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Axial compressive behavior of square ice filled steel tubular stub columns

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HIGHLIGHTS

- Square IFT column is proposed to combine the advantages of ice and steel tube.
- Influence of width-to-thickness ratio of steel tubes on square IFT is analyzed.
- Bearing capacity of IFT increases with the decrease of width-to-thickness ratio.
- Good composite action between outer steel tube and ice core is achieved.
- Equations for predicting bearing capacity of square IFT columns are proposed.

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ABSTRACT

Concrete has many limitations in the building construction in cold areas. However, there is abundant ice in those regions. Therefore, using ice as a substitute for concrete has been explored by researchers. Inspired by the idea of square concrete filled steel tube (CFT), a new column form termed square ice filled steel tubular (IFT) column is proposed in this study. It consists of a square outer steel tube with the inner space filled with ice. A total of eighteen stub columns were made and tested under axial compression, including three circular plain ice specimens, nine square IFT specimens and six hollow square steel tubes, to demonstrate the advantages of the composite column. The width-to-thickness (B/t) ratio of the steel tubes varies from 39.5 to 77. The test results confirmed that the ice core is effectively confined by the steel tube, and the inward local buckling of the steel tube is suppressed by the inner ice, leading to higher strength and better ductility of the square IFT specimens compared with hollow steel tubes and plain ice columns. A simplified axial bearing capacity equation for square IFT stub columns is proposed and it provides reasonable and accurate predictions of the test results.

1. Introduction

It is difficult to mix, pour and cure concrete in cold regions such as Arctic areas, where the temperature is below 0 °C throughout the year. It is also very expensive to transport component materials of concrete to such areas. The idea of using ice as building materials was successfully achieved by Inuit people living near the North Pole [1]. The ongoing freezing and refreezing processes harden their igloos made of ice blocks, which confirms that the utilization of ice as a substitute for traditional building material (i.e., concrete) is feasible.

In the 1990's, many researches [2–8] were performed to study the compressive strength of ice. The impetus behind the research on ice was the development of the oil and gas industry in Arctic areas, the construction of hydropower infrastructures, and the design of icebreaker and lighthouse. Ice load is usually the predominant design criterion for hydro-structures used in cold regions, and the compressive strength of ice is a key parameter in the calculation of ice load [9]. In recent years, the research on the compressive behavior of ice is still ongoing. Ice is a material which is strong in compression and weak in tension, especially at colder temperatures well below the freezing point [10]. The mechanical properties of ice and snow were reviewed by Petrovic [11]. The tensile strength of ice was 0.7–3.1 MPa and the compressive strength was 5–25 MPa over the temperature range from −10 °C to −20 °C. The ice compressive strength increased with decreasing temperature and increasing strain rate, but the tensile strength was relatively insensitive to these variables. Ice strength depends on many variables such as temperature, strain rate, test specimen

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volume, and ice grain size [11]. Barrette and Jordaan [12] investigated the compressive behavior of freshwater ice (i.e., laboratory-grown ice and iceberg ice) subjected to a nominally constant compressive stress of 15 MPa while under confining pressures ranging from 10 to 65 MPa. Test temperature varied from about −5 to −26 °C. The iceberg ice tended to show a higher scatter than the laboratory ice. Their results were consistent with those of other investigators [13–16] obtained from constant strain rate experiments. The peak stresses of ice reported in the work by Dutta et al. [17] were 6.53 ± 1.44 MPa and 6.77 ± 3.23 MPa at −10 °C under quasi-static and dynamic loading conditions, respectively. Tests of uniaxial compression strength of columnar sea ice were conducted by Moslet [18] in field in Svalbard, Norway. Both horizontal and vertical samples were tested and the relationship between the strength and sample directions seemed not to be constant. However, the strength of sea ice was dependent on temperature [18]. Shazly et al. [19] studied the dynamic response of ice under uniaxial compression in the range of strain rates from 60 to 1400 s^{-1} and at initial test temperatures of −10 and −30 °C. According to the test results, the compressive strength of ice showed positive strain rate sensitivity over the employed range of strain rates. Moreover, unlike in the case of uniaxial quasi-static compression of ice, the effect of specimen end-constraint during the high rate compression was found to be negligible. Zhang et al. [9] investigated the strength of artificial freshwater ice under uniaxial compression with test parameters including temperature and strain rate. The 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. More than 340 experiments were conducted by Zhang et al. [20] to study the compressive strength of reservoir ice at different temperatures and strain rates. The relationship among the uniaxial compressive strength of ice, strain rate and temperature was established. All aforementioned researches indicated that ice is a weak material and its mechanical properties are strongly dependent on temperature and strain rate. Therefore, plain ice is not a reliable material used for structural members subjected to large or explosive loads. Owing to its brittleness it was dangerous to regard any reasonable stresses as safe for constructional purposes [21].

In order to improve the behavior of plain ice, many methods have been tried to reinforce it. The Inuit people have traditionally reinforced the snow blocks for their igloos with lichen, and many ice roads across the northern Baltic built in the period of Soviet Union used sawdust as a reinforcing agent [22]. Nixon and Smith [22] tested a number of ice composites reinforced by some wood-based materials (i.e., newspaper, wood pulp, sawdust, blotting paper and crushed bark) to determine the fracture toughness of such composites. The test results showed that the fracture toughness of freshwater ice increased by 5–20 times after introducing 5–20% reinforcing materials in weight, and it was concluded that reinforced ice could be used as a construction material in Arctic regions [22]. Considering that it is expensive to transport reinforcing materials to Arctic areas, Nixon [23] suggested using alluvium as an alternative reinforcing agent, which is readily available either in the form of seabed silt in the Arctic offshore or from various onshore deposits. Test results showed that ice could be significantly strengthened by the addition of alluvium. The degree of strengthening was found to be dependent on both type and amount of the alluvium used. The bending strength of reinforced ice tended to increase with the decreasing particle size, and there existed one critical percentage of reinforcement, above which value considerably higher bending strength was obtained [23]. Vasiliev [24] studied the strength of ice strengthened by fiberglass net and fiberglass cloth. Specimens of reinforced and plain ice cubes with the dimension of 70 × 70 × 70 mm^3 were tested under uniaxial compression while the reinforced and plain ice beams with the dimension of 40 × 40 × 160 mm^3 were subjected to three-point bending. It was found that crack propagation in the reinforced ice was prevented by the reinforcing agents. Both the compressive and flexural strengths of ice were effectively increased after introducing fiberglass into ice. Nowadays there is a growing interest in the ice-soil composites created by the method of cryotropic gel formation (CGF) [25–27]. 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. Materials created by CGF method have low permeability, which has been used as a reliable material for building weirs and other hydraulic engineering constructions in cold regions [25]. According to the test results of Vasiliev et al. [26], the strength of the ice-soil composites depends on many different factors, including the 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 a mixture of sawdust or some other form of wood pulp (such as paper) and ice. In view of the similarity to concrete and in honor of Mr. Geoffrey Pyke who firstly proposed the construction of aircraft carriers using ice, the mixture was given the code name of pykrete (Pyke's concrete) [21]. A total of 50 cylinders and 50 beams made of pykrete were manufactured and tested by Vasiliev et al. [28] to investigate both the compressive and flexural strengths of such composites. The compressive and flexural strengths of pykrete with 10% sawdust were 12 MPa and 3.7 MPa, respectively, which were three times as large as those of plain ice.

As shown in the previous discussion, the mechanical properties of plain ice can be improved with the introduction of some reinforcing materials into ice. However, the extent of improvement in the compressive strength of ice by this means is limited. The strength of reinforced ice is still lower than that of normal concrete and can not be used for structural members subjected to larger loads. Therefore, it is necessary to find alternative ways to help ice to achieve higher strength and better ductility. Recently, concrete filled steel tubular (CFT) members have been widely used in routine structural design as piles, building columns and bridge piers [29]. These columns have demonstrated excellent earthquake-resistant properties, namely high stiffness, high strength, high ductility, and large energy-absorption capacity [30]. The enhancement of structural properties of CFT columns is mainly due to the composite action of steel hollow section and concrete core. The confining effect from the steel hollow section causes the concrete core to behave in a triaxial stress state while the concrete core prevents the wall of the steel hollow section from buckling inward [31]. It should be noted that the circular cross-section provides the strongest confinement to the concrete core, and the local buckling is more likely to occur in square or rectangular cross-sections [32]. However, square and rectangular CFT columns are still increasingly used in civil engineering due to easier construction in beam-to-column connection, high cross-sectional bending stiffness and aesthetic reasons [32]. A lot of researches have been carried out on the behavior of square CFT columns under axial compression [33–36] or bending load [37–40]. Inspired by the idea of circular CFT columns, the authors innovatively proposed a new type of structural member termed circular ice filled steel tubular (IFT) column in which the concrete was replaced by ice [41]. The test results demonstrated that the circular steel tube worked well with the inner ice, leading to higher strength and better ductility of circular IFT columns than those of hollow steel tubes and plain ice columns.

Based on the existing studies on circular IFT columns [41] and square CFT columns [29,32], an exploratory experimental study was designed to investigate the behavior of square IFT stub