Calculation Method of Flexural Capacity of Composite Beam in Negative Moment Area after Corrosion of Interfacial Bolt

Bo Xu\textsuperscript{1,2}, Weiqing Zhu\textsuperscript{1} and Yang Shang\textsuperscript{2}

1. School of Highway, Chang’an University, Xi’an 710064, China
2. Ordos Institute of Technology, Ordos 017000, China

Abstract. In order to quantitatively calculate the stud shear bearing capacity after corrosion, this paper used the stud shear bearing capacity factor after corrosion to represent the stud corrosion degradation effects, and based on the analysis of the reasons for its reduction, the product between stud effective section area after corrosion and stud tensile strength was proposed to calculate the shear capacity coefficient. At the same time, based on the assumption of plasticity theory, the simplified calculation formula of the composite beam flexural capacity under hogging moment was derived by simplifying the sum of the flexural capacity of the steel beam, the longitudinal reinforcement in the concrete plate and the stud. The effect of interface stud corrosion for the flexural bearing capacity of steel-composite composite beam was considered by multiplying the stud shear capacity coefficient after its corrosion, and the experimental data of 11 beams were combined to verify. The results showed that the calculated results of this method were highly consistent with the experimental results in the literature. The calculated results were on average less than 2% of the experimental results, and the coefficient of variation was only 0.01. The calculated results of the formula were consistent with the results of theoretical analysis in the literature, and the calculation method was simple and convenient. It can be evaluated for the composite beam flexural capacity under hogging moment with corroded shear studs.

Keywords: steel-concrete composite beam; negative bending moment; stud corrosion; shear capacity coefficient

1. Introduction

In recent years, steel-concrete composite beams have been widely used in the construction of sea-crossing and river-crossing bridges in southeastern coastal areas of China due to their advantages of light weight, high bearing capacity, high structural efficiency and convenient construction (LIU et al. 2017; GE et al. 2010; NIE 2011). As a result of the corrosive environment influence in coastal areas, the durability of steel-concrete composite beams has gradually become the focus of scholars’ attention. The negative moment zone of composite beams is easy to crack due to the coupling effects of negative moment, self-shrinkage and creep, environmental corrosion and external fatigue loads. The chloride ion in the environment can easily enter the steel-concrete composite interface through the cracks, which results in the environmental corrosion of the interface bolts. The results of bolt corrosion test of composite beams with cracks in Weng Ya-gu (WEI et al. 2016) under negative bending moment showed that the accelerated corrosion effect of cracks was obvious, and the maximum corrosion rate of bolts could reach about 19% after one-year dry-wet cyclic test. Xue Wen (Xue et al. 2013) and others used sponge-wrapped on-line corrosion to separately corrode some bolts in the negative bending moment zone of six steel-concrete composite beams. The results showed that the higher the corrosion
rate of bolts, the more obvious the reduction of ultimate bending capacity of composite beams. In reference (Chen J et al. 2014), the law and calculation method of the bending capacity of composite beams in negative moment region after bolt corrosion were further studied through experiments. The results showed that the bending capacity of composite beams decreased with the increase of corrosion rate. It can be seen that the corrosion of bolts has an obvious effect on the bearing capacity of composite beams. When composite beams are in corrosive environment, there is no quantitative method to calculate the effect of interface bolt corrosion on the structural bearing capacity. Generally, the safety and durability of structure are guaranteed only by strengthening the anti-corrosion measures of components.

In view of this, on the basis of reference to the simplified calculation method of ultimate flexural capacity in negative moment zone of non-corroded composite beams (WU 2008; WU et al. 2008; YU et al. 2014), considering the deterioration of the composite beams caused by bolt corrosion, a simplified calculation method of ultimate flexural capacity in negative moment zone of composite beams after bolt corrosion is proposed, and its test verification and analysis are carried out.

2. Calculation Method

2.1 Calculation Assumption

Before the composite beams reach the ultimate state, the strain of steel beams in the top flange and steel bars in the concrete slabs has exceeded the yield strain of materials, and the plastic properties of sections have developed sufficiently. The plastic theory can be used to approximate the ultimate flexural capacity of composite beams. This method is adopted in The Japanese Guidelines for Design and Construction of Composite Bridges (Technical Association of Prestressed Concrete et al. 2014) and the European Code 4 (EN2004-2, 2005). In China, Wang Qing-li (WANG et al. 2014) and Yu Zhi-wu (YU et al. 2014) also calculated the ultimate flexural capacity of composite beams in the negative moment region by using the simplified plastic theory, and compared with the calculation results of the code, which met the requirements of the code. The premise of using plastic theory to calculate the flexural capacity of composite beams is that the composite beams can form plastic hinges, and most of the sections yield. To this end, the calculation is based on the following assumptions:

1. Plastic hinges are formed before the negative moment region of composite beams reaches its ultimate state, and the material of components can reach its yield strength. That is to say, when the negative moment region reaches its ultimate state, the stresses of steel bars, bolts and steel beams in concrete slabs reach their yield strength respectively.

2. Assuming that the corrosion environment is uniform to the interface bolts of composite beams and ignoring the difference of individual bolt corrosion, the corrosion rate of the same batch of bolts is the average corrosion rate of bolts of the same composite beams under the same environment.

3. Assuming that the failure of composite beams is marked by the shear failure of bolts after corrosion, the shear capacity of bolts after corrosion is calculated only considering the influence of the change of the section area of the bolts and the tensile strength of the bolts after corrosion.

2.2 Shear Bearing Capacity Coefficient of Corroded Bolts

A lot of research results show that (SHI 2013; GONG 2009; LI 2014; SUN et al. 2008; JIN et al. 2009; WU 2011): the reasons for the reduction of shear capacity after bolt corrosion are similar to those of reinforced concrete beams after reinforcement corrosion, which mainly include the following points:

1. Corrosion of bolts will reduce the cross-section area of bolts and the tensile strength of bolts, which will lead to the decrease of the shear capacity of bolts.

2. The corrosion products of bolts will produce volume expansion (2-4 times), which will lead to cracking damage of concrete around bolts, deterioration in the cooperative working performance of bolts and concrete, and further aggravating the deterioration of corrosion.

3. The rust pits on the surface of the studs due to uneven rust easily lead to stress concentration, which seriously affects the fatigue performance of the studs. When calculating the shear capacity of bolts after rusting, neglecting the effect of stress concentration caused
by rusting, the shear capacity of bolts is mainly affected by the reduction of the area of bolts after rusting and the reduction of the tensile strength of bolts. Considering the overlapping effect, the formula for calculating the shear capacity coefficient of bolts which is $K_i$ after rusting is given.

$$K_i = f_v(\rho_i)f_A(\rho_i)$$ \hspace{1cm} (1)$$

In the formula, $\rho_i$ is stud area corrosion rate, $f_v(\rho_i)$ is the shear strength factor after bolt corrosion, according to the specifications, there is a quantitative proportional relationship between the shear strength and the tensile strength of steel, which can be fitted according to the experimental data of the tensile strength material after bolt corrosion. In this paper, 30 groups of different corrosion rates (corrosion rates in the range of 0-16.05%) in the literature (LI 2014) are selected directly. The fitting formula of nominal yield tensile strength of studs with corrosion rate is shown in formula (2). $f_A(\rho_i)$ is the area factor of corroded bolts, which can be expressed by the effective area ratio of corroded bolts, and it is shown in formula (3)?

$$f_v(\rho_i) = 1.0091e^{-0.0279\rho_i}$$ \hspace{1cm} (2)$$

$$f_A(\rho_i) = 1 - \rho_i$$ \hspace{1cm} (3)$$

By substituting formula (2-3) into formula (1), the expression of shear bearing capacity coefficient of corroded bolts can be obtained.

$$K_i = 1.0091e^{-0.0279\rho_i}(1 - \rho_i)$$ \hspace{1cm} (4)$$

2.3 Calculation Method of Negative Bending Moment Flexural Bearing Capacity

It is assumed that the longitudinal strength of steel bars of the upper and lower layers within the effective width of concrete flange slabs, bolts and steel beams reaches their yield strength, when the negative moment region of steel-concrete composite beams reaches the ultimate flexural capacity. The ultimate flexural capacity can be regarded as the sum of the three parts of the flexural capacity provided by the steel beam, the upper and lower longitudinal loaded steel bars and the bolts. As shown in Figure 1, the bearing capacity of each part is simplified calculation by the following formulas.

Figure 1. Simplified calculation diagram of composite beam negative flexural capacity (Neutral axis in steel beam web)

\[ M_{un} = M_{ps} + M_{ns} + M_d \] \hspace{1cm} (5)$$

\[ M_{ps} = f_{yb}W_{px} \] \hspace{1cm} (6)$$

\[ M_{ns} = M_{nst} + M_{nsb} \] \hspace{1cm} (7)$$
In the formula, \( M_{\text{un}} \) is the flexural capacity of composite beams in negative moment zone after bolt corrosion. \( M_{\text{ps}} \) is the bending capacity of steel beam. \( M_{\text{ns}} \) is the flexural capacity of the longitudinal reinforced bar, which is the sum of the upper \( M_{\text{nst}} \) and lower \( M_{\text{nst}} \) layers of the longitudinal reinforced bar. \( M_{\text{d}} \) is the flexural capacity of the studs in the negative moment zone. \( f_{\text{yb}}, f_{\text{yd}}, f_{\text{yst}}, \) and \( f_{\text{ysb}} \) are respective the yielding strength of steel beams, studs and upper and lower longitudinal steel bars. \( W_{\text{px}} \) is the plastic resistance moment of steel beam; \( A_{\text{st}} \) and \( A_{\text{sb}} \) are the area of upper and lower longitudinal steel bars. \( d_{\text{st}} \) and \( d_{\text{sb}} \) are the distance from the center of upper and lower longitudinal steel bars section to the center of \( d_t \) and \( d_t \) is the distance from the center of steel beam section to the neutral axis of composite section. \( d_{\text{d}} \) is the distance from the center of the bolt to the center of the \( d_t \); \( K_1 \) is the shear capacity coefficient of the corroded studs, which is calculated according to the formula. \( N_{\text{vo}} \) is the shear capacity of non-corroded bolts, and the calculation is based on 7.2.1 in the Code for Design of Steel-concrete Composite Bridges - GB50917-2013(Ministry 2013)? \( n \) is the number of studs? For continuous beams, it is the number sum of studs in the range of 1/4 spans at the left and right ends of the maximum negative moment section. According to the concept of effective width, the number of studs in this range have a significant influence on the bending capacity of the maximum negative moment section. For test simply supported beams, the number of bolts in pure bending section is generally taken for \( n \).

\[ d_t = \left( f_{\text{yb}} A_t - f_{\text{st}} A_{\text{st}} - f_{\text{sb}} A_{\text{sb}} - nK_1N_{\text{vo}} \right) / 2f_{\text{yb}} \]  

Then, \( d_{\text{st}}, d_{\text{sb}}, d_{\text{d}} \) in the formulas mentioned above, they can be expressed as follows:

\[ d_{\text{st}} = d_g - a_{\text{st}} - \frac{1}{4} h_g + \frac{1}{2} d_t \]  

\[ d_{\text{sb}} = d_g - a_{\text{sb}} - \frac{1}{4} h_g + \frac{1}{2} d_t \]  

\[ d_{\text{d}} = d_g - a_d - \frac{1}{4} h_g + \frac{1}{2} d_t \]

In the formula, \( a_{\text{st}}, a_{\text{sb}}, \) and \( a_{\text{d}} \) are respectively the distance from the center of upper and lower longitudinal steel bars and the stud to the upper flange of the concrete slab of the composite beam in the negative moment zone.

### 3. Document Data Validation

In order to verify the rationality and accuracy of the simplified calculation method proposed in this paper, the experimental data of the bending capacity of composite beams in negative moment zone after the corrosion of interfacial bolts are verified (Xue et al. 2013; Chen J et al. 2014). The experimental and theoretical values in the literature are compared with the predicted values in this paper. The comparison results can be seen in table 1 and image2. Among them, the experimental environment...
in the literature is the accelerated corrosion environment, which is the same as the experimental environment of the literature data used in the derivation formula (4) in this paper, and the experimental data and theoretical calculation assumptions are basically the same. The data used in the calculation of the predicted value in this paper is selected according to the literature, and the number of bolts in the pure bending section of the test beam is taken as the bolt number. Experimental data and theoretical formulas of specific literature can be referred to the relevant literature.

Table 1. Comparison with calculated and test values of bearing capacity of the specimen in the negative bending moment

| Specimen source (Xue et al. 2013) | Specimen number | Corrosion rate of studs (%) | Literature test value $M_E$ (KN·m) | Theoretical value of literature $Mc$ (KN·m) | Prediction in this paper $Mc/M_E$ |
|----------------------------------|-----------------|----------------------------|---------------------------------|---------------------------------|-------------------------------|
| L0                               | 0               | 126                        | 106.36                          | 0.84                            | 123.51                        |
| L1                               | 3.81            | 124.75                     | 106.36                          | 0.85                            | 122.18                        |
| L2                               | 8.07            | 122.75                     | 106.36                          | 0.87                            | 120.81                        |
| L3                               | 11.49           | 119.75                     | 106.36                          | 0.89                            | 119.84                        |
| L4                               | 16.49           | 121.75                     | 106.36                          | 0.87                            | 118.63                        |
| L5                               | 23.2            | 120.5                      | 106.36                          | 0.88                            | 117.32                        |
| L6                               | 25.86           | 119.5                      | 106.36                          | 0.89                            | 116.88                        |
| Mean value of $\mu$              |                 |                            |                                | 0.87                            | 0.98                          |
| Coefficient of variation CV CV   |                 |                            |                                | 0.02                            | 0.01                          |

| Specimen source (Chen J et al. 2014) | Specimen number | Corrosion rate of studs (%) | Literature test value $M_E$ (KN·m) | Theoretical value of literature $Mc$ (KN·m) | Prediction in this paper $Mc/M_E$ |
|-------------------------------------|-----------------|----------------------------|---------------------------------|---------------------------------|-------------------------------|
| CB0-A                               | 0               | 122.4                      | 119.9                           | 0.98                            | 122.47                        |
| CB0-B                               | 0               | 123.9                      | 119.9                           | 0.97                            | 122.47                        |
| CB10                                | 6.1             | 120                        | 118.3                           | 0.99                            | 119.88                        |
| CB20                                | 16.4            | 119.1                      | 117.3                           | 0.99                            | 116.47                        |
| CB30                                | 19.6            | 117.3                      | 116.2                           | 0.99                            | 115.64                        |
| Mean value of $\mu$                |                 |                            |                                | 0.98                            | 0.98                          |
| Coefficient of variation CV CV      |                 |                            |                                | 0.009                           | 0.008                         |

![Graph](image-url)  
(a) Literature 5
From the data analysis chart, it can be seen that the calculated results of the formula in this paper are highly consistent with the experimental values in the literature. The theoretical values are less than the experimental values. The average value of the ratio of the two values is 0.98, and the coefficient of variation is only 0.01. Compared with the theoretical value in reference (Xue et al. 2013), the theoretical value in this paper considers the effect of bolt corrosion on the flexural capacity of composite beams, which is in good agreement with the experimental value and is only 2% smaller than the experimental value. The theoretical value in reference (Xue et al. 2013) does not consider the contribution of bolt shear to the bearing capacity of composite beams, so the calculation result does not change, and is 13% smaller than the experimental value on average. The theoretical value of reference (Chen J et al. 2014) takes into account the tensile effect of concrete, and divides the flexural capacity of composite beams in negative moment zone into the sum of the three parts of steel beams, longitudinal reinforced bars in concrete slabs and cracked concrete. On the basis of theoretical derivation, calculus is used to calculate the flexural capacity of composite beams, and the calculated results are in good agreement with the test results. The calculation results of the simplified formula in this paper are very close to the theoretical values in reference (Chen J et al. 2014). The average values and variation coefficients are identical. The difference is that the contribution of bolt shear resistance to the bearing capacity of composite beams is considered in this paper, while the contribution of cracked concrete to the bearing capacity of composite beams is considered in reference (Chen J et al. 2014). It can be seen from the literature test results that when the failure of the test beam is based on the cutting of the bolt, the tension of the cracked part of concrete is balanced with the bolt shear resistance, and the flexural bearing capacity provided by the two parts is not much different. However, when calculating the bending bearing capacity of the bolt, the paper predicts the shear bearing capacity of the bolt after its corrosion by using the existing corrosion test results, and then figures up the contribution of its bending bearing capacity without calculus analysis. The calculation process is simple and the results meet the accuracy requirements, so the simplified formula can be used to calculate the flexural bearing capacity of composite beam after interface studs rusting.
4. Conclusion

(1) Based on the analysis of the reasons for the reduction for the shear capacity of the rusted bolts, the shear capacity coefficient of the rusted bolts is used to calculate the shear capacity of the corroded bolts. The product of the effective section area of the corroded bolts and the tensile strength of the bolts is proposed to calculate the shear capacity coefficient of the corroded bolts.

(2) Based on the assumption, the flexural capacity of the composite beam in the negative bending moment area is simplified as the sum of the bending capacity of steel beams, studs and longitudinal loads steel bars in concrete slabs, and the calculation formulas are given for each part. Considering the deterioration of studs after corrosion, a simplified method for calculating the flexural capacity of the composite beam with negative bending moment after interface bolts corrosion is presented.

(3) The simplified calculation method is validated by literature data. The results show that the calculation results of this method are in good agreement with the experimental values in literature, and the accuracy of the theoretical analysis results is in agreement with that of literature. The calculation method is simple and convenient, and can be used to evaluate the flexural capacity of composite beams in negative moment zone under the corrosion of interface bolts.

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