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Mechanical properties of headed studs at low temperatures in Arctic infrastructure

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ABSTRACT

The increasing engineering applications of steel–concrete composite structures in the Arctic or other cold regions have brought challenges for the mechanical properties of headed studs at low temperatures. This study experimentally investigated the mechanical properties of headed studs used in steel–concrete composite structures at low temperatures. A total of 56 tensile tests were performed on headed studs at low temperatures ranging from −80 °C to +20 °C. The mechanical properties of headed studs at low temperatures were reported, analysed, and discussed, including their strain–stress behaviour; yield and ultimate strengths; and yield, ultimate, and fracture strains. Based on the experimental results, regression analyses were also carried out to develop empirical prediction equations for the yield and ultimate strengths of headed studs at low temperatures from 20 °C to −80 °C. Finally, empirical prediction equations were proposed, and their accuracy was validated through a comparison with the predictions of experimental results.

1. Introduction

Steel–concrete composite (SCC) structures that combine the advantages of steel and concrete have become popular in engineering infrastructure. Recently, this structural system has been used in a wide variety of engineering constructions in cold regions and harsh environments, e.g. ice-resistant walls in offshore platforms for oil and gas exploration in the Arctic, steel–concrete composite bridges and other infrastructure in cold regions (see Fig. 1), liquefied natural gas (LNG) containers, prestressed concrete (PC) structures, and nuclear cooling towers [1–4]. SCC structures built in cold regions are exposed to harsh environmental conditions, particularly the low temperatures in those regions. As reported by Serreze and Barry [5], the lowest temperatures in Arctic regions can reach −70 °C. For other cold regions, e.g. Canada, Greenland, Tibet, and Northeast China, the lowest recorded temperature is about −60 °C [6, 7]. Headed studs are the most commonly used shear connectors, and are thus key components in determining the structural performance of SCC structures. Owing to their important role, the mechanical properties of headed studs in SCC structures built in the Arctic and other cold regions need to be carefully investigated and evaluated for the design of these SCC structures.

Extensive studies have been carried out to investigate the shear behaviour of headed studs used in SCC structures. Ollgaard et al. [8], Lam [9], and Xue et al. [10] experimentally investigated the shear behaviour of headed studs embedded in concrete simulating the working scenario in SSC structures. Han et al. [11] experimentally studied the influence of the rubber content on the shear behaviour of headed studs. The shear and tensile behaviours of headed studs at room temperature were investigated by Pallares and Hajjar [12, 13]. Mirza and Uy [14] and Shahabi et al. [15] investigated the shear behaviour of headed studs at elevated temperatures. Hanswille et al. [16, 17] experimentally and analytically studied the fatigue behaviour of headed studs. Yan et al. [18] applied the finite element method to investigate the shear behaviour of headed studs at Arctic low temperatures. However, these studies mainly focused on the structural behaviour of headed studs at ambient and elevated temperatures, or only studied the behaviour of headed studs at low temperatures numerically. Few experiments have been carried out to investigate the structural behaviour of headed studs at low temperatures.

Recently, some studies have explored the mechanical properties of construction materials at low temperatures. Elices et al. [19] investigated the behaviours of cold-stretched and hot-rolled steel at cryogenic temperatures reaching −180 °C. They found that the strength of both cold-stretched and hot-rolled steel increased with decreasing temperature, and low temperatures have a more significant influence on the

Abbreviations: COV, coefficient of variation; LNG, liquefied natural gas; RC, reinforced concrete; PC, prestressed concrete.

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Nomenclature

A_0	original cross-sectional area of the headed stud
A_u	smallest cross-sectional area of the headed stud at the fracture point
D	diameter of the headed stud
E_s	elastic Young's modulus of the headed studs
H	length of the headed studs
T	low temperatures
T_0	ambient temperature
a, b	constants which can be calculated from the tests results, in 1/°C
f_y	yield strength of the headed studs
f_u	ultimate strength of the headed studs
f_{y0}	yield strength of the headed studs at ambient temperature
f_{u0}	ultimate strength of the headed studs at ambient temperature
f_{yT}	yield strength of the headed studs at low temperatures
f_{uT}	ultimate strength of the headed studs at low temperatures
α, β	sensitivity coefficients for the yield and ultimate strengths to different low temperature levels, in 1/K
ψ	reduction in the cross-sectional area of headed studs
ε_y	yield strain of the headed studs
ε_u	ultimate strain of the headed studs
ε_F	fracture strain of the headed studs
σ	tensile stress of the headed studs

ductility of hot-rolled steel than cold-stretched steel. The mechanical properties of steel reinforcements at temperatures of +20 °C, −60 °C, −110 °C, and −165 °C were investigated by Lahlou et al. [20], and significant increases in both the yield and ultimate strengths of mild steel reinforcements with decreasing temperature were observed. Yan and Xie [3] carried out 63 tensile tests on hot-rolled mild steel reinforcements at low temperatures from +20 °C to −165 °C. The test results indicated that both the yield and ultimate strength of the steel reinforcements increased significantly with the decrease in temperature to −165 °C, but the ductility of the steel was reduced. Yan et al. [21] also experimentally studied the mechanical properties of high and normal strength steel plates at Arctic temperatures ranging from +20 °C to −80 °C. They found that the yield and ultimate strength of the steel plates increased significantly, whereas the fracture strain was not markedly affected by the low temperature. However, these previous tests only concentrated on the tensile stress–strain behaviour of construction materials at low temperatures, particularly focusing on steel reinforcements in RC or PC structures and steel plates in steel structures. Because headed studs have different production processes, chemical compositions, and microstructures than steel reinforcements and steel plates, the mechanical properties of headed studs used in SCC structures at low temperatures are still not fully understood. Thus, it is important to carry out experimental studies to obtain necessary information on the mechanical properties of headed studs at low temperatures relevant to cold environments. These experimental results can then be used as input data and will contribute to the design of SCC structures and the numerical analysis of their structural behaviour at low temperatures.

This study first establishes a testing programme to investigate the mechanical properties of representative headed studs used in SCC structures at low temperatures ranging from an ambient temperature of +20 °C to −80 °C. This testing programme utilises 56 headed stud specimens, which are tested at five temperatures: −80 °C, −60 °C, −30 °C, 0 °C, and +20 °C. The mechanical properties of the headed studs at these low temperatures are investigated, including the stress–strain behaviour, elastic modulus, yield and ultimate strengths, reduction in cross-sectional area (ψ), yield strain (ε_y), ultimate strain (ε_u), and fracture strain (ε_F). Then, the influence of low temperatures on these mechanical properties is analysed and discussed. Finally, empirical prediction formulae are developed to describe the mathematical relationship between the mechanical properties of mild steel headed studs and the low temperatures of their environment.

2. Testing programme

2.1. Details of test specimens

To investigate the mechanical properties of headed studs at low temperatures, a total of 56 specimens were prepared for tensile testing. Fig. 2 shows a typical specimen for the tensile tests. This representative specimen consists of one headed stud welded to a bottom welded holding steel plate. This bottom steel plate has a width of 100 mm and thickness of 30 mm, and was used to hold the root of the stud during the tests. The headed studs were made of mild steel, and their chemical compositions are listed in Table 1. The parameters investigated with this testing programme are different low temperatures and varying diameters of the headed studs. Headed studs with diameters of 13, 16, 19, and 22 mm were prepared for the tests. Thus, the 56 specimens can be grouped into four categories. In each category, 15 specimens were tested at five target temperatures, i.e. −80 °C, −60 °C, −30 °C, 0 °C, and +20 °C, with three identical specimens tested at each temperature level. As reported by Serreze and Barry [5], the lowest temperature on record in the Arctic region is approximately −70 °C during winter. In addition, lowest recorded temperatures in Tibet and Northeast China are approximately −50 °C [7]. Thus, the temperature range for this test programme is from +20 °C to −80 °C.

2.2. Test setup

Fig. 2 shows the typical setup for the tensile tests on headed studs, consisting of a hydraulic-servo loading system, a cooling chamber, and a data acquisition system. All specimens were tested under this servo-hydraulic testing frame with a capacity of 100 tons. The specimens were anchored to the testing frame with two steel clamps (see Fig. 2).

Simulation of the low-temperature environment in the Arctic and cold regions was achieved using a sealed cooling chamber surrounding the specimens accompanied by injection of liquid nitrogen. This cooling chamber has dimensions of 450 × 400 × 600 mm (length × width × height). Four PT100 thermocouples were installed inside the cooling chamber to monitor the environmental temperature during the tests.

2.3. Loadings and measurements

Cooling of the specimens was performed after their installation on the loading machine. The cooling rate of the environmental temperature in the chamber was 2–4 °C/min [22]. To monitor the temperature of the specimens, two PT100 thermocouples were installed at their middle regions. After achieving the target temperature, an additional 30 min were required to ensure the average distribution of the target low temperature according to GB/T 13239-2006 [23], and the PT100 readings were used to assist in controlling the temperature. Once the target low temperature was achieved, the tensile tests were performed. Tensile loading on the headed studs was performed in a displacement-controlled mode, and the corresponding reaction forces at each displacement increment were monitored by a load cell attached to the reaction frame. The displacement loading rate was 0.04 mm/min before the yield point and 0.4 mm/min after yielding, according to ASTM: A370-13 [24]. Two linear strain gauges were mounted on the middle surface of the headed stud to measure the strains, particularly those