Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

COMPARATIVE STUDY ON THE BENDING PROPERTIES FOR TWO TYPES OF COMPOSITE BEAMS

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The difference between the steel and concrete composite-laminated action beam and the double steel and concrete composite action beam is in the connection of the top concrete slab and the steel top flange. The bending properties about the composite-laminated beam and the double composite beam in the negative flexural region are investigated in this paper. The relation of the cross section bending moment-curvature for the two types of composite beams under the action of negative bending moment are drawn by the whole process analysis method, and then the corresponding cracking moment, elastic ultimate bending moment and plastic ultimate bending moment are obtained. The analysis results have a good agreement with test data. Although the sectional bending stiffness and bending-carrying capacity of the composite-laminated beam and the double composite beam are comparable in the elastic state, the crack resistance of the composite-laminated beam is much better than that of the double composite beam.

Keywords: Composite-laminated beam (CLB), Double composite beam (DCB), Bending moment-curvature relation, Crack resistance.

1 INTRODUCTION

The double steel and concrete composite action beam (referred to as double composite beam, DCB) is a kind of advantageous structure used in the negative flexural region, it is proposed by Reiner (1996). In the DCB, attaching additional concrete slab to steel bottom flange can improve local buckling strength and increase the sectional stiffness (Duan *et al*. 2010). But a crack may appear in advance because of height descending of sectional neutral axis, which then influences bridge durability.

The experimental results conducted by Nie *et al*. (1991) have shown that the cracking of the top concrete slab could be relieved by reducing shear connectors. Apart from that, changing the arrangement of the shear connectors, i.e., no connection is set in the certain range, the cracking bending moment of the top concrete slab can be improved, and the maximum width of cracks can be reduced (Liu and Chang 2008). Based on the facts, a new type of structure, steel-concrete composite-laminated action beam (referred to as composite-laminated beam, CLB) is proposed by Duan *et al*. (2016). In the CLB, the top concrete slab and the steel top flange are connected by the uplift-restricted and slip-permitted connectors (referred as uplift-restricted connector as follows) (Nie *et al*. 2015), meanwhile the bottom concrete slab and the steel bottom flange are connected by shear connectors. With the uplift-restricted connectors, a laminated interface is formed between the top concrete slab and the steel top flange, which allows the top concrete slab slides freely in horizontal direction (Wang *et al*. 2018), meanwhile a composite interface is formed between the bottom concrete slab and the steel bottom flange in the action of shear connectors. Not only in the CLB but also in the DCB, the structure composited by the bottom concrete slab and the steel profile is referred as bottom composite beam.

In the negative flexural region, applying the uplift-restricted connectors, the tensile stress of the top concrete slab is effectively released; meanwhile the top concrete slab and bottom composite beam in the CLB have the same bending curvature, which is not equivalent to the laminated beam in the general sense. Beyond that, the CLB is different from the classical laminated beam because it is no longer consistent with the assumption of material continuity, result from the cracking of the top concrete slab.

The main cross-sectional characteristics of the DCB and the CLB are shown in Figure 1(a) and (b) respectively. The bending moment-curvature relations (referred to M-Ø curves) in the negative flexural region of the two types of beams are obtained by the whole process analysis. Combined with the test results conducted by Wang (2018, in press), the bending properties including cracking moment, sectional bending stiffness and bending-carrying capacity of the two types of composite beams are discussed.

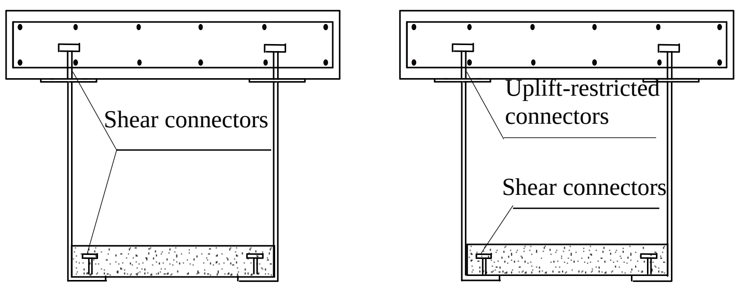

Figure 1. Cross Section

2 APPROACH OF M-Ø CURVE BY WHOLE PROCESS ANALYSIS

The basic assumptions are: (1) The member strain distribution remains linear from the beginning of stress to the member failure. (2) The tensile strength of concrete is ignored. (3) Does not consider the composite interface slip. (4) The cross section is a compact one, that means the steel profile wouldn't lose the stability under pressure before the cross-sectional strength is reached, and the connectors are not damaged.

The sectional bending stiffness and strength can be reflected from the M-Ø curves, which is the basis to study the bending performance of cross sections. The M-Ø curves will be deduced by the whole process analysis method. At first, the cross section is divided into numerous strips and the stress on each strip is uniform. Then the internal force and moment of the cross section are calculated according to the deformation conditions and the stress-strain relations of materials. At last, based on the equilibrium equations, the M-Ø curves are obtained.

Take the position of sectional neutral axis as the coordinate origin in the DCB. The bending deformations of the top concrete slab and the bottom composite beam are independent when load acts on the CLB, i.e. there are two neutral axes in the CLB. Take the top concrete slab neutral axis as itself coordinate origin, at the same time, take the bottom composite beam neutral axis as itself coordinate origin. In this case, the sectional stress distribution can be schematically depicted as Figure 2(a) and (b).

2.1 Stress-Strain Relations of Materials

The stress-strain relations of materials are selected from the Code for Design of Concrete Structures (GB50010 2010).

(1) The nonlinear stress - strain relation of concrete in compressive zone is shown in Figure 3 (a) and in Eq. (1).

$$\sigma_c = \begin{cases} f_c\left[1-\left(1-\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right](\varepsilon_c \le \varepsilon_0) \\ f_c(\varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu}) \end{cases} \quad (1)$$

where σ_c is compressive resistance of concrete; f_c is concrete strength of axial compressive; ε_0 is the concrete compressive strain when $\sigma_c=f_c$; ε_{cu} is ultimate compressive strain of concrete, $\varepsilon_{cu}\le 0.033$;

(2) The stress-strain relation of steel is shown in Figure 3(b), where, E_s is elasticity modulus of steel; ε_y is yield strain of steel, $\varepsilon_y=f_y/E_s$, f_y is yield strength; $\varepsilon_{s,u}$ is ultimate strain of steel, f_u is ultimate strength of steel, and $E_s'=0.01E_s$.

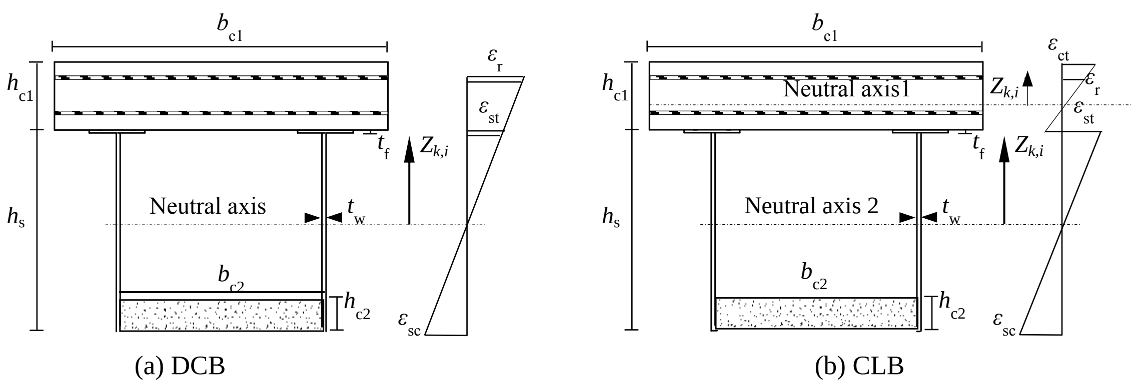

Figure 2. Analysis diagrams.

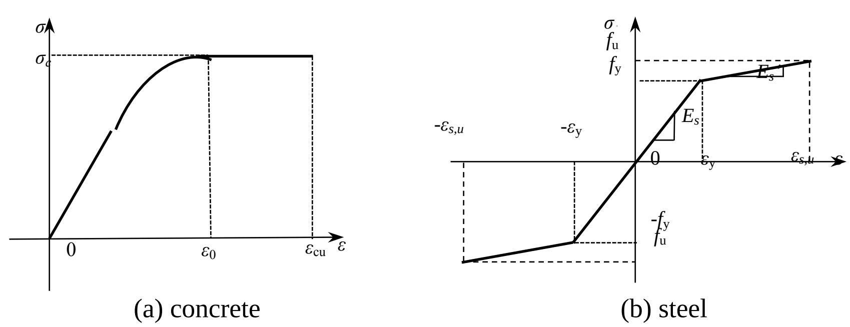

Figure 3. Stress – strain relations.

2.2 The Internal Force and Moment

In this and next sections, we will only take the DCB as the analysis object. At first, divide the cross section into different zones according to materials and section shape, such as steel reinforcement zone, steel profile zone, concrete zone, and so on. Then the different zones are divided into numerous strips. With the plane cross-section assumption and a given φ, the section strain $\varepsilon_{k,i}$ in *i* strip of *k* zone can be represented as in Eq. (2):

$$\varepsilon_{k,i} = z_{k,i}\varphi \tag{2}$$

where $z_{k,i}$ is the distance from the *i* strip of *k* zone to the neutral axis of cross section. The internal force in the *i* strip of *k* zone $N_{k,i}$, as follows in Eq. (3):

$$N_{k,i} = \sigma_{k,i}\Delta A_{k,i} \tag{3}$$

where $\sigma_{k,i}$ is the strain in the *i* strip of *k* zone, $\sigma_{k,i=}\varepsilon_{k,i}E_k$, E_k is the elasticity modulus of *k* zone; $\Delta A_{k,i}$ is the area of this strip. The bending moment in the *i* strip of *k* zone $M_{k,i}$, as fin Eq. (4):

$$M_{k,i} = N_{k,i}z_{k,i} \tag{4}$$

The total internal force and moment of the cross section can be written in the form in Eq. (1):

$$M = \sum_{k=1}^{m}\sum_{i=1}^{n} M_{k,i} \tag{5}$$

At last, the equilibrium equations are given according to the mechanical characteristics of composite beam in the negative bending zone as follows in Eq. (6):

$$\sum N_i = 0, \sum M_i = M \tag{6}$$

In general, it is defined as the cross-sectional ultimate strength of the DCB, when the strain of steel reinforcement or steel profile reaches the ultimate strain of the material. Define M_{u1} as the cross sectional bending moment when the strain of steel reinforcement reaches ultimate tensile strain $\varepsilon_{s,u}$, and define M_{u2} as the cross sectional bending moment when the strain of steel profile reaches ultimate compressive strain $\varepsilon_{s,u}$. Then the cross-sectional ultimate strength of the DCB takes the smaller one of M_{u1} and M_{u2}.

In the CLB, the top concrete slab and the bottom composite beam act independently under the action of negative bending moment except the consistence of vertical deformation. Define M_{u1}' as the cross-sectional bending moment when the bending-carrying capacity of the top concrete slab is reached and define M_{u2}' as the cross-sectional bending moment when the bending-carrying capacity of the bottom composite beam is reached. The cross-sectional ultimate strength of the CLB is the smaller one of M_{u1}' and M_{u2}'.

2.3 M-Ø Curves

The M-Ø curves could be obtained by the equations (2)-(6), the specific steps are shown as below:

(1) $\varphi_j=\varphi_{j-1}+\Delta\varphi$, where $\Delta\varphi$ could be set and the $\varphi_1=0$.

(2) Using the formula of force equilibrium equations and internal force formulas, the location of neutral axis can be obtained.

(3) The strain of every stripe can be obtained by the location of neutral axis and φ_j.
(4) Determine whether φ_j has achieved the ultimate curvature of the section, if have not, repeat steps (1)-(3). After numerous cycles the M-Ø curves can be obtained.

3 NUMERICAL EXAMPLE AND DISCUSSION

Cracking bending moment, cross sectional bending stiffness and bending-carrying capacity of the DCB and the CLB are analyzed and compared in this part. Through the whole process analysis, the M-Ø curves of two types of composite beams are obtained, combined with test results (Wang 2018, to appear), the crack resistance and bending-carrying capacity of two types of beams are discussed.

The cross sections dimensional size of test specimens (one DCB and two CLBs) are shown in Figure 4. The main characteristics of the DCB and the CLB are almost same except the difference of the connectors in the interface between top concrete slab and steel top flange, the layout of the connector is shown in Figure 1. Material properties of test specimens are summarized in Table 1.

Table 1. Material parameters.

	Steel profile	**Reinforcement**		**Concrete**
Area	9504mm^2	904mm^2	E_c	3.3×10^4 MPa
E_s	2×10^5 MPa	2.06×10^5	f_c	28MPa
f_y	378MPa	455MPa	ε_0	0.00196
ε_y	17×10^{-6}	22×10^{-6}	ε_u	0.0033

Under the action of negative bending moment, the strain of the bottom concrete slab first reaches ultimate compressive strain of concrete, soon the strain of the steel bottom flange reaches ultimate compressive strain. At this time, the ultimate strength of cross section is reached. The M-Ø curves can be derived from φ_j and the corresponding M. The M-Ø curves including analysis results and test results (represented by CLB(E) and DCB(E)) are given in Figure 5. The results of CLB(E) are the average values of the two test CLBs.

According to Figure 5, we can find that the analysis results have a good agreement with the tests results (Wang 2018, to appear). The specific values of the cracking bending moment, the yield bending moment and the ultimate bending moment are given in Table 2.

Table 2. Yield bending moment and ultimate bending moment (kN·m).

	Cracking bending moment		**Yield bending moment**		**Ultimate bending moment**	
	DCB	**CLB**	**DCB**	**CLB**	**DCB**	**CLB**
Theoretical analysis values	29.6	54.0	242.6	226.3	297.1	251.1
Experimental values	26.8	52.6	231.4	216.8	295.7	256.1

From Table 2, the yield bending moment of the CLB and the DCB is almost equivalent, and the service state of the bridge in engineering is generally within this range. Although the ultimate bending moment of the CLB is smaller than that of the DCB, it is much higher than that of the classical composite beams.

The cracking bending moment of the CLB is about two times that of the DCB. The top concrete slab in the DCB is almost in the axial tension state, the axial tensile cracks are generated, however the flexural cracks are generated in the CLB. So that, the distance between two cracks and the maximum cracks width in the CLB is much smaller than that in the DCB.

4 CONCLUSION

By analyzing and comparing bending properties of the CLB and DCB, it can be concluded that:

(1) The analyzed results have a good agreement with the test results. The cross-sectional bending stiffness and strength of the CLB is almost equivalent to the ones of DCB in the elastic state.

(2) The CLB has a good crack resistance, that the cracking moment of CLB is about two times that of DCB.

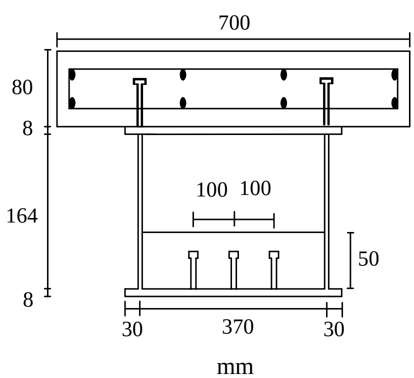

Figure 4. Cross section of test beams.

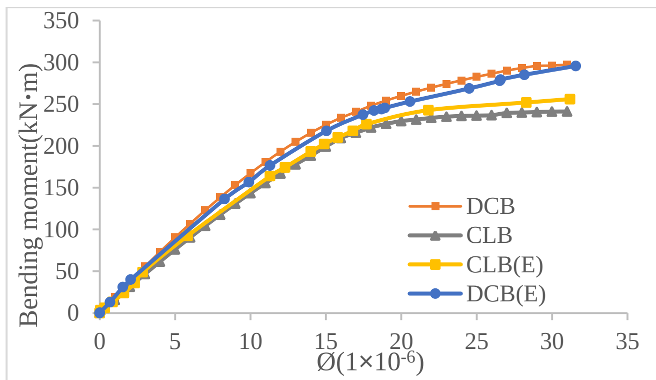

Figure 5. M-Ø curves.

Acknowledgments

The work is supported by key project of Natural Science Foundation of Hebei Education Department, China (Contact No. ZD2018025). and the Shijiazhuang Tiedao University's Graduate Innovation Fund Project, China (No. YC2018001).

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