Research and development of frost resistance of concrete filled steel tube

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Abstract. This paper mainly introduces the general situation of research on the frost resistance of CFST in China in recent years, expounds the mechanism of the frost damage of CFST and the main factors affecting the frost resistance of CFST, and further discusses the existing problems and defects in the existing research. In order to improve the frost resistance of CFST, some reasonable suggestions are put forward to provide theoretical support for practical projects.

1. Introduction
Concrete filled steel tube is a composite structural component filled with plain concrete in the steel tube. The steel tube and its core concrete can jointly bear the external load. According to different section forms, it is divided into circular concrete-filled steel tube, square concrete-filled steel tube, rectangular concrete-filled steel tube, polygonal concrete-filled steel tube and hollow concrete-filled steel tube [1] (as shown in Figure 1). It is widely used in the field of construction engineering because of its high compressive capacity, good plasticity and toughness, convenient construction and good fire resistance.

Figure 1. Concrete filled steel tubular member form.

Frost resistance is an important index of the durability of CFST and an important factor affecting the long-term service life of CFST. Especially in the construction engineering in the cold area, the damage of CFST structure caused by freeze-thaw cycle has become the main disease in the process of structural work [1]. However, in the three northern areas of China, the temperature is cold in winter, the lowest temperature can reach - 50 °C and the freezing damage of CFST components is widespread; in East China and central China, the temperature is mild, but the freezing still occurs in winter, and the freeze-thaw damage of CFST still exists. Therefore, the research on the frost resistance of CFST becomes more and more important. The effective control of the freeze-thaw damage of CFST becomes the key to ensure the safety of the structure.
In view of this, this paper refers to the relevant literature of the research on the frost resistance of CFST at home and abroad in recent years, through the analysis of the research status of the frost resistance of CFST and the reported engineering accidents, lists the influencing factors of the frost resistance of CFST, and puts forward reasonable suggestions on how to improve the frost resistance of CFST, so as to provide theoretical support for the actual project.

2. Research status of frost resistance of concrete filled steel tube

With the application of CFST in construction engineering, more and more scholars pay attention to its frost resistance. Especially in recent years, there have been many engineering accidents of concrete-filled steel tube structure damaged by freezing in China, which threaten the safety of human life and property. Based on this, the research trend of the frost resistance of CFST is urgent. Scholars at home and abroad have carried out a lot of research on the frost resistance of CFST.

2.1. Case analysis of concrete-filled steel tube frost damage

Peiqiong Wang et al. [2] introduced the accident of longitudinal cracking of concrete-filled steel tubular columns damaged by freeze-thaw in a substation building, and analyzed and studied the cracking mechanism of concrete-filled steel tubular columns. The research shows that the causes of longitudinal cracking of concrete-filled steel tubular columns are as follows: (1) There is no structural measure between the inner surface of the steel tube and the core concrete to make it closely connected, which results in the less binding force between the core concrete and the steel tube and is easy to get out of space; (2) The coefficient of thermal expansion of ordinary concrete is smaller than that of steel, with the change of outside air temperature, the cold shrinkage and thermal expansion of concrete and steel are different, so the deformation is not harmonious, leading to the separation of core concrete and inner wall of steel tube; (3) there are defects or free water in the production of concrete-filled steel tube, and the free water is frozen and expanded. It will have a negative impact on concrete filled steel tube; (4) the free water in concrete filled steel tube increases with the increase of the year, and the free water will expand in the steel tube wall by freezing, which will produce the circumferential tensile stress. When the circumferential tensile stress produced by frost heave is greater than the yield tensile stress of steel tube, the steel tube will produce damage and crack.

Qing Wang et al. [3] discussed the frost crack accident of concrete-filled steel tubular columns in a new heavy hydrogenation reactor manufacturing plant in an industrial area. From the point of view of design and construction, the causes of frost crack, reinforcement scheme, forming quality and guarantee measures of CFST columns are analyzed, and the structural performance of CFST columns after frost crack is further analyzed [3]. The conclusion shows that: (1) the reason for the frost crack of concrete filled steel tube column is that it needs to wash the pump pipe with water at intervals during the process of pumping concrete, so there is relatively more water retained in the pipe, which results in more water in the concrete actually poured in the steel tube. When the free water is frozen in the negative temperature environment, the frost heave of the steel tube results in the frost crack of the concrete filled steel tube column Accidents; (2) after the concrete-filled steel tube is frozen and cracked, the constraint of steel tube to core concrete has failed, and it is difficult to re-establish the effective constraint after reinforcement.

2.2. Experimental study on frost resistance of concrete filled steel tube

Kai Cao et al. [1] designed 15 short concrete-filled steel tubular columns with different strength grades, and carried out the axial compression performance tests of circular and square section concrete-filled steel tubular columns subjected to freeze-thaw cycles. The effects of steel content, freeze-thaw cycles and material strength on the axial compression performance of concrete-filled steel tubular columns subjected to freeze-thaw cycles were studied and analyzed. The theoretical analysis model is established by using the finite element software ABAQUS. The results show that the results of finite element analysis are basically consistent with the test results. The concrete-filled steel tubular specimens damaged by freeze-thaw and not damaged by freeze-thaw have higher later bearing capacity and better
deformation capacity. The combined elastic modulus of CFST decreases with the increase of freeze-thaw cycles.

Lanzhou Yang et al. [4] designed 16 concrete-filled steel tubular (CFST) specimens and 13 ordinary concrete specimens and tested their frost resistance. Their frost resistance was analyzed by testing the relative elastic modulus, mass loss, frost heaving stress, compressive strength change and chloride ion penetration after freeze-thaw. The test results show that: (1) the mass loss rate can't be used to evaluate the freeze-thaw performance of the concrete filled steel tube; (2) the concrete filled steel tube plays a role of restraining and effectively preventing the external moisture from entering the concrete, making the core concrete less damaged by the freeze-thaw cycle, significantly improving the freeze-thaw durability of the concrete; (3) The reason of freeze-thaw damage is that the free water is retained in the concrete filled steel tube, and the temperature is lower than 0 ℃, the free water freezes continuously to produce the ice swelling stress. When the ice swelling stress is greater than the tensile strength of the concrete, the cracks in the concrete will occur and develop. The larger the water cement ratio is, the greater the water content of the remaining frozen water is, and the freeze-thaw cycle is the effect of hooping on the strength is also greater.

To sum up, scholars at home and abroad have carried out a lot of experimental research and theoretical analysis on the frost resistance of CFST. They believe that the main reason for the frost damage of CFST is closely related to its core concrete.

3. Failure mechanism of concrete filled steel tube during freeze-thaw

The main reason for the freeze-thaw damage of CFST is that there is free water in the core concrete that does not participate in the hydration reaction. In the process of freeze-thaw, the free water will freeze and melt back and forth, which will have a negative impact on the core concrete, and then lead to the freeze-thaw damage of CFST.

3.1. Failure mechanism of core concrete during freeze-thaw

The freeze-thaw failure process of core concrete in concrete filled steel tube is a complex physical change process. Concrete is a composite material composed of hardened cement paste and aggregate with pores. In order to obtain the necessary workability for concrete pouring in the construction process of concrete filled steel tube, the mixing water is always more than the water required for cement hydration, and concrete filled steel tube is a closed body, excess water can’t be volatilized and retained in the concrete, forming a certain volume of connected pores [4]. When the concrete is at a negative temperature, the water in its internal pores will change from liquid phase to solid phase [4]. There are several hypotheses about the mechanism of freeze-thaw failure of concrete.

3.1.1. Hydrostatic hypothesis. The volume of freezing water in concrete expands about 10% when it is frozen, which forces the unfrozen pore solution to move outward from the frozen area, resulting in hydrostatic pressure. The hydrostatic pressure hypothesis theory holds that the internal structure of concrete will generate hydrostatic pressure in the process of freezing, when the hydrostatic pressure exceeds the ultimate tensile strength of concrete, it will cause concrete cracking and damage.

3.1.2. Osmotic pressure hypothesis. The pore solution of concrete contains salt ions such as K⁺ and Na⁻. According to the osmotic pressure hypothesis theory, during the freezing process of concrete, after the solution in the large pore of concrete internal structure freezes, the concentration difference between the salt concentration of unfrozen solution and the solution in the surrounding small pore will be formed, resulting in the osmotic pressure. If the osmotic pressure exceeds the ultimate tensile strength of concrete, the concrete will be damaged.

3.1.3. Critical saturation value of freeze-thaw. According to the theory of "critical water saturation value of freeze-thaw", there is a critical value for the content of freezing water that can be contained in the
internal structure of concrete. When the amount of freezing water reaches the critical value, the concrete will be destroyed.

3.2. Failure mechanism of steel tube
Concrete and steel have similar coefficient of linear expansion, therefore, the core concrete and steel tube are deformation coordinated in frost heaving state. In the process of freeze-thaw cycle of concrete-filled steel tube, the free water in the concrete is frozen and expanded, which is constrained by the steel tube to produce the ice expansion stress. The ice expansion stress acts on the steel tube and the core concrete, which produces a certain degree of hoop stress on the steel tube. When the hoop stress is greater than the tensile yield strength of the steel tube, the steel tube will be damaged.

3.2.1. Calculation model of steel tube damaged by freezing.
In the process of concrete freezing, the volume expansion will squeeze the steel tube, which will lead to the hoop effect of steel tube on concrete. Suppose that the hoop stress produced by the steel tube is \(\Delta \sigma\), and the restraint stress of the hoop action of the steel tube to the concrete is \(p\), then the relationship between the two actions is shown in Figure 2.

![Figure 2. The relationship between hoop stress \(\Delta \sigma\) and restraint stress \(p\).](image)

According to figure 2, the length of the steel pipe along the axial direction is taken as \(l\), and the balance according to the force system is as follows:

\[
\int_0^\pi p l \frac{D}{2} \sin \varphi \, d\varphi = 2\Delta \sigma l t
\]

Where \(D\) is the internal diameter of the steel tube, the relationship between the restraint stress \(p\) of the steel tube hoop on the concrete and the hoop stress \(\Delta \sigma\) of the steel tube is obtained after integration:

\[
p = 2t \cdot \frac{\Delta \sigma}{D}
\]

It is assumed that the ice heaving stress of concrete under the freezing condition is \(\sigma\), because the steel tube is squeezed, the restrained stress \(P\) is produced on the concrete. Therefore, the actual stress acting on the core concrete in the concrete filled steel tube is \(\sigma - p\), and the stress produced by the concrete crack under this stress state is \(\sigma'\). When \(\sigma' \leq f_{tk}\) (\(f_{tk}\) is the ultimate tensile strength of concrete), the concrete will not produce crack expansion, otherwise the concrete will be destroyed. When the hoop stress of steel pipe \(\Delta \sigma \geq f_{sy}\) (\(f_{sy}\) is the yield value of hoop stress of steel pipe), the steel pipe will be destroyed.

4. Influencing factors of frost resistance of concrete-filled steel tube and suggested measures
There are many factors that affect the frost resistance of CFST. According to the mechanism of freeze-thaw damage, the frost resistance of CFST is directly related to its core concrete. The main influencing factors are water cement ratio, saturated state, frozen age, air content, concrete strength, admixture, cement variety and aggregate quality, steel pipe material strength, etc.\(^\text{[1]}\).
4.1. Water cement ratio
The water cement ratio directly affects the content of free water in concrete, the strength of concrete and the frost resistance of concrete. The larger the water cement ratio is, the more the content of free water in the concrete is, the larger the expansion rate of the frozen volume of free water under the negative temperature environment is, the greater the hoop stress on the steel pipe is. When the hoop stress is greater than the yield strength of the steel pipe, the steel pipe will be damaged by frost heave. Therefore, it is necessary to control the frost resistance of CFST by controlling the water cement ratio.

4.2. Saturation state
The frost resistance of concrete is closely related to the degree of water saturation in the voids of concrete. There are three ways of water content in concrete, namely, physical adsorption water, chemical binding water and free water. When the concrete is in the state of water saturation, the content of free water in concrete reaches the maximum, the volume of free water ice expansion increases, causing damage to the core concrete. Therefore, the freeze-thaw damage of concrete is the most serious when it is saturated with water.

4.3. Freezing age
The frost age of concrete is one of the main factors affecting the frost resistance of concrete. The higher the age of concrete is, the better the frost resistance is. Because the longer the age of concrete is, the higher the strength of concrete is, the greater the ability of concrete to resist frost heave is, so the stronger the ability of concrete to resist freeze-thaw cycle damage is. Therefore, the frost resistance of concrete increases with age.

4.4. Gas content
Air content is the main factor affecting the frost resistance of concrete. Adding air entraining agent will form micro pores inside the concrete. These micro pores are not connected with each other, and the solution of internal pores cannot flow with each other. According to the hydrostatic pressure theory, these micro pores can reduce the hydrostatic pressure in the early stage of concrete freezing, so as to achieve the effect of reducing pressure, and then reduce the concrete of frozen damage.

4.5. Concrete strength
The higher the strength grade of concrete is, the greater the tensile and compressive properties and modulus of elasticity are, and the stronger the ability to resist the influence of various adverse factors under the action of freeze-thaw cycle is, so the better the frost resistance performance is; meanwhile, the cement paste of high-strength concrete is relatively dense, and the internal clearance of concrete is less, the content of freezing water in it is relatively less, so the frost resistance is better. Therefore, in the actual project, the frost resistance of CFST can be improved by reasonably increasing the strength of concrete.

4.6. The influence of admixtures and admixtures
Air entraining agent, water reducing agent and can improve the frost resistance of concrete. The way of its effect is: air entraining agent can increase the content of independent air bubbles in concrete, reduce the "pressure" produced in the process of concrete freezing, water reducing agent can reduce the water cement ratio when concrete is mixed, reduce the content of pores, improve the microstructure of concrete, and admixture can improve the microstructure of concrete to make it more compact \(^{(1)}\). In addition, the more admixtures are added, the better. When the amount of admixtures exceeds a certain degree, the amount of cement is too small, which affects the strength of concrete, and finally reduces the frost resistance of concrete.
4.7. Cement type and aggregate quality
The frost resistance of concrete increases with the increase of cement, the frost resistance of ordinary portland cement concrete is better than that of mixed cement concrete, and the frost resistance of pozzolanic cement concrete is worse than the former two \cite{1}. The influence of aggregate on the frost resistance is mainly related to the water absorption and frost resistance of aggregate itself. Generally, the concrete with less water absorption is used, and its frost resistance is better \cite{1}.

4.8. Material strength of steel pipe
The greater the strength grade of steel tube is, the better the frost resistance of concrete filled steel tube is. Among them, when the hoop stress caused by expansion of core concrete in CFST fails to reach the failure strength of CFST when it is frozen, the steel tube can’t be damaged by frost heave, so the frost resistance of concrete filled steel tube can be effectively enhanced.

5. Concluding remarks
In this paper, the research status and development of concrete-filled steel tube (CFST) frost resistance are described, the working mechanism of CFST freeze-thaw damage and the factors affecting the frost resistance of CFST are analyzed in detail, and reasonable suggestions are put forward.

(1) Scholars at home and abroad have carried out extensive research on the frost resistance of CFST, but the theoretical analysis of its freeze-thaw failure mechanism is not perfect, there is no unified theory, which needs further discussion and research.

(2) The frost resistance of concrete-filled steel tube mainly depends on the frost resistance of its core concrete under the constraint of steel tube. The main influencing factors are water cement ratio, water saturation state, frost age, air content, concrete strength, admixture, cement variety and aggregate quality, steel tube material strength, etc. The reasonable control of its core concrete in the construction process is to ensure the steel tube material strength the key to the frost resistance of concrete-filled pipes.

(3) The frost resistance of CFST is an important index of the durability of CFST and an important factor affecting the long-term life of CFST. The research on the frost resistance of CFST is of great value and needs to be improved and perfected in the follow-up research.

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