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Behavior of innovative circular ice filled steel tubular stub columns under axial compression

Yanlei Wang [a,b,*], Guipeng Chen [a,b], Baolin Wan [c], Hao Lin [a,b], Jin Zhang [a,b]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[b] School of Civil Engineering, Dalian University of Technology, Dalian 116024, China
[c] Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI 53201, USA

HIGHLIGHTS

- Circular ice filled steel tubular (IFT) columns are firstly proposed.
- Effects of diameter-to-thickness ratios of steel tubes on the compressive behavior of the IFT columns are studied.
- An increase in diameter-to-thickness ratio leads to a decrease in the bearing capacity and the ductility of the IFT columns.
- Equations for predicting the load bearing capacity of the IFT columns are proposed.

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ABSTRACT

The use of conventional building materials has many limitations in cold regions. Inspired by the idea of concrete filled steel tube (CFT), a new form of construction component named ice filled steel tube (IFT), which effectively combines the advantages of both ice and steel tube, was innovatively proposed in this study. This paper presents an experimental study on circular IFT stub columns under axial compression. The main parameter of the test specimens is the diameter-to-thickness (D/t) ratio of the steel tube. A total of 12 specimens including 3 plain ice columns and 9 circular IFT columns were divided into four series and tested under axial compression. The test results showed that the development of cracks in ice was delayed by the steel tube. As a result, both the ultimate bearing capacity and the ductility of the ice column were improved due to the confinement from the steel tube. The local bucking at the bottom of the steel tube was also delayed by the ice core. Therefore, the circular IFT column has good potential to serve as a structural component in cold regions.

1. Introduction

The use of conventional building materials such as concrete has many limitations in cold regions, where the temperature is below 0 °C all year round. The below freezing temperature causes significant difficulties to mix, pour and cure concrete. The cost of transporting raw materials of concrete to remote cold regions is also very high. However, there is abundant ice in cold areas. Therefore, ice has been used as a construction material for thousands of years. Snow and ice are used to build igloos by the Inuit people, and they are also used as geomaterials for the construction of polar runways [1]. Many researches have been performed to study the mechanical properties of ice. The compressive behavior of ice has been widely investigated [2–6]. Ice is a brittle material that is stronger in compression than in tension [7]. It has thirteen different crystal structures and two amorphous states. The compressive strength of plain ice at −10 °C was reported by Schulson et al. [8] to be 14.8 ± 2.3 MPa in its single-crystal form and in the range of 6.5–9.5 MPa for columnar-grained polycrystal samples. The crystal structure photos taken by Zhang et al. [9] showed that artificial freshwater ice was columnar-grained ice, which was similar to that of natural freshwater ice. More recently, studies of the compressive behavior of ice at high strain rates were carried out by some researchers [10–14]. The peak stress of ice reported by Dutta et al. [10] was 6.53 ± 1.44 and 6.77 ± 3.23 MPa at −10 °C under quasi-static and dynamic loading conditions, respectively. Zhang et al. [9] investigated the strength of artificial freshwater ice subjected to uniaxial compression. The main parameters included both temperature

* Corresponding author at: State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China.
E-mail address: wangyanlei@dlut.edu.cn (Y. Wang).

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(i.e., −5, −10, −15, −20 and −30 °C) and strain rate (varying from 10^{-8} s^{-1} to 10^{-2} s^{-1}). The experimental results showed that the compressive strength of ice was very sensitive to the strain rate. The uniaxial compressive strength of ice increased with the decrease of experimental temperature at the same strain rate. Over 340 specimens were made and tested by Zhang et al. [15] to study the compressive strength of reservoir ice at five different temperatures (i.e., −2, −5, −10, −15 and −20 °C) and a wide range of strain rates (varying from 10^{-8} s^{-1} to 5×10^{-2} s^{-1}), and the relationship among the uniaxial compressive strength of ice, the strain rate and the temperature was established. There is no doubt that ice is a relatively weak material that is low in strength and strongly temperature-dependent. Therefore, it might be unsuitable to use plain ice directly as a construction material when the structure requires high strength. In order to solve this problem, many researches have been carried out with the aim of enhancing the mechanical properties of ice.

It has been proved that the mechanical properties of ice can be improved by reinforcement. Nixon and Smith [16] studied the fracture toughness of ice reinforced with a variety of wood-based materials (newspaper, wood pulp, sawdust, blotting paper and crushed bark). The test results showed that the fracture toughness of freshwater ice increased by 5–20 times after introducing 5–20% reinforcing materials in weight. Another alternative reinforcing agent was alluvium investigated by Nixon [17], which is readily available, either in the form of seabed silt in the Arctic offshore, or from various onshore deposits. The preliminary tests showed that the bending strength of ice can be significantly improved by the addition of alluvium. The degree of strengthening has been found to be dependent on both the type and the amount of alluvium used in ice. Vasiliev [18] investigated the strength of ice reinforced with fiberglass. Specimens of reinforced and plain ice cubes with the dimension of $70 \times 70 \times 70$ mm^3 were tested under uniaxial compression and the reinforced and plain ice beams with the dimension of $40 \times 40 \times 160$ mm^3 were subjected to three-point bending. It was noted that crack propagation in the reinforced ice was prevented by the reinforcing agents and the ultimate load capacity of the composites was increased significantly. There is abundant frozen soil in cold regions such as Arctic sites. Therefore, there is a growing interest in the ice-soil composites created by the method of cryotropic gel formation (CGF) in recent years. In the CGF method, strong hydrogels are formed from an aqueous polymer solution such as PVA; and other hydrogels are formed by means of a freezing and thawing process in which PVA solutions are frozen at −5 to −20 °C and then allowed to thaw at a positive temperature. PVA is an ecological nontoxic material. Materials created by CGF method have low permeability and can be used in a wide range of temperatures above and below 0 °C [19]. An example of the application is the creation of reliable materials for building weirs and other hydraulic engineering constructions. The studies conducted by Vasiliev et al. [20] showed that the strength of the ice-soil composites depends on many different factors, including quality and quantity of PVA used, time of thawing, number of freezing-thawing cycles, soil characteristics, and water content of the soils with gel. Pykrete is another popular form of reinforced ice composites, which is made of approximately 14% sawdust or some other form of wood pulp (such as paper) and 86% ice by weight. The Pykrete Dome built in Juuka with a span of 29.06 m and height of 9.75 m was the first realized project in which pykrete was used on such a scale. A total of 50 cylinders and 50 beams made of pykrete were tested by Vasiliev et al. [21] to investigate the compressive and flexural strengths of pykrete samples. The compressive and flexural strengths of pykrete with 10% sawdust were 12 MPa and 3.7 MPa, respectively, which were three times larger than those of plain ice. In summary, the mechanical properties of plain ice can be improved by the introduction of a reinforcing material.

Although the compressive behavior of ice can be enhanced by various reinforcing methods, the extent of improving compressive strength by simply introducing those reinforcing materials into ice is obviously limited. Therefore, it is needed to find a new material that can directly help to support part of the load when the ice is subjected to compression. If the load is carried by both this material and ice, the bearing capacity of the ice composite column would be improved significantly. Concrete filled steel tubular (CFT) columns have been widely used in engineering structures such as super high-rise buildings and bridge structures due to the successful combination of concrete and steel. In the CFT members, steel and concrete are used such that their natural and most prominent characteristics are taken advantage of. The confinement of concrete is provided by the steel tube, and the local buckling of the steel tube is improved due to the support of the concrete core [22]. According to the results of many researches, CFT columns exhibit high bearing capacity and excellent ductility under axial compression [23–26] or subjected to bending [27–29]. Polymer-based materials [30] or steel fibers [31] were also introduced into the concrete of CFT columns to improve the mechanical properties of specimens under axial compression. Inspired by the idea of concrete filled steel tube (CFT), the authors innovatively proposed a new form of construction component named ice filled steel tube (IFT) in which the concrete is replaced by ice. When the IFT column is subjected to axial compression load, the load is carried by the ice core and the outer steel tube simultaneously. By the use of steel tube, the ice core is in triaxial compression stress state and the corresponding strength of ice can be improved. On the other hand, the stability of the steel tube can be enhanced with the support of filled ice. Therefore, the IFT columns efficiently combine the advantages of both ice and steel tube.

This study focuses on the axial compressive behavior of IFT stub columns because it is the fundamental behavior of a compression member. The influence of overall stability generally does not need to be considered for stub columns. An experimental study was conducted to investigate the behavior of IFT stub columns under axial compression. It aimed to identify whether remarkable composite actions existed between the inner ice and the outer steel tube, and to check how much the bearing capacity and ductility of ice columns could be improved with the help of steel tubes. A bearing capacity equation was proposed for circular IFT stub columns and the calculated results were in good agreement with the experimental data.

2. Experimental program

2.1. Test specimens

A total of 12 specimens divided into four series were manufactured and tested under uniaxial compression. Three of these specimens were plain ice columns and the remaining nine were ice filled steel tubular (IFT) columns. Each series included three identical specimens. Each specimen had a diameter of 150 mm, measured at the outer surface of the ice core, and a height of 300 mm. The height-to-diameter ratio was 2.0 so that the specimens would be stub columns with little influence from end effect and overall buckling. Details of the specimens are reported in Table 1, in which D and t are the outer diameter and the thickness of the steel tubes, respectively. N_e and N_u are the load bearing capacity of each specimen obtained from experiment and calculation, respectively. The steel tubes used in the same series had the same diameter-to-thickness (D/t) ratio, but the D/t ratios were different for different series. Therefore, the D/t ratio of the steel tube was a major parameter to be investigated in this study. Each specimen was given a name, which started with letter C standing for circular IFT column, followed by a number representing the thickness of steel tube in mm, and the specimen number within the same series.

2.2. Preparation of specimens

Plain steel plates with thickness of 2 mm, 3 mm and 4 mm were rolled up into tubes with circular section, and the butt seam was welded together. A 200 mm by 200 mm square steel end-plate with 10 mm thickness was welded to the bottom of