Effect of the interaction between rebar and concrete cover on the concrete compressive strength

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Abstract: In order to analyze the effect of rebar size on the compressive strength of concrete cover, the axial behavior of a prism with a central rebar was experimentally and theoretically investigated. The test results indicated that the concrete compressive strength with rebar was relatively smaller than the axial compressive strength of prism that was similar with the concrete strength of cylinder. Further, the degree of reduction in the concrete compressive strength increased as the diameter–thickness ratio increased. Moreover, based on the test results and walled cylinder theory, the influence of rebar on the concrete compressive strength can be better understood. Lastly, in the structural design, the small rebar size and big concrete cover thickness should be chosen so that the effect of splitting action on concrete cover was weaken.

1. Introduction

With the development of high-rise buildings and large-span bridges, larger-sized structures with rebars of large diameters are comprehensively adopted. In addition, high-strength concrete is used in the development of structures, thus relatively reducing the concrete cover. Further, recent years have seen increase in brittleness of concrete used in a compression zone; especially, the brittleness of concrete cover is increasing. Moreover, the load-bearing capacity of the acting axial compressive force, eccentric loading, and cyclic loading of members may be affected by the concrete cover under many conditions. Thus, more attention must be placed on the problem of how the rebar affects the compressive strength of concrete cover.

First, a large number of experiments on axial compressive members demonstrated that the stirrup restraint could improve the compressive strength of concrete, and stress–strain constitutive models, such as Park model [1], Mander model [2], and Legeron model [3], for concrete confined by stirrup were proposed. Such studies indicated that an interaction existed between stirrup and concrete, suggesting that stirrup restraint can improve the mechanical properties of concrete.

The preceding studies also showed that the expansion of corrosion steel bar had an important effect on the axial load-bearing capacity of members and concrete strength. For instance, the load-bearing capacity of members and concrete compressive strength reduced with the increase in the corrosion rate of rebar [4]. Moreover, the concrete compressive strength reduced by 25%, especially before the cracking of concrete induced by corroded rebar [5]. In addition, with the increase in corrosion rate, the load-bearing capacity of members subjected to eccentric loading was affected by corrosion.
reinforcement, the load of which was lower than that of the original member [6]. Zhou et al. [7] proposed a model for determining the load-bearing capacity by considering the eccentric loading before the corrosion cracking of concrete, the compressive strength of which was reduced owing to the action of rebar corrosion expansive force on it. Another experimental study was conducted to examine the effects of corrosion on the seismic performance of reinforced concrete columns [8]. The authors showed that the lateral load-carrying capacity of corroded reinforced concrete columns reduced by 27% and 55.5% when the columns were corroded up to 10% and 15% of corrosion degrees, respectively. In conclusion, a steel bar was observed to have undergone cross-sectional loss due to corrosion; this affected the bearing capacity of members. However, the concrete compressive strength was also affected by the corrosion-induced expansive force, indicating that the existence of the corrosion-induced expansive force between concrete and a longitudinal bar. This was an unfavorable factor affecting the concrete compressive strength before and after concrete cracking.

Moreover, some researchers found that by reducing the corrosion rate and diameter of the steel bar and increasing the concrete cover thickness, the cracking resistance of concrete could be improved [9-13].

In summary, the effect of the splitting action of noncorroded longitudinal bar to concrete cover on the compressive strength of concrete cover has rarely been reported. Therefore, it is necessary to study the mechanism of the interaction between longitudinal rebar and concrete cover. The analytical factors of this study include rebar size and concrete cover, reflecting the effect of diameter–thickness ratio on concrete compressive strength. Then, the influence of rebar on the concrete compressive strength was investigated through axial compression test and theoretical analysis.

2. Experimental program

2.1 Material properties

Table 1 summarizes the mixture proportions of the concrete used in this study. The P42.5 Portland cement type was used, and the mix consisted of medium sand as the fine aggregate (with an average diameter of 2.7 mm) and crushed pebble stones as the coarse aggregate (with an average diameter of 5–25 mm). The slump of the concrete was 160 ± 20 mm. The material properties of concrete are listed in table 2. When tested according to the Chinese standards for the mechanical properties of concrete [14], the average compressive strength of the standard 150-mm cubic concrete samples was 65.57 MPa, the average compressive strength of the standard 150×150×300 mm prismatic concrete samples was 48.77 MPa, and the average tensile strength of the standard 150×150×150 mm cubic concrete samples was 3.48 MPa.

| Table 1. Mix proportions of concrete. |
|-------------------------------------|
| Grade number | Water (kg/m³) | Cement (kg/m³) | Sand (kg/m³) | Gravel (kg/m³) |
|--------------|----------------|----------------|--------------|----------------|
| C60          | 158            | 395            | 672          | 1051           |

| Table 2. Material properties of concrete. |
|------------------------------------------|
| Prism volume (mm³) | Ultimate strain | Axial strength (MPa) | Poisson’s ratio |
| 150×150×300         | 0.00199         | 48.77             | 0.2            |

The material properties of the steel rebar used in the test specimens are listed in table 3, in which HRB indicates the deformed bar reinforcement. The material properties, including yield strength, ultimate tensile strength, yield strain, and modulus of elasticity, were determined according to the Chinese standard for determining the mechanical properties of steel [15].

| Table 3. Material properties of rebar. |
|---------------------------------------|
| Rebar type | Rebar size (mm) | Yield strength (MPa) | Yield strain | Modulus of elasticity (MPa) |
|------------|-----------------|----------------------|--------------|----------------------------|
| HRB400     | 12              | 478                  | 0.002429     | 196752                     |
|            | 20              | 455                  | 0.002321     | 195233                     |
|            | 28              | 451                  | 0.002353     | 191655                     |
2.2. Specimen description
The interaction between rebar and concrete cover was described in figure.1. The height–width ratio was 2, the purpose of which was to eliminate the end restraint effect. To analyze the influence of the splitting action of rebar from concrete cover, three factors were considered. The member details are shown in figure 2, which included 18 prisms with a single rebar. Three specimens constituted a group. For instance, 54–12–i indicates 54 as the section size, 12 as the rebar size, and i as the number of specimens in a group of specimens, namely, i = 1, 2, 3. The details of specimens and bars are listed in table 4.
3. Test results and discussion

3.1. Failure modes of member
Figure 3 shows the failure modes of members. Many cracks can be observed on the compressive surface of concrete, indicating an interaction between rebar and concrete. The splitting action of rebar from concrete cover caused the cracking of concrete. In other words, the splitting of rebar from concrete would affect concrete compressive strength; this is an unfavorable influence, and should be focused upon more considerably.

3.2. Concrete nominal strength affected by the interaction of rebar and concrete

3.2.1. Concrete nominal strength with same diameter-thickness ratio. In the total component load, the load that concrete shared was equal to the total load minus the load that the rebar shared. The yield strain of the rebar was larger than the ultimate strain of concrete corresponding to the axial compressive strength of concrete. Therefore, the maximum load of the member was obtained when the strain of concrete reached its ultimate value. For this, the rebar load was equal to $c \varepsilon \sigma A$, where $c \varepsilon$ is the strain of concrete corresponding to compressive strength, $\varepsilon \sigma$ is the modulus of elasticity of the rebar, and $A$ is area of rebar. Table 3 lists the material properties of rebar. Table 5 lists the results, including maximum load, nominal strength, and average nominal strength. Figure 4 shows the relationship of the average nominal strength of concrete and section size, in which the strength was constant with the increase in the section size. Moreover, the average nominal strength of concrete was smaller than the axial concrete compressive strength that was similar to strength of the cylinder (figure 5). The reduction ratio of concrete strength was in the range of 10%–12%, and the interaction between rebar and concrete was strong. These factors indicate that the splitting action of rebar from the concrete cover was identical when the diameter–thickness ratio was a constant. In addition, this splitting action was observed to affect the average nominal strength of concrete, and thus should be considered in structural design.

| Test no. | Maximum load (kN) | Nominal strength of concrete (MPa) | Average nominal strength of concrete (MPa) |
|----------|-------------------|-----------------------------------|------------------------------------------|
| 54–12–1  | 165.10            | 43                                | 43                                       |
| 90–20–1  | 441.23            | 41                                | 44                                       |
| 90–20–2  | 490.40            | 47                                | 44                                       |
| 126–28–1 | 903.10            | 44                                | 44                                       |
3.2.2. Nominal strength of concrete affected by rebar size. The method of calculating the nominal strength of concrete was the same as described previously and the test results are listed in Table 6. Figure 6 shows the relationship between the average nominal strength of concrete and diameter–thickness ratio $d/t$, where the average nominal strength reduced with the increase in $d/t$. The reduction ratio of the average nominal strength is illustrated in Figure 7, which shows that the degree of reduction increased with the increase of $d/t$. The reduction ratio of strength of concrete ranged from 10% to 20%. This reveals that the interaction between rebar and concrete was pronounced, indicating that the splitting action of rebar from concrete was stronger with the increase of rebar size.

| Test no. | Maximum load (kN) | Nominal strength of concrete (MPa) | Average nominal strength of concrete (MPa) |
|----------|-------------------|-----------------------------------|------------------------------------------|
| 90–20–1  | 441.23            | 41                                | 44                                       |
| 90–20–2  | 490.40            | 47                                | 47                                       |
| 90–28–1  | 545.70            | 41                                | 41                                       |
| 90–28–2  | 523.16            | 38                                | 39                                       |
| 90–28–3  | 531.37            |                                    | 39                                       |

3.2.3. Nominal strength of concrete affected by concrete cover. By using the method mentioned earlier, the nominal strength of concrete was calculated and the results are listed in Table 7. Figure 8 shows the relationship between the average nominal strength of concrete and diameter–thickness ratio $d/t$. As shown, the average nominal strength increased with the decrease of $d/t$. Moreover, Figure 9 illustrates the reduction ratio of the average nominal strength of concrete and shows that the degree of reduction

Figure 6. Average nominal strength of concrete for different rebar sizes

Figure 7. Reduction ratio of concrete strength considering different rebar sizes
reduced with the decrease of d/t. The reduction ratio of concrete strength ranged from 6% to 20%. The figure also demonstrates an obvious interaction between rebar and concrete. In other words, the splitting action of rebar from the concrete cover was weakened with the increase of the concrete cover.

Table 7. Concrete strength with different concrete cover.

| Test no.  | Maximum load (kN) | Nominal concrete strength (MPa) | Average strength (MPa) |
|-----------|-------------------|---------------------------------|------------------------|
| 90–28–1   | 545.7             | 41                              |                        |
| 90–28–2   | 523.2             | 38                              | 39                     |
| 90–28–3   | 531.4             | 39                              |                        |
| 126–28–1  | 903.1             | 44                              | 44                     |
| 162–28–1  | 1437.6            | 47                              | 47                     |
| 162–28–2  | 1373.9            | 44                              |                        |

Figure 8. Average nominal strength of concrete for different concrete cover

Figure 9. Reduction ratio of concrete strength with respect to different concrete cover

4. Theoretical analysis of interaction between rebar and concrete

4.1. Basic assumption of theoretical model

According to the thick-walled cylinder theory, cross-sectional circumferential stress along the radial direction is nonlinear, and is induced by the pressure due to the interaction between rebar and concrete. To facilitate mathematical analysis, the following assumptions were made.

1. The nonlinear hoop stress translates into an equivalent stress block.
2. Internal pressure is uniform along the interface between rebar and concrete.
3. The nominal strength of concrete is defined as the maximum load that the concrete shared divided by the cross-sectional area.
4. The concrete modulus is equal to the secant modulus, that is, $\sigma_L/\varepsilon_0$, where $\sigma_L$ is the axial compressive strength and $\varepsilon_0$ is concrete strain corresponding to the compressive strength.
5. The lateral concrete is considered to possess confined pressure, for which only the radial deformation of the rebar is considered.

4.2. Establishment of theoretical model

Based upon Poisson’s ratio between rebar and concrete, the interface produced compressive deformation when the axial load acted on the surface of the member. The deformation of rebar extended outward along the radial direction. For convenience of calculations, the deformation of concrete should be not considered (figure 10).

The compressive surface of concrete produces hoop stress due to the action of internal pressure. Therefore, the concrete element is in a state of tension–compression stress when the axial load acts on the member, as shown in figure 11, where $\sigma_L$ is the axial compressive strength of concrete and $\sigma_\theta$ is the hoop stress.
is the hoop stress.

![Deformation](image)

**Figure 10. Interaction between rebar and concrete**

According to the thick-walled cylinder theory, the equation for calculating $\sigma_\theta$ is expressed as

$$
\sigma_\theta = \frac{0.25d^2p}{(R_0 / \cos(\theta))^2 - 0.25d^2} \left(1 + \frac{(R_0 / \cos(\theta))^2}{r^2}\right)
$$

(1)

where $d$ is the rebar size, $R_0$ is 0.5 times width, $r$ was the arbitrary distance from the center of geometry to compressive surface of concrete, and $p$ is the internal pressure.

The hoop stress is nonlinear along the radial direction (figure 10). For the convenience of calculation, the hoop stress is reduced to an equivalent stress block. The equation is expressed as

$$
J = \left(\int_{0.5d}^{R_0 / \cos(\theta)} \sigma_\theta dr\right) (R_0 / \cos(\theta) - 0.5d)^{-1}
$$

(2)

The hoop stress is also nonlinear along the hoop direction. Therefore, equation 2 is reduced to the equivalent stress block in triangle ABCD (Figure 10), and the equation is expressed as

$$
L = \left(\int_0^{\pi} \int_{0.5d}^{R_0 / \cos(\theta)} r \frac{0.5dp}{R_0 / \cos(\theta) - R} dr d\theta\right) \left(R_0^2 - \frac{1}{32} \pi d^2\right)^{-1}
$$

(3)

After integration,

$$
L = 0.25dp\left(0.88137R_0 + 0.125\pi d\right) \left(R_0^2 - \frac{1}{32} \pi d^2\right)^{-1}
$$

(4)

The internal pressure is produced by the interaction between steel rebar and concrete and has a more complicated mechanism. For the convenience of calculation, the external concrete was used as the confining pressure. The pressure reduced by the deformation of rebar is expressed as

$$
p = k \frac{0.5\varepsilon_\nu d}{R_0 - 0.5d} E_r
$$

(5)

where $k$ is the modified coefficient that considers the influence of the radial deformation of concrete to the interaction, $\nu_\nu$ is Poisson’s ratio of rebar, $E_r$ is the modulus of elasticity of rebar, $E_c$ is the secant modulus of concrete, and $\varepsilon_c$ is the strain of concrete that corresponds to the compressive
strength.

The nominal strength of concrete in a state of tension–compression is expressed as [16]

$$\sigma_y = \sigma_c (1 - L/f_c),$$

(6)

where $\sigma_y$ is the axial concrete compressive strength, and $f_c$ is the axial tensile strength of concrete.

The strength of rebar is expressed as

$$\sigma_s = E_s \varepsilon_s,$$

(7)

where $\varepsilon_s$ is the strain of rebar. If this strain reaches the yield strain, $\sigma_y$ is equal to the yield strength.

The load-bearing capacity of the member is expressed as

$$F = \sigma_y A_c + \sigma_s A_s,$$

(8)

where $A_c$ and $A_s$ are the areas of concrete and rebar, respectively, and $\sigma_y$ and $\sigma_s$ are the strengths of concrete and rebar, respectively.

4.3. Modified coefficient $k$ of internal pressure $p$

Based on the test data and equation (6), the relationship of modified coefficient $k$ and diameter–thickness ratio is pictured in figure 12. As the diameter-thickness ratio increased, the modified coefficient $k$ reduced linearly. Therefore, by linear fitting of the data, the equation of the modified coefficient is expressed as

$$k = -0.068(d/t) + 0.4663$$

(9)

Figure 12. Relationship between modified coefficient and diameter–thickness ratio d/t

4.4. Theoretical model analysis

The nominal strength of concrete was calculated using equation 6. The required material properties are listed in table 8 and figure 13 shows the relationship between the nominal strength of concrete, rebar size, and concrete cover. As shown, the nominal strength of concrete increased with the increase of concrete cover, and the increasing slope of nominal strength decreased with the decrease in the rebar size. Moreover, the nominal strength decrease as the rebar size increased, and the reducing slope of the nominal strength decrease with the increase in the concrete cover.

Figure 14 reflects the reduction ratio of concrete strength affected by the interaction between rebar size and concrete cover. As shown in figure 14, the concrete strength reduced by 97.99% when rebar size and concrete cover respectively were 50 and 27mm, indicating that the splitting action of rebar from concrete was strong.

Thus, the degree of reduction of concrete strength increased with the diameter–thickness ratio. In addition, the selection of a large concrete cover and small rebar size was the best scheme for the structural design.
Table 8. Material properties of rebar and concrete.

| $\nu_s$ | $\sigma_L$ (MPa) | $\varepsilon_c$ | $E_s$ (MPa) | $E_t$ (MPa) |
|--------|------------------|-----------------|-------------|-------------|
| 0.3    | 48.77            | 0.00199         | 200000      | 24507       |

Note: $\nu_s$ is Poisson’s ratio of rebar; $\sigma_L$ is compressive strength of concrete; $\varepsilon_c$ is strain of concrete corresponding to compressive strength; $E_s$ is secant modulus of concrete at a stress of compressive strength.

Figure 13. Relationship of nominal strength with rebar size and concrete cover

Figure 14. Reduction ratio of different rebar size and concrete cover

To accurately reflect the nominal strength of concrete that was affected by the interaction between rebar size and concrete cover, within the scope of the test design, the results with more design points are illustrated in figure 15. The results indicate that the splitting action of rebar from concrete is the same, as shown in figure 15(a); the splitting action was strengthened with the increase in the diameter–thickness ratio, as shown in figure 15(b) and figure 15(c). Moreover, under the range of test design, the relationship between the nominal strength of concrete and diameter–thickness ratio was approximately linear, and was consistent with the test results.

Figure 15. Nominal strength of concrete affected by rebar size and concrete cover: (a) d/t is constant; (b) Influence of rebar size; (c) Influence of concrete cover
5. Conclusions
This study investigated the effect on the concrete compressive strength by the interaction between concrete cover and rebar size. The splitting effect of rebar from the concrete cover was existent, and affected the concrete compressive strength. The following conclusions can be drawn from this research.

1) The concrete compressive strength with respect to a central rebar was lower than the axial compressive strength of concrete due to the splitting action of rebar.

2) Degree of reduction of concrete compressive strength was a constant when the diameter–thickness ratio was a constant. However, the degree of reduction increased as the diameter–thickness ratio increased.

3) Based on the test results and the thick-walled cylinder theory, the effect of rebar on the concrete compressive strength was well understood. Moreover, in the structural design, the small rebar size and big concrete cover should be chosen so that the effect of the splitting action on concrete cover thickness was weaken.

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