Study on concrete beams under the action of steel corrosion and freeze-thaw cycles

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Abstract—In order to study the effect of rust - freeze coupling on the flexural bearing capacity of concrete beams, a rapid corrosion test, rapid freeze-thaw test and a rust-freezing coupling test were carried out for 18 model beams. Under the joint action of the corrosion of steel bars and the freeze-thaw cycle, the yield strength ratio of the test beam decreases with the increase of rust rate and freeze-thaw cycle, resulting in the decrease of its resistance to deformation. Based on the present proposed calculation formula under the action of corrosion and freeze-thaw cycles, through comparing and analyzing experimental data to establish the a new calculation model under the action of the reinforcement corrosion and the freeze-thaw cycle of flexural bearing capacity.

1. INTRODUCTION
As is known to us all, the reinforced concrete structure has been widely used in the world, not only because it combines the reinforced high tensile strength and compressive strength of concrete with considerable advantages, but it can also use local materials, low cost, and have good fire resistance. But for a number of reasons, a large number of reinforced concrete structures will fail in advance, the most of which is caused by insufficient structural durability.

Steel corrosion and freeze-thaw cycles are the two main reasons that affect the durability of reinforced concrete structures, which have become a common concern all over the world. Wei Jun[1] found that slightly corroded steel bars had slightly increased bond strength than stainless steel bars, but the growth was limited; when the corrosion rate is relatively large, mechanical interlocking effect between steel bar and concrete basic recession, resulting in the decrease of both bond strength. Abdullah A[2] studied the flexural behavior of corroded reinforced concrete slabs by rapid corrosion test, which got the relationship curve of the ultimate strength and the corrosion rate of the steel. This paper mainly studies the flexural performance of concrete beams under the action of the the corrosion and freeze-thaw cycles in practical engineering application provides support for its durability theory.

2. THE BEARING CAPACITY OF THE CONCRETE BEAM UNDER THE ACTION OF THE RUST - FREEZING COUPLING
The results of cracking load and ultimate load of concrete beam under the action of the rust-freezing coupling are shown in Table 1 and the degradation law of the ultimate bearing capacity of the beam under the double action of melting and reinforcing steel corrosion is shown in Figure 1 and 2.
TABLE 1. THE BEARING CAPACITY COMPARISON

| Corrosion rate η (%) | freeze-thaw cycles / Times | Cracking load Pcr /kN | Ultimate load Pu /kN |
|----------------------|---------------------------|-----------------------|----------------------|
| 0                    | 0                         | 14                    | 91                   |
| 0                    | 90                        | 11                    | 82.5                 |
| 0                    | 180                       | 9                     | 78                   |
| 3.53                 | 0                         | 26                    | 86                   |
| 4.05                 | 90                        | 20                    | 79                   |
| 3.83                 | 180                       | 17                    | 74                   |
| 8.07                 | 0                         | 18                    | 79                   |
| 8.36                 | 90                        | 18.5                  | 76.5                 |
| 8.51                 | 180                       | 17                    | 70                   |

Figure 1. Ultimate load variation curves with corrosion rate change

Figure 2. Ultimate load variation curves with freeze-thaw cycles change

It can be figured out from Table 1 and Figure 1 that in the same conditions as the number of freeze-thaw cycles, the ultimate bearing capacity of the beam shows a downward trend with the increase of corrosion rate.
Table 1 and Figure 2 shows that Comparison between the corrosion rate of 3.53%, 4.05% and 3.83% of three beams, the ultimate load decreases with the number of freeze-thaw cycles increased, when the number of freeze-thaw cycles up to 90 times, carrying capacity decline increased by 1.4%, and when the number of freeze-thaw cycles up to 180 times, down 2.4 % increase the ultimate bearing capacity, which shows the effect of freeze-thaw cycles on the bearing capacity of corroded reinforced concrete beams and ordinary concrete has a great influence. Comparison between the corrosion rate of 8.07%, 8.36% and 8.51% of the three beams, when the number of freeze-thaw cycles up to 90 times, the ultimate bearing capacity decline has increased 0.2 %, when the number of freeze-thaw cycles up to 180 times, the decline has increased only 0.75 %. Through the above data analysis that indicated when the corrosion rate is small, the freeze-thaw cycle has a negative impact on the bearing capacity of the beam, while the corrosion rate is the opposite. It can be concluded that there is some coupling relation of mutual inhibition between the steel corrosion and freeze-thaw action, not simple superposition.

3. The Calculation Model of the Beam Under the Action of Rust-Freezing Coupling

3.1. Calculation Model of Beams with Corroded Steel
Reducing the bond strength between concrete and steel bending is one of the main factors reduce the bearing capacity of concrete beams with corroded steel bar. Considering the influence of bonding degradation on the flexural properties of beams, it is necessary to introduce the coordination coefficient to the original formula, which are Formula 1 and Formula 2. The result of the flexural capacity of different models are shown in Table 2.

\[ \sum X = 0 \quad \alpha \cdot f_c b x = k_b f_{y,c} A_{y,c} \]  
\[ \sum M = 0 \quad M_{cu} = \alpha \cdot f_c b x (h_0 - \frac{x}{2}) \]

Where: \( M_{cu} \)-flexural and flexural capacity of corroded reinforced concrete beams(kN·m); \( \alpha \)-the ratio between the stress and the design value of concrete compressive strength of concrete rectangular stress diagram in compression area; \( f_c \)-axial compressive strength of concrete(MPa); \( f_{y,c}, f_{y,e} \)-the nominal yield strength of tensile and compressive steel(MPa); \( A_{y,c}, A_{y,e} \)-the effective cross section area of tensile and compressive steel(mm²); \( k_b \)-the coordination coefficient of Corroded reinforced concrete.

| Corrosion rate /% | Hui Yunling /kN·m | Wang Qinglin /kN·m | Zhang Weiping /kN·m | Niu Ditao /kN·m | Jin Weiliang /kN·m |
|-------------------|-------------------|-------------------|--------------------|-----------------|-------------------|
| 0                 | 2.6594            | 2.6594            | 2.6594             | 2.6594          | 2.6594            |
| 3.73              | 2.5386            | 2.5356            | 2.5152             | 2.5386          | 2.5386            |
| 3.33              | 2.4990            | 2.4968            | 2.4817             | 2.4990          | 2.4990            |
| 8.07              | 2.2979            | 2.2915            | 2.2491             | 2.2954          | 2.2921            |

The Table 2 shows that the various models of the working coefficient of steel and concrete have similar influence on the flexural bearing capacity of corroded reinforced concrete beams. Therefore, in this experiment, Formula 3 is chosen as a reasonable model of cooperative work coefficient.

\[ k_b = 1 - (\omega - 0.25)(0.24 \frac{f_p}{l} - 0.06) \]

3.2. Calculation Model of Beams under Freeze-Thaw Cycle Cycle
The results of static load test of the beam under freeze-thaw cycle cycle shows that under the action of freeze-thaw cycles, the yield and ultimate loads of beams decrease with the increasing number of
freeze-thaw cycles. Through analysis on the relationship between reinforced concrete beams flexural ultimate load capacity and the number of freeze-thaw cycles presented, a fitting formula is proposed.

3.3. Calculation model of beams under the action of rust-freezing coupling

In this paper, on the basis of the previous proposed calculation model of the bending bearing capacity of the beam under the independent action of the steel corrosion and freeze-thaw cycle, the model is modified appropriately. But after steel corrosion, reinforced beam surface position produce multiple long crack, through the freeze-thaw cycles, the crack number, length and width of the beam increases and the surface erosion is more serious, which will affect the bond performance of steel and concrete, and then affect the synergistic effect of steel and concrete. On the other hand, under the action of electric current, the modulus of elasticity, the compressive strength and the tensile strength of the concrete specimen will be lowered when the steel bar is corroded, and the degree of degradation will be the greatest after corrosion cracking. These factors, especially the change of initial compressive strength, will greatly reduce the frost resistance of concrete.

Therefore, the influence of steel corrosion on the frost resistance of concrete must be considered in the calculation of the flexural capacity of beams under the double action of steel corrosion and freezing thawing, a novel calculation method of flexural capacity of beams under double action of steel corrosion and freeze-thaw cycles is proposed as following, which takes 0.93 as Coupling coefficient of rust-freezing.

4. CONCLUSION

A. Through the analysis of the freeze-thaw test, the ultimate load of contrast reinforcement corrosion test and the rust-freeze coupling test, the variation law of the beam bearing capacity under the double action of steel corrosion and freezing thawing is summarized, that is, the corrosion and freeze-thaw effect of steel are not simple superposition, but the coupling relationship of mutual inhibition.

B. Under the combined action of steel corrosion and freeze-thaw cycles, the strength ratio of specimens decreases gradually with the increase of corrosion rate and freeze-thaw cycles, resulting in the decrease of their resistance to deformation.

C. In this paper, on the basis of the previous proposed calculation model of the bending bearing capacity of the beam under the independent action of the steel corrosion and freeze-thaw cycle, a new calculation method of flexural capacity of beams under double action of steel corrosion and freeze-thaw cycles is proposed.

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