Study of factors affecting bond behavior between stainless steel rebar and concrete

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Abstract: With the improvement of smelting process of stainless steel, stainless steel has great advantages in economy, rigidity and durability, so it has been widely used in recent years. However, the properties of stainless steel rebar are very different from those of traditional steel rebar. The stainless steel rebar has no obvious yield strength, and its ductility is excellent. It is essential to determine whether stainless steel rebar can be used in building structures. The bond behavior between stainless rebar and concrete is the basic issue to study before the application of stainless steel. Therefore, the effects of concrete strength, diameter of reinforcement, relative thickness of protective layer, anchorage length of stainless steel bar and casting method on the bond force between the stainless steel bar and concrete were analyzed through central pulling tests of 39 specimens. The results showed that the stainless steel rebar has high bond force with concrete and the empirical formula of bond force between stainless steel rebar and concrete was established based on the regression analysis of the experimental data.

1. Introduction
Protection of natural resources and environment is significant for any modern research [1]. Reinforced concrete has been widely used at present because it is economical and can be designed in the desired shape according to the engineering requirements, and it exhibits high strength. However, the steel bars in reinforced concrete are easy to be rusted, which leads to reduction in strength and even loss in workability [2, 3]. So many people have to rebuild or repair these buildings, which results in a great quantity waste in economy and resources. Up to now, this problem is still not solved fundamentally. Although there are many methods to prevent steel corrosion at present, such as electrode protection method, galvanizing method and thickness reinforcement method [4], none of them can solve the problem of steel corrosion fundamentally.

The advantages of stainless steel, such as high strength, renewable utilization and rust protection, have attracted people's attention gradually[5]. At present, many scholars have carried out experimental research on stainless steel and some scholars have studied bond force between recycled aggregate concrete and steel. Robert Prince studied Bond the behavior between recycled aggregate concrete and deformed steel bars [6]. Cha studied the axial compression performance of stainless steel pipe concrete [7]. Li conducted a comparative study in the bond force between stainless steel bar, ordinary steel bar and concrete [8]. Dorleta studied the bond behavior of flat stainless steel rebar in concrete [9]. However, generally speaking, there are still short of research achievements on stainless steel reinforced concrete, and there is no systematic study on the factors affecting the bond force between...
the stainless steel rebar and concrete. Therefore, the influencing factors of the bonding strength between the stainless steel rebar and concrete were mainly studied in this study, and the regression equation was calculated to present reference for other researchers.

2. Experimental program

2.1. Test design
In this study, 39 specimens were prepared for central pull-out experiments. In order to ensure the reliability of the experimental results, the specimens were divided into 13 groups, and each group contains 3 specimens. The average value of the three values for each group was taken as the final result. During the course of experiments, the influence of concrete strength, diameter of stainless steel rebar, relative thickness of concrete cover, relative anchorage length and casting direction on the bonding strength were mainly studied. The concrete properties and specimen grouping are shown in Table 1 and Table 2, respectively (c /d and l/d represent relative thickness of concrete cover and relative anchorage length, respectively).

| Table 1. Concrete properties |
|-----------------------------|
| Strength grade of concrete  | Slump (mm) | Strength for 28 d (MPa) |
| C25                         | 35         | 28                      |
| C30                         | 32         | 38.1                    |
| C40                         | 33         | 43.7                    |

The selected specimen moulds are wood pattern. The specimen size is not standard, and round holes should be opened in the middle on the moulds bottom. For the wood pattern, it is easy to open holes, which has great effect on the accuracy of the experiment results. Neither plastic nor iron pattern can meet the accuracy requirements [10].

| Table 2. Sample grouping |
|--------------------------|
| Specimen ID | Strength grade of concrete | d/mm | c/d | l/d | Pouring way | Side length of specimen (mm) | Specimen amount |
| SJ1          | C25                        | 16   | 4.5 | 5   | cross pouring | 160                          | 3               |
| SJ2          | C30                        | 16   | 4.5 | 5   | cross pouring | 160                          | 3               |
| SJ3          | C40                        | 16   | 4.5 | 5   | cross pouring | 160                          | 3               |
| SJ4          | C30                        | 12   | 4.5 | 5   | cross pouring | 120                          | 3               |
| SJ5          | C30                        | 25   | 4.5 | 5   | cross pouring | 250                          | 3               |
| SJ6          | C30                        | 16   | 3.3 | 5   | cross pouring | 120                          | 3               |
| SJ7          | C30                        | 16   | 5.8 | 5   | cross pouring | 200                          | 3               |
| SJ8          | C30                        | 16   | 7.3 | 5   | cross pouring | 250                          | 3               |
| SJ9          | C30                        | 16   | 4.5 | 3   | cross pouring | 160                          | 3               |
| SJ10         | C30                        | 16   | 4.5 | 4   | cross pouring | 160                          | 3               |
| SJ11         | C30                        | 16   | 4.5 | 6   | cross pouring | 160                          | 3               |
| SJ12         | C30                        | 16   | 4.5 | 5   | vertical pouring | 160                          | 3               |
| SJ13         | C30                        | 25   | 4.5 | 5   | vertical pouring | 250                          | 3               |

2.2. Experimental method
In this study, 1000kN New Sansi Electro-hydraulic Servo Testing Machine was used to measure the pull-out stress, which is shown in Fig.1. The specimen was placed in the hanging basket, and the upper end of the reaction frame was fixed to the upper clamp of the testing machine. The lower end was tightened keeping the stainless steel rebar outside. The loading rate was kept at 100N/s until the end of the experiment.
3. Results and discussion

Table 3 Experimental results

| Specimen ID | Failure model | F (kN) | $\tau_0$ (MPa) |
|-------------|---------------|--------|----------------|
| SJ1-1       | Pulling-out   | 73.3   | 18.2           |
| SJ1-2       | Pulling-out   | 66.3   | 16.5           |
| SJ1-3       | Pulling-out   | 70.3   | 17.5           |
| SJ2-1       | Pulling-out   | 84.0   | 20.9           |
| SJ2-2       | Pulling-out   | 79.6   | 19.8           |
| SJ2-3       | Pulling-out   | 80.4   | 20.0           |
| SJ3-1       | split         | 88.4   | 22.0           |
| SJ3-2       | Pulling-out   | 88.8   | 22.1           |
| SJ3-3       | Pulling-out   | 89.1   | 22.2           |
| SJ4-1       | Pulling-out   | 44.0   | 19.5           |
| SJ4-2       | Pulling-out   | 46.9   | 20.7           |
| SJ4-3       | split         | 42.0   | 18.6           |
| SJ5-1       | split         | 207.1  | 21.1           |
| SJ5-2       | Pulling-out   | 179.4  | 18.3           |
| SJ5-3       | split         | 190.6  | 19.4           |
| SJ6-1       | split         | 61.9   | 15.4           |
| SJ6-2       | split         | 69.9   | 17.4           |
| SJ6-3       | split         | 64.7   | 16.1           |
| SJ7-1       | Pulling-out   | 81.4   | 20.3           |
| SJ7-2       | Pulling-out   | 77.7   | 19.3           |
| SJ7-3       | Pulling-out   | 83.4   | 20.8           |
| SJ8-1       | Pulling-out   | 80.3   | 20.0           |
| SJ8-2       | Pulling-out   | 78.9   | 19.6           |
| SJ8-3       | Pulling-out   | 82.4   | 20.5           |
| SJ9-1       | Pulling-out   | 45.0   | 18.7           |
| SJ9-2       | Pulling-out   | 46.6   | 19.3           |
| SJ9-3       | Pulling-out   | 44.9   | 18.6           |
| SJ10-1      | Pulling-out   | 66.2   | 20.6           |
| SJ10-2      | Pulling-out   | 62.4   | 19.4           |
| SJ10-3      | Pulling-out   | 61.1   | 19.0           |
| SJ11-1      | Pulling-out   | 101.3  | 21.0           |
| SJ11-2      | Pulling-out   | 107.1  | 22.2           |
3.1. Experimental phenomena and failure characteristics
The maximum tensile force and failure modes of all the specimens are shown in Table 3. In summary, there are two kinds of failure modes including pulling out failure of stainless steel bars and the splitting failure of concrete [12, 13].

The bond force along the whole anchorage length of the stainless steel rebar can be considered to be uniformly distributed in this study. The bond strength can be expressed as follows:

\[ \tau_0 = \frac{P_0}{\pi d l_0} \]

where \( \tau_0 \) is the peak bond force between concrete and stainless steel rebar, MPa; \( P_0 \) is the peak load, kN; \( d \) is the diameter of the steel rebar, mm; and \( l_0 \) is the embedded length of the steel rebar, mm.

The related results were calculated according to Eq.(1) [1], which can be seen in Table 3.

| Specimen   | Failure Mode | Tensile Force | Displacement |
|------------|--------------|---------------|--------------|
| SJ11-3     | Pulling-out  | 100.3         | 20.8         |
| SJ12-1     | Split        | 89.6          | 22.3         |
| SJ12-2     | Split        | 92.0          | 22.9         |
| SJ12-3     | Split        | 88.0          | 21.9         |
| SJ13-1     | Split        | 213.0         | 21.7         |
| SJ13-2     | Split        | 216.2         | 22.0         |
| SJ13-3     | Split        | 221.1         | 22.4         |
was flattened. When the specimen was fractured, the concrete specimen was divided into two or three pieces accompanied by a loud noise. As is shown in Fig. 3, there is a small fraction of concrete was pulled up and most of the concrete bulges can be observed there in the junction of stainless steel and concrete.

According to the expression of the bond force, the average value and individual value of the bond force for the specimens were calculated, which can be seen in Table 4.

### Table 4. The bond force between stainless steel bars and concrete

| Specimen ID | $\tau_1$(MP) | $\tau_2$(MP) | $\tau_3$(MP) | $\tau_0$(MP) |
|-------------|--------------|--------------|--------------|--------------|
| SJ1         | 18.2         | 16.5         | 17.5         | 17.4         |
| SJ2         | 20.9         | 19.8         | 20.0         | 20.2         |
| SJ3         | 22.0         | 22.1         | 22.2         | 22.1         |
| SJ4         | 19.5         | 20.7         | 18.6         | 19.6         |
| SJ5         | 21.1         | 18.3         | 19.4         | 19.6         |
| SJ6         | 15.4         | 17.4         | 16.1         | 16.3         |
| SJ7         | 20.3         | 19.3         | 20.8         | 20.1         |
| SJ8         | 20.0         | 19.6         | 20.5         | 20.0         |
| SJ9         | 18.7         | 19.3         | 18.6         | 18.9         |
| SJ10        | 20.6         | 19.4         | 19.0         | 19.7         |
| SJ11        | 21.0         | 22.2         | 20.8         | 21.3         |
| SJ12        | 22.3         | 22.9         | 21.9         | 22.4         |
| SJ13        | 21.7         | 22.0         | 22.4         | 22.0         |

3.2. Analysis of the influence of various factors

#### 3.2.1. Effect of concrete strength on bond force

When other conditions remain unchanged, the three groups of specimens with different concrete strength are described as SJ01, SJ02 and SJ03. Altogether there are 9 specimens in total. Among the specimens, 8 specimens were belong to pulling out failure and only one specimen in SJ3 was splitting failure, which indicate that the concrete strength has no significant influence on the failure modes of the specimen. The relation curve between the bond force and concrete strength can be seen in Fig.4. It has been proved that the strength of concrete is not the only factor which affects the bond strength. By analyzing the slope of the curve, it can be found that the increase of concrete strength has a more significant impact on the increase of bond strength with the increase of concrete strength [13].

#### 3.2.2. Effect of diameter of stainless steel bar on bond force

With other conditions unchanged, the three groups of specimens with different diameters of stainless steel rebar are described as SJ02, SJ04 and SJ05. Altogether there are 9 specimens in total. Among the specimens, 6 specimens were pulling out failure, and 3 specimens were splitting failure in SJ04. One specimen was splitting failure and two specimens were split failure in SJ05. This indicated that the number of specimens with splitting failure became more and more with the increase of the diameter of stainless steel rebar. As the diameter of the stainless steel bars is increased, the bond force between the stainless steel rebar and the concrete at failure is becoming. Therefore, after the bond force is larger than the tensile strength of the concrete, the concrete will be damaged, and thus breaking failure occurs [14].
According to the experimental results, the average bond forces of the three groups of specimens were 19.6MPa, 20.2MPa and 19.6MPa, respectively, and there was no obvious difference due to the variation of the diameter of stainless steel rebar. Therefore, it can be concluded that the bond strength between stainless steel rebar and concrete is insensitive to the diameter of stainless steel rebar, which can be seen in Fig.5.

3.2.3. The influence of thickness of concrete cover on bond force. Specimens of SJ2, SJ6, SJ7 and SJ8 are different in the thickness of concrete cover. The thickness of concrete cover is 52mm, 72mm, 92mm and 117mm, respectively. The relative thickness of concrete cover is 4.5, 3.3, 5.8 and 7.3.

From Table 3, it can be seen that the relative thickness of concrete cover is 3.3, 4.5, 5.8, 7.3 respectively corresponding to the average bond force of 16.3 MPa, 20.2 MPa, 20.0 MPa, and 20.0 MPa. The related curve is shown in Fig. 7. It can be found that the bonding force between the stainless steel bar and the concrete increases when the relative thickness of concrete cover is lower than 4.5 with the increment in relative thickness of concrete cover. After the relative thickness of concrete cover exceeds 4.5, it has no remarkable influence on the bond force, which indicates that after the
thickness of concrete cover reaches a certain value, the thickness of concrete cover does not have an obvious improvement on bond force.

3.2.4. Effect of relative anchorage length on the bond strength. In this study, there are four groups of specimens named with SJ9, SJ10, SJ2, SJ11, respectively with the same relative thickness of concrete cover of 4.5 and different anchorage lengths. The anchorage length of each group specimen was 48 mm, 64 mm, 80 mm and 96 mm respectively.

Altogether the stainless steel rebar of all the 12 specimens in this group was pulled out and the specimens were damaged. The relative thickness of concrete cover was 4.5, and the strength grade of the specimens was 30MPa, which could offer enough tension force to protect the specimens from being splitting failure.

Fig 7. The relationship curve between bonding force and relative thickness of concrete cover

It can be seen from Table 4, the average bond force for these groups of specimens were 18.9 MPa, 19.7 MPa, 20.2 MPa, 21.3 MPa, respectively, and the relative anchorage lengths were 3, 4, 5, 6, respectively. Based on the results, the relation curve between the bond force and the relative anchorage length of the stainless steel rebar in concrete can be obtained, which is shown in Fig.8. The curve slope of every part is larger than zero, and the bond force between the stainless steel rebar and concrete increases obviously with the increase of relative anchorage length.

3.2.5. Effect of casting method on the bond force. For the purpose of comparison, specimens of SJ2 and SJ5 were prepared using the level casting method, and specimens of SJ12 and SJ13 were prepared using vertical casting method. The diameter of stainless steel bars for specimens SJ2 and SJ5 is 16mm, and the diameter of stainless steel bars for specimens SJ5 and SJ13 is 25mm. The relative thickness of concrete cover is 4.5 and the relative anchor length is 5. As is shown in Table 3, splitting failure occurred in all the 6 specimens cast in vertical position. Concrete and stainless steel bar can be closely combined as a whole using vertical casting method. The bite force between stainless steel bars and concrete was relatively higher. As the bite force between the stainless steel rebar and the concrete was much larger using vertical casting method, the bond force of the specimens using vertical casting method was larger than that of the specimens using level pouring method, which also can be proved by the results in Table 3. The bonding degree between the stainless steel rebar and the concrete of the specimens prepared using the level casting method was lower than that of the vertical casting method. Therefore, when the specimen was near the failure, the bite force of the stainless steel bars and the concrete was smaller than ultimate tensile force of the concrete, and as a result, the pulling failure occurs. The variation curve of the specimen's bond force is shown in Fig. 9.
4. Establishment and comparison of empirical expression of bond force

4.1. Establishment of empirical expression for bond force

From the analysis and discussion of the experimental result, it is known that the relative thickness of concrete cover has little influence on the bond force when it is more than 4.5. When the relative thickness of concrete cover is the constant value, the $\sigma_s/f_t$ and $l/d$ is linear relationship according to the results of Teng. The following expression can be obtained:

$$\frac{\sigma_s}{f_t} = 19 + 12 \frac{l}{d}$$  \hspace{1cm} (2)

Where $\sigma_s$ is the stainless steel stress of end loading; $f_t$ is the tensile strength of concrete. Referring to the balanced relationship, expression of $\tau_0$ can be obtained, which can be expressed as follows[15]:

$$\tau_0 = (3 + 4.75d/l)f_t$$  \hspace{1cm} (3)

Using the results of specimens of SJ1 to SJ5 and specimens of SJ9 to SJ11, the regression formula based on Eq.(2) can be obtained as follows:

$$\tau_0 = (9 - 5.85d/l)f_t$$  \hspace{1cm} (4)

The comparison of the predicted and experiment values is presented in Fig.10. ($F_e$ represent the value obtained from the experiment, and $F_p$ represents the predicted value obtained by Eq.(4), and $F$ represents the predicted value by Eq.(3)). It can be obviously found that the results obtained from Eq. (3) are conservative and the predicted values by Eq. (4) are the same with experimental values.
4.2. Comparison with other results

By comparing the related results of Dorleta’s with the calculated numerical values obtained by Eq.(4) in the Fig.11[9], it can be seen that the values obtained from the experiments and Eq.(4) have the similar tendency. However, there are still some predicted values different from the experimental values, which may be caused by the experiment error and the different experimental methods.

5. Conclusions

(1) The concrete strength has no significant influence on the failure modes of the specimen. The strength of concrete is not the only factor which affects the bond strength. And the increase of concrete strength has a more significant impact on the increase of bond strength with the increase of concrete strength.

(2) The number of specimens with splitting failure became more and more with the increase of the diameter of stainless steel rebar, and there was no obvious difference due to the variation of the diameter of stainless steel rebar.

(3) The bonding force between the stainless steel bar and the concrete increases when the relative thickness of concrete cover is lower than 4.5 with the increment of relative thickness of concrete cover. After the relative thickness of concrete cover exceeds 4.5, it has no remarkable influence on the bond force, which indicates that after the thickness of concrete cover reaches a certain value, the thickness of concrete cover does not have an obvious improvement on bond force.

(4) Based on the results, the relation curve between the bond force and the relative anchorage length of the stainless steel rebar in concrete can be obtained. The curve slope of every part is larger than zero,
and the bond force between the stainless steel rebar and concrete increases obviously with the increase of relative anchorage length.

(5) The bonding degree between the stainless steel rebar and the concrete of the specimens prepared using the level casting method was lower than that of the vertical casting method.

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