Premature Failure on Low-Grade R.C. Beams Reinforced with Bonded Steel Plate

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Abstract—Based on the experimental results and theoretical analysis, the study of the classification and mechanism of the premature failure for low-grade R.C. beams reinforced with bonded steel plate is placed on, finally, reasonable measure to overcome the premature failure is introduced.

Keywords— low-grade R.C. beams; reinforced with bonded steel plate; premature failure; the interaction coefficient

I. INTRODUCTION

After the implementation of reinforcing with bonded steel plate of low-grade R.C. beams, we ensure the improving of the bending performance, also hope to realize the ductile failure of component at the same time. In practice, however, it is found that it is prone to the phenomenon of debonding failure of the end or midspan of plate when they are at the lack of reliable anchorage between reinforcing steel and original beam. And the actual capability of bearing bending is much lower than the theoretical value of the normal bending failure (the steel and steel plate yield and have a certain extension of ductility, and the concrete is crushed when they are at failure) when the damage occurs. We call this phenomenon as premature failure on R.C. beams reinforced with bonded steel plate.

II. TEST SECTION

In the test of R.C. beams reinforced with bonded steel plate [1], we poured a total of ten low-grade R.C. beams as A, B, C three groups, and they were tested the capability of bearing bending of two-point loading of three equal respectively (FIGURE I DIAGRAM FOR BEAMS). Among them, the four of group A, for the comparison, were directly loaded but not reinforced; the four of group B were R.C. beams reinforced with bonded steel plate of first loading of reinforcing before loading; the two of group C were R.C. beams reinforced with bonded steel plate of secondary loading of loading to cracked and reinforcing and continuing loading. Table 1 was the summary of undermined results for R.C. beams reinforced with bonded steel plate (groups B and C). We can see that it is a common phenomenon of the premature failure on low-grade R.C. beams reinforced with bonded steel plate.

<table>
<thead>
<tr>
<th>Number of Beams</th>
<th>Strength of Concrete</th>
<th>The measured strain (×10E-6)</th>
<th>Failure modes</th>
<th>Values of theory $M_u^c$ (kN·m)</th>
<th>Values of test $M_u^t$ (kN·m)</th>
<th>$M_u^t/M_u^c$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB1</td>
<td>C7.5</td>
<td>417</td>
<td>Premature failure of degumming of the end</td>
<td>34.2</td>
<td>20.1</td>
<td>0.59</td>
<td>Steels and plates did not yield</td>
</tr>
<tr>
<td>LB2</td>
<td>C10</td>
<td>1017</td>
<td>Premature failure of degumming of the end</td>
<td>36.2</td>
<td>25.2</td>
<td>0.70</td>
<td>Steels and plates did not yield</td>
</tr>
<tr>
<td>LB3</td>
<td>C15</td>
<td>1324</td>
<td>Premature failure of degumming of the end</td>
<td>38.3</td>
<td>35.1</td>
<td>0.92</td>
<td>Steels and plates did not yield</td>
</tr>
<tr>
<td>LB4</td>
<td>C20</td>
<td>3570</td>
<td>Normal failure</td>
<td>39.3</td>
<td>40.1</td>
<td>1.02</td>
<td>Steels and plates yielded</td>
</tr>
<tr>
<td>LC3</td>
<td>C15</td>
<td>1893</td>
<td>Premature failure of degumming of the midspan</td>
<td>38.4</td>
<td>23.2</td>
<td>0.60</td>
<td>Plates did not yield</td>
</tr>
<tr>
<td>LC4</td>
<td>C20</td>
<td>1588</td>
<td>Premature failure of degumming of the midspan</td>
<td>39.3</td>
<td>25.7</td>
<td>0.65</td>
<td>Plates did not yield</td>
</tr>
</tbody>
</table>

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III. MECHANISM OF PREMATURF Failure ON R.C. Beams REINFORCED WITH BONDED STEEL PLATE

A. Bonding Shear Stress between the Plate and R.C. Beams

Take micro-element dx of section of shearing span of reinforced beam for objects (as FIGURE III shown) to study the bonding shear stress between the plate and R.C. beams. Because beams are in elastic phase in the premature failure. Strain of normal section should meet the plane-section assumption.

1) Bonding shear stress between the plate and bonding adhesive layer: The force balance equation

\[ T_p + dT_p - T_p = \tau_{pg} b_p dx \]  \hspace{1cm} (1)

By bending theory

\[ \frac{dT_p}{A_p E_p} = \frac{dM \cdot y_p}{I_p E_c} = \frac{V \cdot dx \cdot y_p}{I_p E_c} \]  \hspace{1cm} (2)

To sum up

\[ \tau_{pg} = \frac{1}{b_p} \frac{dT_p}{dx} = \frac{V \cdot A_p \cdot y_p \cdot \alpha_{pc}}{I_p b_p} \]  \hspace{1cm} (3)

Among them, the \( \tau_{pg} \) is the bonding stress between the adhesive layer and plate bonding interface; \( b_p \) is width of the steel plate section; \( A_p \) is the area of the steel plate section; \( y_p \) is the distance from neutral axis to the midline of steel plate section; \( \alpha_{pc} = \frac{E_p}{E_c} \approx 8.0 \); \( I_T \) is the moment of inertia of the concrete section converted by entire section.

2) Bonding shear stress between the adhesive layer and the concrete bonding interface: The force balance equation

\[ \tau_{gg} = \frac{dT_g + dT_g}{b_g dx} \]  \hspace{1cm} (4)

By bending theory

\[ \frac{dT_g}{A_g E_g} = \frac{dM \cdot y_g}{I_g E_c} = \frac{V \cdot dx \cdot y_g}{I_g E_c} \]  \hspace{1cm} (5)
\[ dT^\tau_{\text{gc}} = \frac{V \cdot dx \cdot y_g \cdot \alpha_{\text{gc}} \cdot A_g}{I_T} \]  \hfill (6)

Among them, the \( \tau_{\text{gc}} \) is the bonding shear stress between the adhesive layer and the concrete bonding interface; \( b_g \) is the width of plastic section; \( A_g \) is the area of the plastic section; \( y_g \) is the distance from neutral axis to the midline of plastic section; \( \alpha_{\text{gc}} \) is the elastic modulus ratio of adhesive layer and the concrete (\( \alpha_{\text{gc}} = \frac{E_g}{E_c} = 0.03 \sim 0.3 \)).

Because of \( \rho_g b_g \approx \rho_g A_g \), so for the \( dT^p_g \), \( dT^g \) can be negligible, and it is obtained:

\[ \tau_{\text{gc}} = \tau_{\text{pg}} = \frac{V \cdot A_p \cdot y_p \cdot \alpha_{\text{pc}}}{I_T b_p} = \frac{V \cdot y_p \cdot \alpha_{\text{pc}} \cdot t_p}{I_T} \]  \hfill (7)

Combining the experimental results and the theoretical analysis above, it is known that premature failure of low-grade R.C. beams reinforced with bonded steel plate generally occurs in the section of bending and shearing generally. This is because the bonding shear stress between the steel plate and concrete is caused by the rate of bending moment of beam which is the shearing force of beam section, and it increases with the increasing of shearing force.

B. Mechanism of Peeling Failure of the Midspan of Steel Plate

As FIGURE IV shown, within the section of bending and shearing, the concrete cover between two adjacent cracks taken as the studying object, bonding shear stress \( \tau_{\text{gc}} \) acted on its joint surface of steel plate and the end of R.C. beams generally occurs in the section of bending and shearing of beams generally. This is because the bonding shear stress between the steel plate and concrete is caused by the rate of bending moment of beam which is the shearing force of beam section, and it increases with the increasing of shearing force.

To balance the bonding shear stress \( \tau_{\text{gc}} \), there must be inverse shear stress in the bonding interface \( AB \) of the steel and concrete. Shear stress of point \( A \) is \( \tau_A = \frac{b_g}{b} \cdot \tau_{\text{gc}} \).

To balance the trend of torsion formed by bonding shear stress, there must be tension and compression stress in the bonding interface \( AB \) of the steel and concrete. Normal stress of point \( A \) is \( \sigma_A = \frac{M_A}{2l_{\text{cr}} I_A} \), in which the \( I_A \) is section moment of inertia of concrete bonding interface within cracks, \( I_A = bl^3_{\text{cr}} / 12 \); \( M_A \) is the torsion caused by bonding shear stress, \( M_A = \tau_{\text{gc}} \cdot l_{\text{cr}} b_g c \); \( l_{\text{cr}} \) is the crack spacing; \( c \) is the thickness of concrete cover.

In all kinds of material strength of adhesive layer, shear and tensile strength of the concrete itself is poor. When the bonding shear stress \( \tau_A \) that point A born met the shear strength of concrete \( f_{\text{cr}} \), the section generated bonding shear failure; when the peeling tensile stress \( \sigma_A \) that point A born met the tensile strength of concrete \( f_i \), the section generated stripping failure of the steel plate, and they formed peeling failure of steel plate together. There are peeling failure equation: \( \tau_A \leq f_{\text{cr}} \) and \( \sigma_A \leq f_i \).

In fact, bonding shear stress is not evenly distributed, bonding shear failure often occurs in the peak of shear stress, however, peeling tensile stress is effected by crack spacing \( l_{\text{cr}} \) in a large extent. The shorter the crack spacing is, the bigger the peeling tensile stress is. For beam reinforced with bonded steel plate of secondary loading, it has been loaded before sticking steel, so the concrete of the end of beam can be pulled cracking easily; after sticking steel, due to the section of bending and shearing being near concentrated force, moment and shear force of section are larger. Within two cracks having the shorter spacing of sections of bending and shearing in the midspan of reinforcement beam, it occurs firstly and easily of the phenomenon of peeling failure of the midspan of steel plate.

C. Mechanism of Peeling Failure of the End of Steel Plate

1) The bonding shear stress of the end of plate: As FIGURE V shown, within anchorage area of the bearing and the end of plate, reinforced steel plate begins from A-A section, and the distance from bearing is \( l_0 \); B-B section is the place of fully functioning of steel plate. \( l_0 \) is the length of anchoring section. Tensile stress \( \sigma_p \) of reinforcing steel plate is equal to
0 in A-A section, in the B-B section:
\[
\sigma_p = \frac{M_p \cdot y_p \cdot \alpha_{pc}}{I_T} = \frac{V(l_0 + l_a) \cdot y_p \cdot \alpha_{pc}}{I_T}.
\]  
(8)

Then the average bonding shear stress \(\tau\) between the steel plate of the x and concrete is:

\[
\tau = \frac{\sigma_p l_a}{l_a} = \left(1 + \frac{l_a}{l_a}\right)\frac{V \cdot y_p \cdot \alpha_{pc} \cdot t_p}{I_T},
\]

(9)
which shows that when the anchorage length \(l_a\) is insufficient, it will lead to the increase of the average bonding shear stress.

2) Peeling stress of the end of plate: Referring to FIGURE IV and the formula

\[
\sigma_x = \frac{M_p l_{cr}}{2l_a}
\]
changing \(l_{cr}\) to \(l_a\), it is also known that, to balance the torsion formed by the bonding shear stress, when there is tensile stress at the end of reinforced steel plate (called the peeling tensile stress) and the anchorage length is insufficient, peeling tensile stress will increase. It is the stress concentration (shear and tensile stress) generated at the end of reinforced steel plate that causes the bonding failure of the end of steel plate or the peeling failure of the concrete cover.

IV. SIMPLIFIED CALCULATION AND ANCHORING

A. Simplified Calculation of the Anchoring Length

It is given of simplified calculation formula of anchorage length of bonded steel plate in Code for the Strengthening [2]. But it does not take the peeling tensile stress of the end of steel plate into account, and this is its shortcoming.

B. The Calculation of Bearing Capability Considering the Interaction Coefficient

In order to ensure the reliability of the strengthened components, in the calculation of bearing capability, it is proposed to introduce the interaction coefficient \(\beta\) to take factors of premature failure into account. Combined with the calculation formula of bearing capability of normal bending failure of R.C. beams reinforced with bonded steel plate, the following formulas are given:

\[
f_yb_x + f_y' A_y' = f_y A_y + \beta \cdot f_p A_p
\]

(11)

\[
M_u = f_yb_x(h_0 - x/2) + f_y' A_y'(h_0 - \alpha_y') + \beta \cdot f_p A_p(\alpha_x + t_p/2)
\]

(12)

For R.C. beams reinforced with bonded steel plate of excellent adhesion or anchoring measures, it is proposed that \(\beta = 0.8-0.9\); for general R.C. beams reinforced with bonded steel plate, it depends on the effect of reinforcement.

C. Anchoring of Reinforcing Steel

For R.C. beams reinforced with bonded steel plate born of first loading, even the anchorage length of steel plate calculated according to the formula of Code for the Strengthening [2] meets requirements, it should also be considered adding the U-shaped hoop plate or bolt anchorage [3] on the end of plate in the structure to eliminate the effect of stress concentration and to prevent the premature peeling failure on the end. Considering the end of frame beam usually being dense area of hoop reinforcement, it is difficult to anchor the end of plate with bolt, but U-shaped hoop plate is appropriate.

For R.C. beams reinforced with bonded steel plate of secondary loading, at the time of bonding steel plate, the bonding cracks often have been generated in the section of bending and shearing of reinforced beam. There also are bonding shear stress and peeling tensile stress between the steel plate and concrete, and it will make the steel plates of the section of bending and shearing fall off from the concrete. Therefore, additional anchorage measure must be taken. For example a number of U-shaped hoop plate or bolt anchorage [3] should be set evenly along the reinforced plate.

V. CONCLUSION

Due to the existence of bonding shear stress and peeling tensile stress on the bonding interface of steel plate and concrete, it makes the phenomena of premature peeling failure of R.C. beams reinforced with bonded steel plate within the section of bending and shearing of the end of plate and the midspan of beam easily. Premature failure occurs suddenly, and the tensile strength of the steel plate is not being fully utilized, and it is a brittle failure. The interaction coefficients need to be taken to reflect the impact of premature failure in the calculation of bearing capability of R.C. beams reinforced with bonded steel plate. Meanwhile, the anchorage measure should be taken to the reinforced plate.

REFERENCES

