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Experimental studies on mechanical properties of steel reinforcements under cryogenic temperatures

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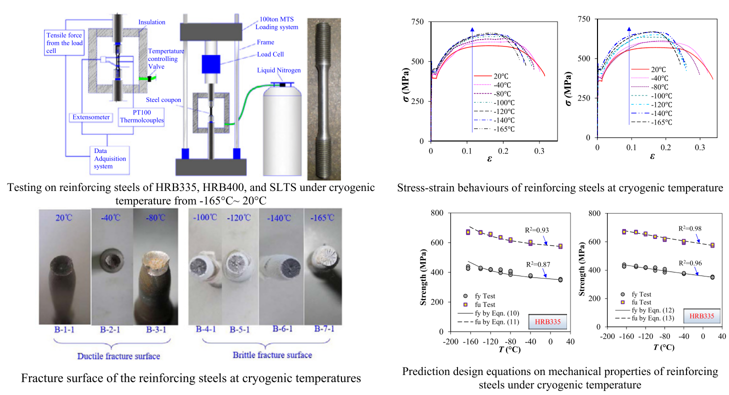
HIGHLIGHTS

- Cryogenic temperature increases yield and ultimate strength of reinforcements.
- Cryogenic temperature reduces the ductility of the reinforcing steels.
- The failure of reinforcing steel changes from ductile to brittle mode at −80 °C.
- Proposed equations predict well the strength of steel at cryogenic temperature.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing demands of the liquid natural gas (LNG) container and engineering constructions in the cold regions require the reinforcing steels could work under the cryogenic temperatures. This paper reported the experimental studies on the mechanical properties of HRB335, HRB400, and SLTS type of reinforcing steels that were used in the reinforced concrete structures and LNG containers. A test program consisted of 63 steel coupons was performed under different cryogenic temperatures ranging from −165 °C to 20 °C. The test results revealed the influences of the cryogenic temperatures on the mechanical properties of the different reinforcing steels that included stress-strain behaviours, elastic Young's modulus, yield and ultimate strength, fracture strain, and percentage of reduction in the cross sectional area. Discussions were also made on the differences of the influences of the cryogenic temperatures on the mechanical properties among different types of reinforcing steels. Based on the test results, empirical design equations were developed through the regression analysis on the reported test results. The accuracies of these developed equations were checked through validations of the predictions against the test results. Conclusions and design recommendations were made based on these experimental and analytical studies.

1. Introduction

Due to the development of the world's economy, the demand for liquefied natural gas (LNG) keeps on increasing. LNG container

Abbreviations: LNG, liquid natural gas; RC, reinforced concrete; COV, coefficient of variation; SLTS, special low temperature steel.

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Nomenclature

A, B	constants that can be determined from the test results, in 1/°C
A_0	the area of the cross section of the reinforcing steel before test
A_u	the area of the cross at the fracture point of the reinforcing steel
E_s	elastic modulus of the steel
L_0	the original length of the measured region by extensometer
L_u	the length of the measured region at the fracture.
T	cryogenic temperature level
T_0	ambient temperature
f_0	fracture strength of the reinforcing steel
f_y, f_u	yield and ultimate strength of the reinforcing steels
f_{ya}, f_{ua}	yield and ultimate strength of the reinforcing steels at ambient temperature
f_{yT}, f_{uT}	yield and ultimate strength of the reinforcing steels at ambient temperature T
ψ	percentage of reduction in cross sectional area of reinforcing steel
α, β	sensitive coefficients of the steels to the temperatures for yield and ultimate strength
ε_u	fracture strain of the steel
σ	tensile stress of steel
υ	Poisson's ratio

thus has been widely built to facilitate the transportation and storage of the LNG. The LNG containers usually comprised several layers of materials. Its inner layer is usually the 9%Ni steel that is directly exposed to the cryogenic temperature. The external wall of the LNG container was usually made of reinforced concrete structure that is probably exposed to cryogenic temperature of about −162 °C in the scenario of LNG leakage. Between the external concrete structure and the inner steel container are several layers of the insulation materials, e.g., loose perlite, foam-glass brick, and fiber glass etc. Different types of steel have been used under low temperatures that include Q235, 16MnV, 15MnV, 16Mnq, and 14MnNbq [1]. During the early stage, addition of small amount of titanium, niobium or aluminium in the steel products to improve their mechanical properties under low temperatures [2]. This tends to increase the cost of the steel products. Since the external reinforced concrete thick shell was only exposed to the low temperature in case of the leakage of the LNG, normal hot rolled or cold formed mild steel reinforcements have been widely used in the construction of the LNG container [3–5]. The HRB 355 and HRB 400 type of mild steel reinforcements have been extensively used in the LNG container in China [6–8]. Including the LNG container, more and more reinforced concrete type of engineering facilities have been built in Northern China, Tibet, and Arctic region. The temperatures in the Northern China could be as low to −53.4 °C [9]. In the Arctic region, the temperature could be even lower to about −70 °C [10,11]. It can be found that all these constructed reinforced concrete (RC) structures suffer cryogenic temperature in such harsh environment in winter. This cryogenic temperature affects the mechanical properties of the steel reinforcements and concretes that further influences the performances of the RC structure. This attracts the research interests on the mechanical properties of the steels and concretes under cryogenic temperatures.

Elices et al. [12] experimentally studied the mechanical properties of the hot rolled reinforcing steels in RC structure at cryogenic temperatures. Their experimental studies on mechanical properties of the steel reinforcements at 20 °C, −80 °C, and −180 °C showed that the strengths of the steels increased with the decrease of the temperature but the ductility was not affected. Lahlou et al. [2] tested the mild steel at ambient temperature and −195 °C and observed that the strength and elastic modulus of the steel all increased with the decrease of the temperature whilst the ductility exhibited significant decrease as the temperature decreased to −195 °C. Filiatrault et al. [13] reported the mechanical properties of the reinforcing steel under different strain rates within temperature interval of 20 °C to −40 °C. These reported test results showed that the influences of the cryogenic temperature on the mechanical properties greatly depended on the steel products themselves [13–18]. In addition, these reinforcing steels used in the experimental studies were different from those used in P.R. China. In addition, the variations in the steel materials and different laboratory testing conditions may lead to the differences of the test results. Thus, these test results could not be directly used for the determination of the influences of the low temperature on the mechanical properties of the reinforcing steels that were widely used in the RC structure constructed in P.R. China. Xi et al. [16], Wang et al. [17], and Zhang [19] have reported the experiments on the mechanical properties of the steels under low temperature in China. However, most of these tests focused on the mechanical properties above −80 °C that considered the steel structures in Tibet region. Liu et al. [1] reported limited experimental studies on the reinforcing steels at the temperature intervals of −80 °C to −180 °C. The information on the mechanical properties of the reinforcing steels used in the concrete structure within temperature ranging 30 °C to −180 °C is still quite limited. Thus, it is still of interest to investigate the representative steel reinforcements under cryogenic temperatures that were widely in the engineering constructions for the LNG container, cold storage, and in RC structures in the cold regions of P. R. China.

This paper reported a test program on hot rolled steel bars HRB335, HRB400 and special low temperature steels (SLTS) for LNG container. For each type of steel, 21 specimens with three identical specimens at each temperature level were prepared at seven temperature levels, i.e., 20 °C, −40 °C, −80 °C, −100 °C, −120 °C, −140 °C, and −165 °C. The behaviours of these different reinforcing steels under different low temperatures were reported based on the test results in terms of tensile stress-strain behaviours, yield strength, ultimate strength, elastic modulus, fracture strains, and percentage of area reduction at the fracture point. Based on these test results, regression analyses were also carried out to develop the empirical design equations to incorporate the influences of the low temperatures on the mechanical properties of the reinforcing steels. Finally, some conclusions were drawn based on these analyses and experimental studies.

2. Test program

This section firstly introduced the details of the specimens involved in the tests. The test setup especially the cooling chamber for the specimens is introduced.

2.1. Specimens

Three representative types of steel reinforcements that are widely used in the engineering constructions in the cold regions