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Preliminary communication

Nonlinear FEM Analysis on Composite Beams with Web Opening Under Negative Bending Moment

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Abstract: In order to investigate the shear behaviour and main factors of steel-concrete composite beam with web opening under negative moment, simply supported composite beam under concentrated load was analysis through finite element method. The finite element software ANSYS is used to calculate and analyse nonlinearly ten specimens. The main changing parameters are thickness, reinforcement ratio of slab and size of opening. The analysis indicates that stiffness and ultimate capacity will reduce greatly after web opening under negative bending moment. Through increasing the thickness of concrete slab, its bearing capacity can be enhanced markedly, and increasing the reinforcement ratio of concrete slab can improve its deformability effectively. Concrete slab makes a great contribution to shear capacity of web opening composite beam under negative moment. With the increase of the height or width of opening, the shear force that concrete slab undertakes will increase relatively.

Keywords: composite beam; finite element analysis; negative moment; shear bearing capacity; web opening

1 INTRODUCTION

The steel-concrete composite beam is one of the most widely used structural forms in large span structures and high-rise buildings [1-5]. By opening holes in the web of composite beams to allow various piping facilities (water supply and drainage, electrical equipment, heating ventilation, etc.) to pass through (Fig.1) can be reduced the use of construction space and the floor height can also be reduced, in order to reduce the engineering cost, obtain better economic and social benefits. Therefore, the composite beams with web opening have been more and more paid attention to in practical works. The web opening will bring adverse effects on the mechanical properties of composite beams. The current researches mainly focus on the composite beams with web opening under normal bending moment. Redwood [6-8], Clawson [9, 10], Chung [11, 12] et al. studied the effect of opening position、opening shape and bending shear ratio on mechanical properties of composite beams with web openings in normal bending moment through experiments. Zhou Donghua [13-15] et al. studied the shear transferring mechanism and bearing capacity of composite beam with web opening under normal bending moment and obtained the calculation method.

Figure 1 Composite beam with web opening

In some practical constructions, it is also necessary to set up openings in the negative bending moment section of continuous composite beams. However, there are few studies on the composite beams with web openings under negative bending moment [16] and little understanding of their failure modes and mechanical properties. Many questions need to be studied: what are the differences in mechanical properties of composite beams with web opening under negative bending moment, which is compared with the sagging moment area? Is the shear force mainly undertaken by the concrete slab above the opening? What are the changes of mechanical properties and shear capacity under different parameters? In order to solve the above problems, in this paper, it has been carried out nonlinear finite element analysis for composite beams with web opening under negative bending moment. Taking the thickness of the concrete slab, the ratio of reinforcement and the size of the opening as the main parameters, studying the mechanical characteristic and its main influencing factors of composite beam with web opening under negative bending moment, provides a basis for further experimental and theoretical research.

2 PARAMETER SETTING

Ten specimens of steel-concrete composite beams are designed from numbered CB-1 to CB-10. It includes different thickness of concrete slab, different reinforcement ratio and different opening size as variable parameters. Among them, specimen of CB-1 is without web opening. As the comparative specimen, the rest are composite beams with web opening. The central line of opening is recombined with the steel beam centre-axis and all openings are located in the negative bending area. All pieces are designed as full composite sections. The studs with 80mm length are uniformly arranged along the whole beam with equal spacing of 100 mm. The geometrical dimensions of the members are shown in Fig. 2 and Fig. 3, in which Fig. 2 is an inverted composite beam. The concrete slab is C30 grade, reinforcement bar is HRB235, steel is Q235B hot-rolled H-section steel, all specified in GB 50017-2003(Chinese Code). The basic parameters of the testing pieces are shown in Tab. 1.

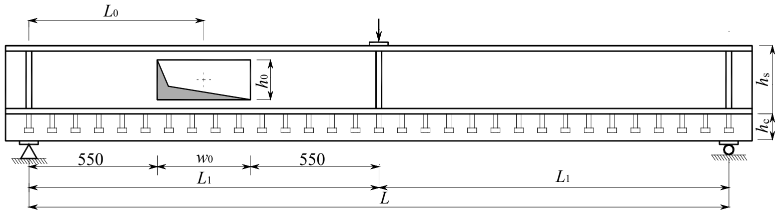


Figure 2 Geometrical sizes of specimen

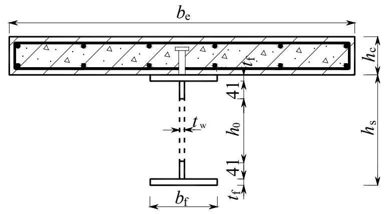


Figure 3 Cross-section of specimen

Table 1 Parameters of Composite beam specimens

No.	Steel section/mm ($h_s \times b_f \times t_w \times t_f$)	Span Length L/mm	Opening location L_0/mm	Load Position L_1/mm	Opening Size $w_0 \times h_0$	Concrete Slab/mm		Reinforcement radio（%）	
						h_c	b_e	Longitudinal	Transverse
CB-1	250×125×6×9	3000	—	1500	—	110	1000	0.8	0.5
CB-2	250×125×6×9	3000	750	1500	400×150	110	1000	0.8	0.5
CB-3	250×125×6×9	3000	750	1500	400×150	125	1000	0.8	0.5
CB-4	250×125×6×9	3000	750	1500	400×150	140	1000	0.8	0.5
CB-5	250×125×6×9	3000	750	1500	400×150	110	1000	1.2	0.5
CB-6	250×125×6×9	3000	750	1500	400×150	110	1000	1.6	0.5
CB-7	250×125×6×9	3000	750	1500	400×100	110	1000	0.8	0.5
CB-8	250×125×6×9	3000	750	1500	400×50	110	1000	0.8	0.5
CB-9	250×125×6×9	3000	750	1500	300×150	110	1000	0.8	0.5
CB-10	250×125×6×9	3000	750	1500	200×150	110	1000	0.8	0.5

* h_s is height of steel, b_f is width of flange, t_w is web thickness, t_f is flange thickness, h_c is slab thickness, b_e is slab width.

3 FINITE ELEMENT MODEL

3.1 Element Selection and Material Properties

In order to accurately calculate the composite beam with web opening under negative bending moment with nonlinear finite element, and correctly reflect its stress process, it has been selected the following element type and the corresponding material relationship:

(1) Concrete slab: concrete using SOLID65 element, a Three-Dimensional entity with eight Node points, and considering cracking and crushing of concrete. Concrete model is adopted multi-linear isotropic strengthening model (MISO). The failure criterion is the five-parameter failure criterion of Willan-Warnke. The constitutive relationship under uniaxial stress is based on Hognestad's [17] suggested stress--strain relation curve (Fig. 4). The ascending segment is a quadratic parabola and the descending segment is an oblique line. Its mathematical expression is shown in the Eq. (1).

$$\sigma = \begin{cases} f_c\left[2\dfrac{\varepsilon}{\varepsilon_0} - \left(\dfrac{\varepsilon}{\varepsilon_0}\right)^2\right], \ \varepsilon \le \varepsilon_0, \\ f_c\left(1 - 0.15\dfrac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0}\right), \ \varepsilon_0 < \varepsilon \le \varepsilon_u. \end{cases} \tag{1}$$

where f_c is the axial compression strength of concrete, ε_0 is the peak compressive strain of concrete, ε is the ultimate compressive strain of concrete.

(2) Steel: flange of steel beam adopts SOLID45 element, web plate of steel beam adopts PLANE42 element. The reinforcement bar adopts LINK8 element. Steel materials adopt multi-linear isotropic reinforcement model and use Von Mises yield criterion. Constitutive relationship selects simplified secondary plastic flow model [18], as shown in Fig. 5, where the stress-strain relationship is divided into elastic stage, yielding stage and strengthening stage. Its corresponding mathematical expression is as shown in Eq. (2).

$$\sigma = \begin{cases} E_s\varepsilon, 0 < \varepsilon < \varepsilon_y, \\ f_y, \varepsilon_y \le \varepsilon < \varepsilon_h, \\ f_y + E_s^{'}(\varepsilon - \varepsilon_h), \ \varepsilon \ge \varepsilon_h \end{cases} \tag{2}$$

where E_s is the elastic modulus of steel; E'_s is the reinforcement modulus and takes $0.01E_s$; f_y is the yield strength of steel; ε_y is the yield strain of steel; ε_h is the strain of reinforcement and takes $12\varepsilon_y$.

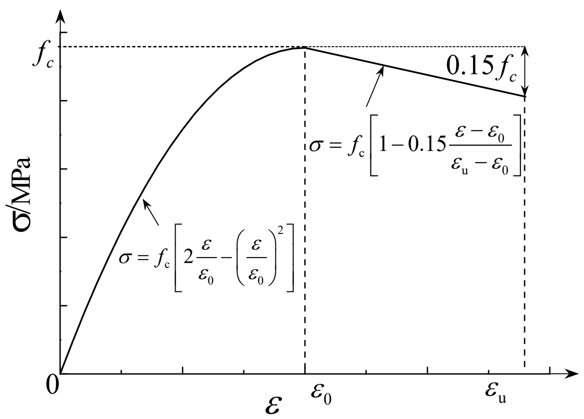


Figure 4 Constitutive law of concrete

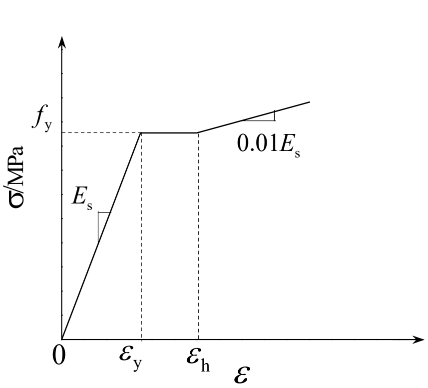


Figure 5 Constitutive law of steel

(3) Stud: in order to simulate vertical and horizontal slippage and vertical lift between concrete slab and steel beam, three orthogonal spring units COMBIN39 are used to simulate the studs. The load-slip relationship of the studs (Fig. 6), using Ollgaard [19], based on launch test is obtained by regression analysis of mathematical model, as shown in Eq. (3).

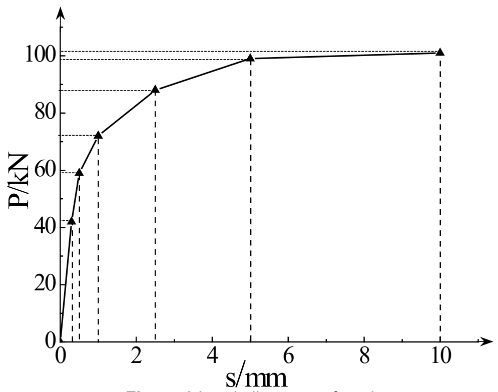


Figure 6 Load-slip curve of stud

$$\begin{cases} P_x = N_v^c(1-e^{-0.71 s_x})^{0.4}, \\ P_y = \dfrac{E_s A_{sd}}{L_s} s_y, \\ P_z = N_v^c(1-e^{-0.71 s_z})^{0.4}. \end{cases} \tag{3}$$

where s_x, s_y and s_z are relative slip values of x, y and z directions, A_{sd} is the cross-section area of the stud, L_s is the length of stud , N_v^c is the shear capacity of a single stud.

3.2 Modelling and Solving

Because of the symmetry of the structure, 1/2 model structure can be modelled and analysed. At the same time, the surrounding elements of the opening area are refined partially during the process of mesh generation. In order to avoid the difficulty of convergence caused by stress concentration, rigid plates and stiffeners are installed at the loading point and the bearing. The finite element model is shown in Fig. 7. Force loading method is used in finite element analysis, Von-Mises yield criterion and displacement convergence criterion, and Newton-Raphson equilibrium iteration method is used to solve nonlinear solution.

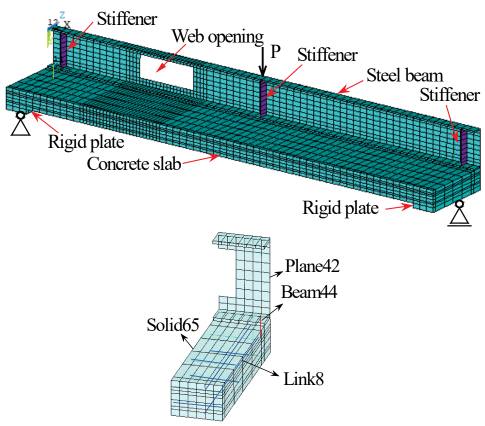


Figure 7 Finite element model

4 ANALYSIS OF CALCULATION RESULT

4.1 Variation of Concrete Slab Thickness

Changing the thickness of the concrete slab, the results are as shown in Fig. 8 when the reinforcement rate and the parameters of opening are unchanged. The results show that compared with web opening specimen CB-2 and without web opening specimen CB-1, bearing capacity is reduced by 46.5%, the deformation ability is reduced by 55%. It can be seen that the bearing capacity and deformation capacity of composite beams under negative bending moment are greatly reduced after web opening. Compared with CB-2, CB-3 and CB-4 of testing pieces, beam thickness increased by 15cm and 30cm respectively, its capacity increased 19.8% and 33.4% respectively, and deformation capacity increased only 2.4% and 6.9%. It can be seen that the shear capacity of concrete slab increases with the increase of slab thickness. Increasing the thickness of the concrete slab can improve the bearing capacity of the composite beam with web opening under negative bending moment, but it cannot improve the deformation ability effectively.

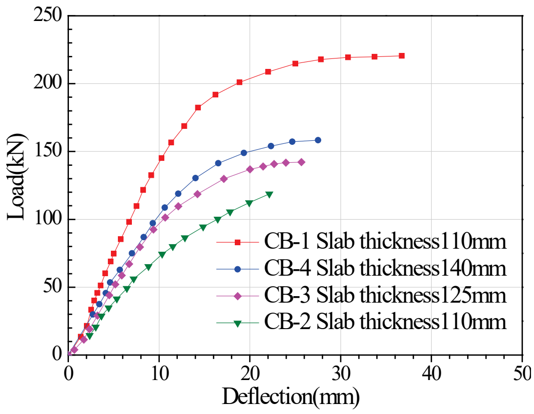


Figure 8 Variation of concrete slab thickness

4.2 Variation of Reinforcement Ratio

Changing the reinforcement ratio, the results are as shown in Fig. 9 when the thickness of the concrete slab and the parameters of opening are unchanged. The results show that compared with CB-2, CB-5 and CB-6 of testing pieces, the ratio of reinforcement increased 0.4% and 0.8% respectively, its capacity increased 4.9% and 9.1%, respectively, and the deformation capacity increased 24.3% and 40.2%. It can be seen that increasing the reinforcement ratio can greatly improve the deformation ability of composite beam with web opening under negative bending moment, but the increase of its bearing capacity is small. The main reason is that the failure of the composite beam after web opening is controlled by the section strength at the four corners of the opening. The secondary bending moment of the upper and lower section on the left side of the opening is positive bending moment, and the secondary bending moment of the upper and lower section on the right side of the opening is negative bending moment. It can be seen from Fig. 10. Only the steel bar located at the bottom of the concrete slab on the right of the opening can play a more effective role.

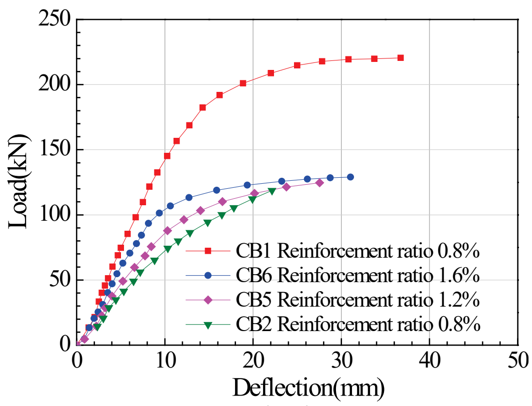
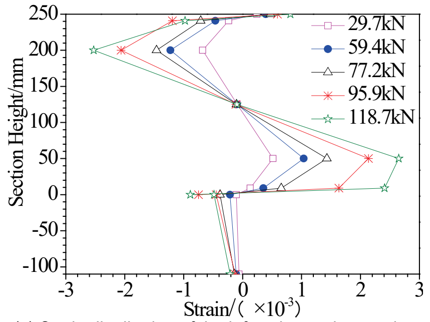
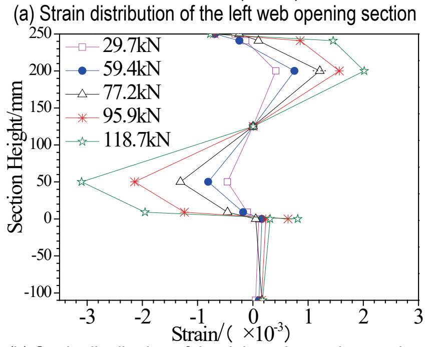


Figure 9 Variation of reinforcement ratio



(a) Strain distribution of the left web opening section



(b) Strain distribution of the right web opening section

Figure 10 Strain distributions of opening section for CB-2

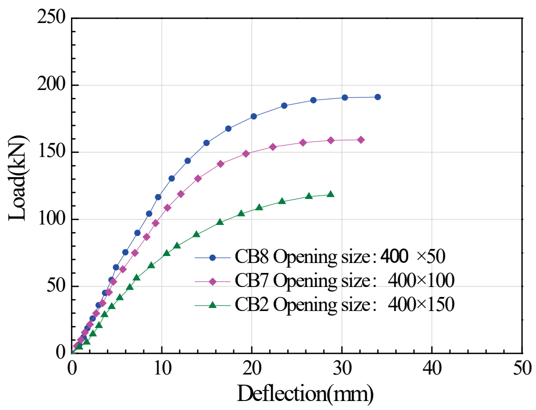


Figure 11 Variation of opening height

4.3 Variation of Opening Height

Change the height of opening from 150 mm to 100 mm and 50 mm. The results are as shown in Fig. 11 when the thickness of the slab and the reinforcement rate are unchanged. The results show that: the testing pieces CB-7 and CB-8 are compared with CB-2 when the width of the opening is the same and the height decreases 50mm in turn, the carrying capacity increased by 24.0% and 39.2% respectively, the deformation capacity increased by 11.6% and 18.2%. It can be seen that with the decrease of the opening height, the bearing capacity of the composite beam with web openings under negative bending moment will increase and the deformation capacity has also improved, but it has limited scope.

4.4 Variation of Opening Width

Change the width of opening from 400 mm to 300 mm and 200 mm. The results are as shown in Fig. 12 when the thickness of the slab and the reinforcement rate are unchanged. The results show that: the testing pieces CB-9 and CB-10 are compared with CB-2 when the width of opening is the same and the height decreases 100mm in turn, the carrying capacity increased by 16.4% and 45.2% respectively, and the deformation capacity increased by 27.4% and 39.3%. With the decrease of opening width, the bearing capacity of the composite beam with web openings under negative bending moment will increase and the deformation capacity has also improved. When the opening width is reduced to 200 mm, the bearing capacity and the deformation capacity of testing piece CB-10 are greatly improved.

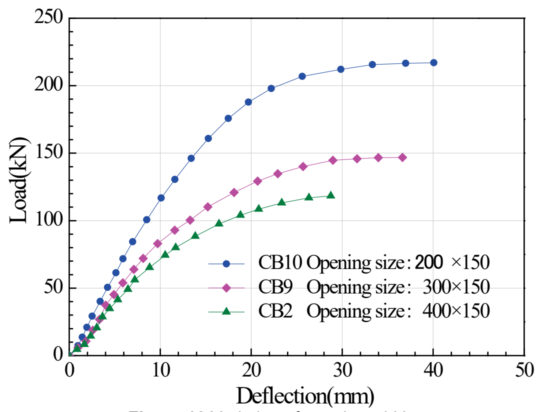


Figure 12 Variation of opening width

4.5 Analysis of Shearing Behaviour

Through finite element analysis and calculation, it is obtained the shear force of each part of the composite beam with web opening under negative bending moment under the ultimate state. The shear force values of corresponding sections of each testing piece are shown in Tab. 2.

Table 2 Shear force of partial section at web opening region

No.	P_u	V	V_c	V_t	V_b	V_c/V	V_t/V	V_b/V
CB-1	219.6	109.8	28.7	81.1	—	26.1%	73.9%	—
CB-2	118.7	52.35	43.7	6.60	2.1	83.5%	12.4%	4.1%
CB-3	142.2	67.10	57.2	6.76	3.1	85.2%	10.1%	4.7%
CB-4	158.3	76.15	68.4	5.41	2.7	89.3%	7.10%	3.6%
CB-5	124.6	56.30	47.4	6.31	2.6	84.2%	11.2%	4.6%
CB-6	128.9	59.45	50.8	6.77	1.8	85.6%	11.4%	3.0%
CB-7	147.3	67.6	44.1	13.8	9.7	65.3%	20.5%	14.2%
CB-8	165.2	75.7	45.2	17.3	13.2	59.7%	22.9%	17.4%
CB-9	138.2	63.1.	48.1	8.39	6.6	76.3%	13.3%	10.4%
CB-10	172.5	79.2	55.8	13.5	9.9	70.5%	17.0%	12.5%

*P_u is ultimate load, which is obtained from load-deflection curve; V is total shear force; V_c is shear force of concrete slab; V_t is shear force above the opening; V_b is shear force below the opening.

The calculation results in Tab. 2 show that: for the non-opening composite beam CB-1, the steel beam bears 73.9% of the total shear force of the section, and the concrete slab bears 26.1%. It can be seen that steel beam is bearing a large part of the shear force on the cross section of the non-opening composite beam, and concrete slab has also made significant contributions to shear resistance.

For the composite beam with web opening under negative bending moment (CB-2~CB-10), Tab. 2 results show that:

(1) The shear force of the concrete slab above the opening can reach 59.7-89.3% of the total shear force of the section. It can be seen that the existing relevant codes [20, 21] do not take into account the contribution of concrete slab to the shear capacity, which is quite conservative and the strength of the material is not fully utilized.

(2) When the thickness of concrete slab is the variation parameter（CB-2, CB-3 and CB-4), the shear force of the concrete slab above the opening can reach 83.5-89.3% of the total shear force of the section. It can be seen that the shear force of concrete increases with the increase of slab thickness and the shear capacity of composite beams is also greater.

(3) When the ratio of reinforcement is the variable parameter（CB-2, CB-5 and CB-6）, the shear force of the concrete slab above the opening bears 83.5-85.6% of the total shear force of the section. It can be seen that with the increase of reinforcement ratio, the shear force of concrete slab will increase, but the increase is smaller, the shear capacity of composite beams with web opening under negative bending moment cannot be improved effectively.

(4) When the height of opening is the variation parameter (CB-2, CB-7 and CB-7), the shear force of the concrete slab above the opening bears 59.7-83.5% of the total shear force of the section, it can be seen that as the height of opening decreases, the shear force of the concrete slab will decrease. The reason is that with the height of opening decreasing, the remaining web area increases correspondingly, and the shear force of steel beam will increase relatively.

(5) When the width of the hole opening is taken as the variation parameter, the composite beams CB-2, CB-9 and CB-10 above the opening bear 70.5-83.5% of the total shear force of the section. It can be seen that the shear force of concrete slabs decreases with the decrease of opening width, but the shear force of steel beam increases correspondingly.

Fig. 13 shows the shear distribution of the concrete slab and the steel beam at different loading stages along the length direction of the composite beam without or with web opening under negative bending moment. As seen in Fig. 13(a): in the negative bending moment area, the shear increase of the concrete slab is obviously smaller than that of the steel beam under the same load step. The shear force of steel beam is greater than that of concrete slab at any load stage. When P_u load is reached, the steel beam bears 73.9% of the total shear force. In the load section of $0.75P_u$~P_u, the shear force undertaken by concrete slab increases the fastest and the shear force undertaken by steel beams grows more slowly. It shows that with the development of plasticity, the vertical shear redistribution between concrete slab and steel beam occurs.

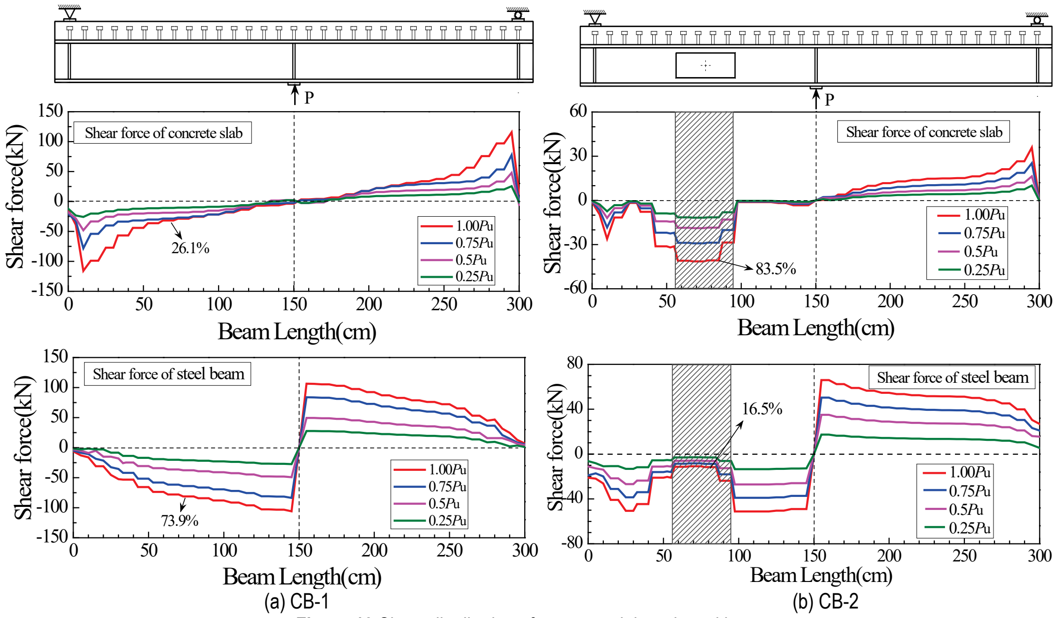


Figure 13 Shear distribution of concrete slab and steel beam

As seen in Fig. 13(b): in the opening area, the shear force undertaken by concrete slab increases with the increase of load, while the shear undertaken by steel beam increases very little. When the P_u load is reached, the concrete plate bears 83.5% of the total shear force in the opening area. In the part of the composite beam outside the opening area, the steel beam still bears most of the shear force. At the load section of $0.5P_u$~P_u, the shear undertaken by steel beams in the opening area basically did not increase, while the shear undertaken by concrete plates increased significantly. The reason is that the four corners of the opening yield because of the stress concentration, and gradually formed the plastic hinge and caused the vertical shear redistribution.

5 CONCLUSION

The following conclusions are obtained by nonlinear finite element analysis of composite beam with web opening under negative bending moment.

(1) Under the action of negative bending moment, the rigidity, bearing capacity and deformation capacity of composite beams are significantly decreased after the web opening.

(2) The shear capacity of composite beam with web opening under negative bending moment can be improved to a certain extent by increasing the thickness of concrete slab, but its deformation capacity does not increase significantly. Increasing the reinforcement ratio can obviously improve the deformation ability of the composite beam with web opening under negative bending moment, but the shear capacity cannot be improved effectively.

(3) With the decreasing of the height or width of the opening, the shear capacity and the deformation capacity of composite beam with web opening under negative bending moment are increased. It is discovered by comparing that the increase of bearing capacity and the deformation capacity after width reduction is greater than that after height reduction. It shows that the influence of width changing on shear capacity of composite beam with web openings under negative bending moment is greater than that of height changing.

(4) Because the opening weakens the cross section of the web, the concrete slab above the opening under negative bending moment bears most of the shear force in the section of the opening area, and the total shear force of cross section is 83.5-89.3%. It shows that the concrete slab has a great contribution to the shear capacity of composite beam with web opening under negative bending moment.

(5) Within the load range of $0.75P_u$~P_u, with the development of plasticity, the vertical shear redistribution between concrete slab and steel beam appears in the non-opening composite beam under negative bending moment. Within the load range of $0.5P_u$~P_u, the four corners of the opening under negative bending moments yield due to stress concentration, gradually form plastic hinge, and cause the vertical shear redistribution.

Acknowledgements

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