Simulation analysis of mechanical properties of shear connectors of steel-concrete composite beams

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Abstract. In order to further study the mechanical properties and development distribution of shear connectors of steel-composite beam under the influence of concrete shrinkage and creep. In this paper, on the basis of the existing experimental research, ABAQUS software is used to establish the steel-composite beam model. The structural forms of the model include simply supported beam and continuous beam, and the shear connectors of steel-composite beam include three types: stud connectors, PBL connectors and composite connectors. The time development and spatial distribution of vertical displacement, connector shear force and slip at interface of each composite beam with concrete creep are calculated by finite element software, and some calculated results are in good agreement with the existing test results. By comprehensively comparing the calculation results of the key sections of each composite beam at some time points, the mechanical properties and their respective applications of the shear connectors of the steel-composite beam are analyzed and summarized, and the research results can guide the design and engineering application of the shear connectors of the steel-composite beam.

1. Introduction
Reasonable calculation of the influence of concrete shrinkage and creep on the mechanical behavior of shear connectors in composite beams is of great significance for the application of connectors [1][3]. At present, most studies on shear connectors by scholars at home and abroad adopt model tests and theoretical calculations, but the model tests are time-consuming and labor-consuming, and the theoretical calculations are complex and inaccurate [1][2][5]. On the basis of predecessors, considering the influence of concrete shrinkage and creep, this paper uses ABAQUS finite element software to analyze the mechanical properties of shear connectors of steel-composite beam.

2. The establishment of finite element model
In this paper, model parameters were selected based on model tests conducted by Fan jian sheng [7][8] and Deng wen qin [6], The composite beam is composed of concrete slabs and I-beams combined by shear connectors, the model is shown in Figure 1.

Figure 1. Finite element model diagram of steel-composite beam.
3. Calculation and analysis of simply supported beams

3.1. Shear force of connector

The longitudinal symmetry of the simply supported beam is calculated by half of the structure. Figure 2 shows the shear distribution of the three connectors at 500 days of typical creep development.

In spatial distribution, the shear force of connector increases parabola from fulcrum section to mid span section. At the same time, the shear force of composite connector is always lower than that of PBL connector, the difference between them is small, and the stress of stud connection is the largest.

In terms of time distribution, with the increase of concrete creep, the shear force of the connector at the same position increases rapidly in the early stage and gentle in the later stage. The shear force of stud connector increases fastest, and the other two increase slowly. At the same position, the shear force of stud connectors is significantly greater than that of PBL and composite connectors, and the latter two are relatively close.

3.2. Slip value of interface

The relative slip at the interface of reinforced concrete composite beams increases the deformation of composite beams, which has great influence on the stress and deformation of composite beams[9][12]. The analysis results are shown in Figure 3.

In terms of time distribution, the slip of the three connection modes increases with time. At the same position, creep aggravates the deformation of concrete slab due to long-term load, which leads to the increase of interface slip. In terms of spatial distribution, the slip of the three kinds of connectors increases from the fulcrum to the middle of the span, and reaches a peak near the middle of the span. The slip at the fulcrum tends to zero, and the longitudinal distribution is close to symmetry.

3.3. Vertical displacement of structure

The connection mode has a great influence on the overall vertical stiffness. The vertical displacement nephogram of simply supported beam is shown in Figure 4 ~ 6, loading age is 500 days.
The results show that under the same load duration, the vertical displacement of the composite connector structure is the smallest, the vertical displacement of the PBL connector structure is in the middle, and the vertical displacement of the stud connector structure is the largest. The stud connector is a flexible connection with low connection stiffness; PBL connection is a rigid connection with high connection stiffness. Combined connection combines the advantages of the first two connectors, and the connection stiffness is the largest.

4. Continuous beam calculation and analysis

4.1. Shear force of connector
Due to the symmetry of the structure, the shear force values of the connectors of half of the structure are shown in Figure 7.

In the spatial distribution, the shear force of connectors increases first and then decreases from the side span fulcrum section to the mid span middle section. The shear force distribution trend of the three kinds of composite beam connectors in positive bending moment region is close, and the shear force of connectors in negative bending moment area is from positive to negative. In terms of time distribution, the shear force of connectors in positive moment region is greatly affected by creep.
Under the same load, the shear growth rate of stud connectors is the fastest, and the shear growth rate of PBL connectors is slightly greater than that of composite connectors.

4.2. Slip value of interface
The calculation and analysis results of slip of three kinds of connectors are shown in figure 8.

In the spatial distribution, the slip values of the three connectors along the span distribution trend is roughly the same, the slip near the fulcrum is close to 0, and the slip value at the middle of the side span reaches two peaks. In terms of time distribution, the development trend of the slip of the three connectors in the positive moment region is consistent with that of the shear force in the positive moment region of the continuous beam. The slip value of the composite connector in the negative moment region changes gently, and the PBL connector and the stud connector increase in turn.

4.3. Vertical displacement of structure
The vertical displacement nephogram of continuous beam is shown in Figure 9～11, and the concrete loading age is 500 days.

For the side span of continuous beams, the vertical displacement of composite beams connected by studs at the same position is the largest, and PBL and composite connectors have the advantages of reducing the vertical displacement of the structure. For the middle span of continuous beam, the vertical displacement of three kinds of connectors on the middle span of the structure is obviously different. For the L/2 of the middle span, the vertical displacement of the stud connector is the largest, the vertical displacement of the PBL connector is in the middle, and the vertical displacement of the composite connector is the smallest.
5. Comparative analysis

5.1. Comparison of shear force of connectors
The shear force comparison results of connectors are shown in Table 1.

| Points | 6 | 11 | 16 | 21 |
|--------|---|----|----|----|
| Structure | S-B | C-B | S-B | C-B | S-B | C-B | S-B | C-B |
| PBL-C | 19.7 | 27.6 | 15.2 | 20.7 | 13.6 | 26.5 | 12.3 | 67.5 |
| Com-C | 24.5 | 35.3 | 20.6 | 27.3 | 18.5 | 46.4 | 15.1 | 39.6 |

Note: PBL-C stands for PBL connector. Com-C stands for composite connector. S-B stands for simply supported beam. C-B stands for continuous beam. The same below.

From Table 1, it can be concluded that: in terms of connector shear force, the reduction rate of PBL connector and composite connector on continuous beam structure to connector shear force is higher than that of simply supported beam, and the maximum reduction rate for continuous beam is 27.6%、39.6%, and maximum reduction rate for simply supported structure is 19.7%、24.5%.

5.2. Comparison of interface slip values
Four sections are selected from the fulcrum to the mid span section of the structure. The reduction rate of the slip between beams and slabs is shown in Table 2.

| Points | 6 | 11 | 16 | 21 |
|--------|---|----|----|----|
| Structure | S-B | C-B | S-B | C-B | S-B | C-B | S-B | C-B |
| PBL-C | 59.8 | 43.8 | 49.3 | 43.9 | 61.8 | 37.1 | 72.3 | 40.5 |
| Com-C | 78.8 | 58.2 | 77.7 | 57.2 | 81.5 | 54.5 | 88.6 | 54.6 |

As can be seen from Table 2, the reduction rate of interface slip of simply supported beam structure by PBL connectors and composite connectors is better than that of continuous beam structure. The maximum reduction rate of continuous beam is 43.9% and 58.2% respectively, and that of simply supported structure is 72.3% and 88.6% respectively.

5.3. Comparison of vertical displacement of structure
Table 3 shows the reduction rate of vertical displacement of PBL connector and composite connector relative to stud connector at four time nodes.

| Time | 15d | 60d | 300d | 500d |
|------|-----|-----|------|------|
| Structure | S-B | C-B | S-B | C-B | S-B | C-B | S-B | C-B |
| PBL-C | 23.1 | 27.6 | 19.7 | 24.6 | 15.5 | 20.7 | 13.6 | 10.5 |
| Com-C | 29.6 | 38.4 | 24.5 | 35.3 | 20.6 | 27.3 | 18.5 | 13.4 |

From Table 3, it can be concluded that the effect of PBL connectors and composite connectors in the early stage of creep development is better, and the maximum reduction rates of vertical displacement of simply supported beams are 23.1% and 29.6%, respectively, and that of continuous beams are 27.6% and 38.4% respectively.

6. Conclusion
(1) As the load time increases, the vertical displacement in the positive bending moment area of the composite beam gradually increases. The stud connectors develop the fastest, and the PBL connectors and composite connectors decrease in turn; in the negative bending moment area, concrete creep can
improve the vertical displacement of structure, The displacement of the combination connectors structure is the smallest, and the PBL connectors and stud connectors increase sequentially.

(2) With the development of creep, the shear force of three kinds of connectors increases gradually. Under the same conditions, the shear growth rate of connectors in positive bending moment region is significantly higher than that in negative bending moment region. The shear force of PBL connector and composite connector in positive bending moment region is significantly less than that of stud connector, while the shear force of PBL connector and composite connector is close to each other in negative bending moment region.

(3) The slip at the interface of the two structures increases gradually with the increase of creep of concrete, which increases rapidly in the early stage and slows down in the later stage. At the same time, the increase of slip in the positive moment zone is obviously higher than that in the negative moment zone. In the same condition, the interface slip of the structure of the stud connector is obvious, PBL connector and the combination connector can significantly improve the interface slip, and the slip is reduced by nearly half compared with the stud connector.

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