Flexural Behaviours of CFRP Sheets Reinforced Steel-Concrete Composite Beams

Lei Tang1,*, Dong Wei2, Zhao Gao2

1School of Civil Engineering, Qingdao University of Technology, Qingdao 266033, China
2Shandong Hi-Speed Engineering Construction Group Co. Ltd., Jinan 250014, China

*Corresponding author’s e-mail: tang.lei2018@outlook.com

Abstract. The finite element simulation was performed for 8 carbon fiber reinforced plastic (CFRP) sheets reinforced steel-concrete composite beams via ABAQUS software, in an effort to further investigate their mechanical properties. Next, the influences of shear connection degree and elasticity modulus, width and constitutive relation of CFRP sheets on the mechanical properties of steel-concrete composite beams were studied. Subsequently, their load-dependent change laws of midspan deflection were reported in detail. The simulation results show that the reinforcement effect on the negative moment region of each composite beam is improved with the increase in the elasticity modulus, width of CFRP sheets and the shear connection degree.

1. Introduction
The form of continuous multi-span beams is usually adopted to enhance the integrity of building structures and bridge structures [1]. However, in the negative moment region of multi-span continuous composite beam, the concrete slabs are susceptible to cracking because the tensioning force and steel beams will easily experience local buckling under compressive force, which leads to the degradation of structural bearing capacity and durability [2-3]. In comparison to the replacement of existing composite beams, a method featured by lower cost and shorter time consumption is to reinforce the damaged composite beams. Therefore, carbon fiber reinforced plastic (CFRP) has been added as an external reinforcement material onto the surface of concrete slabs in the negative moment region of composite beams, thus improving the structural bearing capacity. Many experimental studies show that CFRP sheets integrate the merits of light weight, high tensile strength, corrosion resistance, convenient construction, etc. [4].

It has been proven by an experiment on full-size steel-concrete composite beams [5] that the ultimate bearing capacity of composite beams can be strengthened by bonding the CFRP sheets with epoxy resin glue. Al-Saidy et al. [6] used CFRP sheets to reinforce the web and lower flange of steel beams in composite beams, and the results showed that the ultimate bearing capacity of CFRP sheets-reinforced specimens was improved by 45%, and the deflection upon the failure was much lower than that of unreinforced composite beam specimens. El-Zohairy et al. [7] conducted CFRP sheet reinforcement test in negative moment regions of 6 composite beams, performed a finite element analysis, and explored the influence of shear connection degree on the ultimate bearing capacity of composite beams. The results manifested that the optimal performance of CFRP sheet reinforcement could be achieved when the shear connection degree between steel beam and concrete slab reached...
80%. In addition, both theoretical analysis and experimental results of composite beams indicate that the interface is prone to horizontal slippage if partial shear connection is adopted, which will result in the degradation of ultimate bearing capacity and rigidity of composite beams and the increase of their deformations. Therefore, the mechanical properties of negative moment region in CFRP sheets reinforced steel-concrete composite beams were probed in this study.

2. Finite Element Model

2.1 Modelling

The composite beam specimens were designed into the same size, as shown in Figure 1. The total length and height of each specimen were 3,000 mm and 344 mm, respectively. The width and height of concrete slab were 500 mm and 100 mm, respectively. Two-layer (upper layer and lower layer) longitudinal tensile reinforcements with diameter of 10 mm were arranged in the concrete slab to resist against the tensile stress in the concrete. H-shaped steel sections (dimensions: 244×175×7×11 mm) were selected for the steel beams. In order to simulate the influence of CFRP width on the mechanical properties, the spacings of two-row studs with the diameter of 13 mm and height of 80 mm were set as 140, 300 and 350 mm, respectively. The pasting length of CFRP sheets was 2,400 mm. The CFRP sheets with width of 175 and 500 mm were selected to analyse the influence of CFRP width on the mechanical properties. The composite beams were reinforced using the CFRP sheets with elasticity modulus of 245 and 400 GPa, aiming to analyse the influence of their elasticity modulus on the mechanical properties of composite beams.

![Figure 1: Elevation of Model (unit: mm)](image)

2.2 Constitutive models

The Concrete Damaged Plasticity model was used as the constitutive model of C50 concrete. The stress-strain curves of the concrete under tensile state and compressive state are as shown in Figure 2. The three-broken-line model was taken as the constitutive model of Q355 H-shaped steel, as shown in Figure 3 (a), while double-broken-line model was used for HRB400 ribbed bars and studs, as shown in Figure 3 (b). The data provided by Liu [8] were input into the constitutive models of steel and concrete. The constitutive models of CFRP sheets were elastic material models, namely, Orthotropic model [9-10] and Lamina model [11].

![Figure 2: Stress-Strain Curves of Concrete](image)
2.3 Interaction

The top flange of steel beam served as the master plane and lower surface of concrete slab as the slave plane, and their interactive relationship was defined by the designated contact pairs in general contact. Penalty was used as the tangential behaviour, and the multinomial coefficient of friction was taken as 0.2. Hard contact was used as the normal behaviour to prevent the mutual penetration of contact surface in case of deformation.

Tie constraints were used between steel beam and backing plate and between concrete and backing plate in the finite element model of steel-concrete composite beam, in order to ensure their synchronous deformation. Kinematic Coupling constraint was applied to the steel backing plates at loading points and steel beam parts, and the motion at coupling node was restricted to rigid body motion of loading point. Reinforcement layer and stud were respectively embedded into the concrete slab. Meanwhile, the under surface of studs was tied together with the top face of steel beam.

2.4 Element types and boundary conditions

S4R shell elements were used to simulate the web and flange of steel beam and CFRP sheets. The S4R contained 4 nodes, being insensitive to the shear self-locking effect. The concrete, studs and steel backing plates were simulated using C3D8R solid elements, which included 8 nodes with 1 integral point in the element centre. Under complicated stress state, C3D8R elements could not be so easily affected as to be locked. The adverse effect on calculation accuracy could be mitigated only by dividing the C3D8R elements into at least four layers along the thickness direction. The T3D2 bar elements that did not bear shear force or bending moment were selected to simulate the tensile reinforcements. The T3D2 elements contained two nodes and one integral point, with the plastic and large strain functions. The boundary conditions of simply supported beam were applied to the steel backing plate tied to the left and right ends of concrete slab, as shown in Figure 4. The displacement boundary conditions were applied to two reference points.

Figure 4: Boundary Conditions
3. Analysis results and discussion

The load-deflection curves of different steel-concrete composite beams are as shown in Figure 5. The finite element simulation results of three reinforced composite beam specimens with different constitutive models of CFRP sheets showed that the ultimate bearing capacity of each steel-concrete composite beam was strengthened thanks to the use of CFRP sheets, and the bearing capacity was affected a little by the constitutive model of CFRP sheets. According to the finite element simulation results, the CFRP sheets started exerting their effect only after the composite beams yielded, while bearing a very small tensile stress before the yielding of composite beams.

By analyzing the load-deflection curves of three composite beams with different elasticity moduli of CFRP sheets, it could be known that the ultimate bearing capacity of each composite beam was enhanced with the increase in the elasticity modulus of CFRP sheets. According to the finite element models of three composite beams with different widths of CFRP sheets, the width of CFRP sheets had a great impact on the ultimate bearing capacity of composite beams, and this influence was gradually enhanced with the increase in the width of CFRP sheets, but the width of CFRP sheets had a minor influence on the rigidity of composite beams.

It was found through analyzing the finite element simulation results of 4 composite beams that the shear connection degree was an important factor influencing their flexural rigidity and ultimate bearing capacity. Under the same number of CFRP sheet pasting layers, the ultimate bearing capacity of composite beams was enhanced with the reduction of stud spacing, so was the flexural rigidity. By comparing the composite beam and the control beam with stud spacing of 350 mm, it could be discovered that the CFRP sheets started functioning only after the composite beam reached the yield state for a certain while. When the stud spacing was small, the CFRP sheets started functioning as early as the initial loading phase, and they significantly enhanced the flexural rigidity of composite beams.
Therefore, the tensile characteristics of CFRP sheets can be exerted to the greatest extent if they are applied to steel-concrete composite beams with a high shear connection degree in practical engineering.

4. Conclusions
The short-term structural mechanical properties in the negative moment regions of 8 CFRP sheets reinforced steel-concrete composite beams were explored in this study. The following conclusions were drawn according to the finite element simulation results:

1) The ultimate flexural bearing capacity of midspan section can be enhanced by using the CFRP sheets to reinforce the negative movement region of steel-concrete composite beams. The CFRP sheets start functioning only after the composite beams yield, while bearing a small tensile stress before the yielding.

2) The reinforcement effect on the negative moment region of steel-concrete composite beams is associated with the elasticity modulus and width of CFRP sheets as well as the shear connection degree. The ultimate bearing capacity is elevated with the increase in the elasticity modulus and width of CFRP sheets and the shear connection degree.

3) The mechanical properties of negative moment region can be evidently improved by using two-layer CFRP sheets to reinforce the composite beams with a high shear connection degree. The higher the shear connection degree, the more the CFRP sheets exert their strength, and the more obvious the improvement effect on the bearing capacity and rigidity of composite beams.

References
[1] Nie, J.G., Fan, J.S., Cai, C.S. (2004) Stiffness and Deflection of Steel–Concrete Composite Beams under Negative Bending. J. Struct. Eng., 130: 1842-1851.
[2] Ryu, H.K., Chang, S.P., Kim, Y.J., Kim, B.S. (2005) Crack Control of A Steel and Concrete Composite Plate Girder With Prefabricated Slabs Under Hogging Moments. Eng. Struct., 27: 1613-1624.
[3] Su, Q.T., Yang, G.T., Wu, C. (2012) Experimental Investigation On Inelastic Behavior of Composite Box Girder Under Negative Moment. Int. J. Steel Struct., 12: 71-84.
[4] Afefy, H.M., Sennah, K., Akhlagh-Neja, H. (2016) Experimental and Analytical Investigations On The Flexural Behavior of CFRP Strengthened Composite Girders. J. Constr. Steel. Res., 120: 94-105.
[5] Lin, W.W., Yoda, T., Taniguchi, N. (2013) Fatigue Tests On Straight Steel–Concrete Composite Beams Subjected To Hogging Moment. J. Constr. Steel. Res., 80: 42-56.
[6] Al-Saidy, A.H., Klaiber, F.W., Wipf, T.J. (2007) Strengthening of Steel–Concrete Composite Girders Using Carbon Fiber Reinforced Polymer Plates. Constr. Build. Mater., 21: 295-302.
[7] El-Zohairy, A., Salim, H., Shaaban, H., Mustafa, S., El-Shihy, A. (2017) Experimental and FE Parametric Study On Continuous Steel-Concrete Composite Beams Strengthened With CFRP Laminates Constr. Build. Mater., 127: 885-898.
[8] Liu, Y., Tong, L.W., Sun, B., et al. (2014) FEA and Bending Capacity Calculation for Mechanical Behavior of Steel-Concrete Composite Beams Under Negative Bending. J. Build. Struct., 35: 10-20.
[9] Obaidat, Y.T., Heyden, S., Dahlblom, O., (2010) The Effect of CFRP and CFRP/Concrete Interface Models when Modelling Retrofitted RC Beams with FEM. Compos. Struct., 92: 1391-1398.
[10] Zeng, J.J., Gao, W.Y., Liu, F. (2018) Interfacial Behavior and Debonding Failures of Full-Scale CFRP-Strengthened H-Section Steel Beams. Compos. Struct., 201: 540-552.
[11] Wan, S.C., Huang, Q., Guan, J., Guo, Z.Y. (2018) Strengthening of Continuous Steel-Concrete Composite Beams in Negative Moment Region Using Prestressed Carbon Fiber-Reinforced Polymer Plates. J Jilin Univ., 48: 1114-1123.