gas; LVDT, linear varying displacement transducer; NWC, normal weight concrete; RC, reinforced concrete.

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Nomenclature

A_{fl}	Area of the flexural reinforcement in the section of the beam
B, h	Width and depth of the beam, respectively
E_{ca}	Elastic modulus of the concrete under ambient temperature
E_{cT}	Elastic modulus of the concrete under temperature T°C
L_a	Shear span of the two-point loaded RC beam
$M_{cr,T}$	Cracking moment under temperature T°C
N_{cT}	Compressive forces acted on the cross section of the beam
N_{tT}	Tensile forces acted on the cross section of the beam
P_{cr}	Resistances corresponding to first cracking
P_y	Resistances corresponding to steel yielding
P_u	Ultimate resistance of beam
$V_{c,T}$	Shear resistance of RC beam contributed by concrete
$V_{s,T}$	Shear resistance of RC beam contributed by shear reinforcement
$V_{u,T}$	Ultimate shear resistance of the beam
W_T	Elastic section modulus, and equals $bh^2/6$
f_{cT}	Compressive strength of the concrete under temperature T°C
f_{yT}	Yield strength of the reinforcement under temperature T°C
f_{ca}	Compressive strength of the concrete under ambient temperature
f_{yvT}	Yield strength of the shear reinforcement at T°C
f_{ya}	Yield strength of the reinforcement under ambient temperature
f_{uT}	Yield strength of the reinforcement under temperature T°C
f_{ua}	Yield strength of the reinforcement under ambient temperature
h_e	Effective depth of the neutral axis in the cross section
s	Spacing of the shear reinforcement
x	Position of the neutral axis
ε_{0T}	Compressive strain at ultimate strength of the concrete under T°C
ε_{0a}	Compressive strain at ultimate strength of the concrete under ambient temperature
ρ_{fl}	Flexural reinforcing steel ratio of the cross section
σ_c	Uniaxial compressive stress of concrete
σ_t	Uniaxial tensile stress of concrete
$\sigma_{t,T}$	Tensile strength of the concrete under temperature T°C
$\sigma_{t,a}$	Tensile strength of the concrete under ambient temperature

for these RC infrastructures is that they are under low temperature or even super low temperature. The lowest temperature in northern China or Tibet could be about −53.4 °C [5]. The temperature in the Arctic could be even lower to about −70 °C [1]. Once the leakage of the LNG occurred, the reinforced concrete structure would be exposed to super low temperature of about −165 °C. Since the low temperature brought significant influences on the mechanical properties of reinforcements and concrete materials, its influences on the structural performances of the RC structure need to be well considered. Thus, the structural behaviour of the RC structures under low temperature or even super low temperature needs to be well understand to make sure they could sustain such super low temperatures during its service life.

There were versatile reported research works on the mechanical properties of the steel reinforcements and concretes under low or super low temperatures. Elices et al. [6] reported tensile tests on steel reinforcements under different low temperature levels to −180 °C. It was found that the yield and ultimate strengths of the hot-rolled steel bar was increased by about 80% and 35%, respectively. However, the maximum elongations were decreased by about 10% and 50% for hot-rolled steel reinforcement and cold-stretched steel reinforcement, respectively. Lahlou et al. [7] also reported that decreasing the temperature from 20 °C to −195 °C increased the yield (or ultimate) strength of the steel reinforcement by about 70% (35%), but decreased the strain at ultimate strength from 0.13 to 0.05. Xi et al. [8], Wang et al. [9], and Zhang [10] experimentally studied the mechanical properties of the U71M n and U75V steels for rail way under low temperature about −60 °C in Tibet, China. Their experimental studies also showed that the strengths of these steels were slightly increased, but their ductility was reduced. Liu et al. [11] experimentally studied the mechanical properties of the reinforcing steels at the temperature intervals of (20 °C∼−40 °C) and (−80 °C∼−180 °C). Their experimental studies revealed that as the low temperature decreased from 20 °C to −180 °C, the yield and ultimate strengths of the mild steel were averagely increased by 75% and 40%, respectively. Sloan [12] also experimentally studied the mechanical properties of the steel reinforcement and concrete under low temperature of −20 °C and −40 °C. It was found that as the testing temperature decreased from 20 °C to −20 °C and −40 °C, the compressive strength of concrete (or yield strength of mild steel) was increased by 27% (11%) and 73% (24%), respectively. Lee et al. [13] found that the compressive strength increased uniformly to about 2.0 times of that at room temperature of 20 °C. However, the influence of the low temperature on the modulus of the elasticity was much smaller than that on compressive strength. Through the tests on air entrained concrete under low temperature, Nasser and Evans [14] found that the strength was increased by about 80% and the modulus of elasticity was increased by 20%. Rostásy and Wiedemann [15] found that the compressive strengths of the water-saturated and normally stored concrete at −170 °C were increased to about 400% and 260% of those at 20 °C. All these improvements on the mechanical properties of the NWC were due to the transformation of the water in the pore or micro cracks to the ice. Thus, the improvements of low temperature on the mechanical properties of the concrete greatly depend on their moisture content. Although there were versatile research works reported on the mechanical properties of the steel reinforcements and concretes, they only concentrated on the material level rather than the structure level. Thus, the experimental studies on the RC structures, e.g., RC beams, under super low temperature are still necessary.

Due to the expensive costing and the limitation of equipment to simulate the cryogenic temperature environment, there is still limited information on the experiments on the ultimate strength behaviour of RC structures. Liu et al. [16] reported quasi-static tests on six scaled RC beams under low temperature to −180 °C. However, the dimension of these tested beams measures 40 mm × 40 mm × 400 mm in width × height × length. Thus, these scaled specimens only provided limited information and could not avoid the size effect on structural behaviour. Larger scale tests are still necessary to obtain more information on the ultimate strength behaviour of the RC beams under different low temperature levels.

This paper firstly reported the experimental studies on the mechanical properties of the reinforcements and normal weight concrete (NWC) under different low temperature levels. Empirical