Steel and Composite Structures, *Vol. 20, No. 6 (2016) 1183-1191*
DOI: http://dx.doi.org/10.12989/scs.2016.20.6.1183

Investigation on the failure mechanism of steel-concrete steel composite beam

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(*Received April 15, 2015, Revised December 21, 2015, Accepted October 21, 2015*)

Abstract. The internal crack propagation, the failure mode and ultimate load bearing capacity of the steel-concrete-steel composite beam under the four-point-bend loading is investigated by the numerical simulation. The results of load - displacement curve and failure mode are in good agreement with experiment. In order to study the failure mechanism, the composite beam has been modeled, which part interface interaction between steel and concrete is considered. The results indicate that there are two failure modes: (a) When the strength of the interface is lower than that of the concrete, failure happens at the interface of steel and concrete; (b) When the strength of the interface is higher than that of the concrete, the failure modes is cohesion failure, i.e., and concrete are stripped because of the shear cracks at concrete edge.

Keywords: steel-concrete-steel composite beam; interface; crack propagation; failure mode; ultimate bearing capacity

1. Introduction

The steel-concrete-steel composite beam is a new structure that concrete is casted between two pieces of steel. To make the steel and the concrete becoming an integrated component, the enough strength and stiffness of shear connection are necessary to insure no horizontal sliding and vertical lifting between the joint of the steel and the concrete. This joint is called rigid connection. Another joint called flexible connection allows the sliding to happen between steel and concrete because of the deformation of itself, e.g., weld screws. No joint means no connection. So there are three types of composite beams (Bowerman *et al*. 2002) as a result of the connection pattern, i.e., the full interaction composite beam, part interaction and no interaction.

Some experiments and numerical simulation (Xie and Chapman 2006, Foundoukos *et al*. 2007, Richard Liew and Sohel 2009, Dai and Richard Liew 2010, Foundoukos and Chapman 2008, Hang 2011, Subedi and Coyle 2002, Oduyemi and Wright 1989, Xie *et al*. 2007, Shanmugam *et al*. 2002) have been performed to study the failure mode and ultimate load bearing capacity of the composite beams for different thickness of steel and space between the joints. The results indicate that the interface strength has much influence on the stripping between the steel and concrete. To enhance the strength, the shear joints are welded on the steel plates, or the steel plates are processed to increase the roughness of interfaces (Subedi and Coyle 2002).

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http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

In order to study the influence of interface strength on the failure mode steel-concrete-steel composite beam and failure mechanism leading to final failure of composite beam, here we study the steel, the interface, the microscopic structure of concrete material by experiment and the numerical model to simulate the failure progress. The interfaces between steel and concrete are defined as the numerical model, though the numerical simulation of the failure progress and failure mode, it is a further understanding for the failure mechanism of composite beam.

2. Numerical simulation method

In the numerical simulation, the non-uniformity property of concrete is considered and the macro failure the process of materials is the accumulation of micro-element failure. From the microscopic point of view, the element of concrete is regarded as uniform and continuous, yet the mechanical properties (Young modulus, strength and Poisson ratio etc.) of the element may be different. The element that contains defect can perform a large dispersion. Here, the dispersion would be described by Weibull distribution. The elements consist of concrete are the finite analysis elements. When the stress meets the maximum tensile stress criterion or Mohr Coulomb failure criterion, the element begins to damage and damage evolution process of failure element with deformation would comply with residual strength criteria. Failure element is described by weakening and degeneration of the Young modulus and strength. In the simulation of quasi-static loading process, external load is applied step by step. In one loading step, using the finite element analysis, the stress and strain distribution of the whole analysis object can be obtained. Then, it is judged that the element is damaged by the maximum tensile stress criterion and Mohr Coulomb failure criterion. For the failure element, Young modulus and other mechanical parameters are decreased gradually according to the residual strength criteria. After entering the analysis of the next loading step, it continues until the end of entire analysis procedure[12-13]. The method not only can obtain the displacement and stress field under each loading step, but also can observe the whole rupture process including the crack initiation, propagation and through the entire structure by realistic graphics display.

3. Model of the full interaction steel-concrete-steel composite beam

According to No.SCS-1 specimen from reference (Hang 2011), the numerical model is built to validate the reliability of the method. As can be seen in Fig. 1, regardless of the interface between the steel and the concrete, the steel-concrete-steel composite beam is considered as the full

Table 1 Weibull distribution parameters of steel plate and concrete materials

Mechanical properties	Concrete	Steel
Mean degree (m)	3	100
Young's modulus E_0 (GPa)	35.6	206
Compressive strength σ_0 (MPa)	146	375
Poisson's ratio μ	0.2	0.3
Tension compression ratio	10	1
Residual strength factor	0.3	1

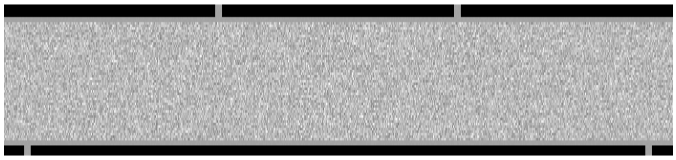


Fig. 1 The numerical model of steel-concrete-steel composite beam

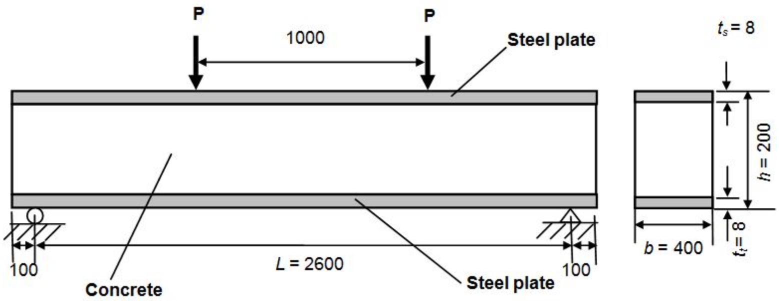


Fig. 2 Dimension of composite beam and loading condition

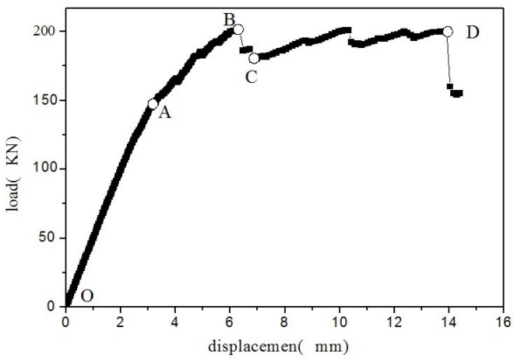
interaction composite beam made up steel and concrete. Different material elements as the steel and concrete are employed in finite element model. The specimen is divided into 50 × 700 = 35000 equal-area quadrate elements, thickness is 400 mm. The loading pattern is the step by step loading method of displacement controlled, the model is simplified to plane stress issues. Fig. 2 shows geometry and loading pattern.

The mechanical properties of steel and concrete are random under the condition of mean degree and average value given. Table 1 shows Young's modulus and Weibull distribution parameter of strength.

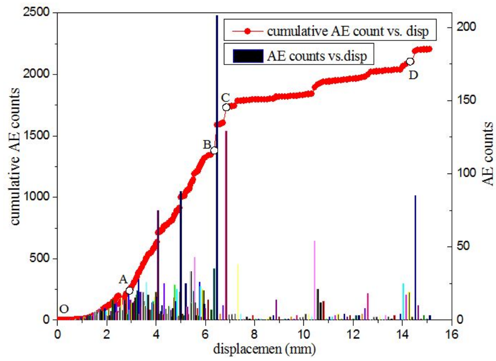
4. Analysis the failure mechanism of full interaction steel-concrete-steel composite beam

Considering the connection of steel and concrete, layer elements between steel are defined with different strength in numerical simulation. Fig. 3 shows the loading- displacement curve of steel-concrete-steel composite beam, acoustic emission (AE) curve, the simulation result of failure process and the experiment result of the failure mode.

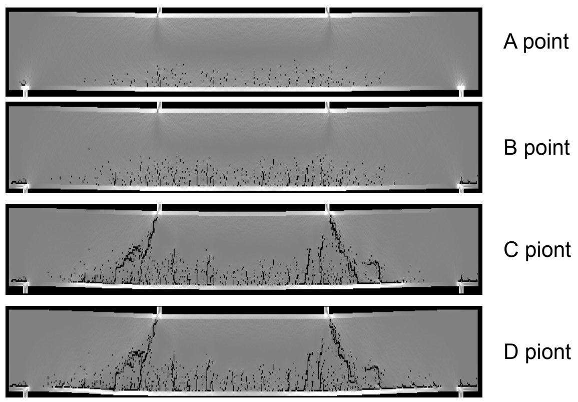
The loading-displacement curve from Fig. 3(a) can be seen three stages: elastic (OA), inelastic (AB) and yield stage (BD). In the elastic stage, the steel plate and the concrete occurs elastic deformation. In the tensile area of the concrete between the two points loading, the low strength elements of concrete are broken, as can be seen in Fig. 3(c) A point, From Fig. 3(b), OA stage, AE signal is weaker; With the loading increasing, more and more concrete elements are broken to develop the micro cracks, as Fig. 3(c) B point, the load - displacement curve continues to rise nonlinearly into inelastic stage. From Fig. 3(b), AB stage, the AE signal is enhanced. When the main crack at left loading point runs through the whole section of steel-concrete-steel composite beam, there is a main crack generating at the right loading point and then the crack runs through the whole section of composite beam quickly, we can see it from Fig. 3(c), C point. Due to instable propagation of crack, the AE signal is enhanced (Fig. 3(c), BC stage),there are two continuous small amplitude declines on the loading-displacement curve, however, bearing capacity of composite beam is still strong; While the yield stage coming, the cracks of concrete keep on propagating, steel plate and concrete start stripping from the origin of the main cracks to the end of beam, and there are many tiny shear crack, the loading - displacement curve presents more than one small amplitude downward trend, and the AE curve shows small rising trend .Because of the failure of the concrete tensile area, the steel plate act the important load-bearing role, it still has ability of deformation. When the down steel plate begin to raise vertically and stripping with the concrete (as can be seen Fig. 3(c), D point), the composite beam is damaged completely, the loading- displacement curve declines rapidly.



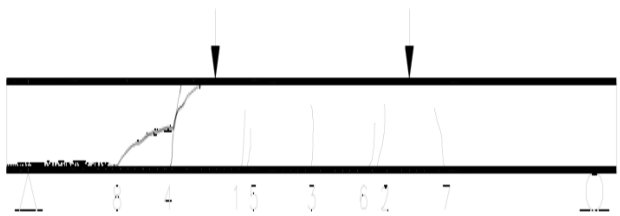
(a) Loading-displacement curve



(b) Acoustic emission (AE) curve



(c) Failure mode of the A, B, C and D point corresponding loading- displacement curved



(d) Experiment result of failure mode

Fig. 3 Failure process of composition beam and experimental result

Table 2 The contrast of ultimate bearing capacity

Experiment result (KN)	Simulation result (KN)	Deviation (%)
186	201	8.06

The simulated result is in good agreement with the experimental result. Comparing Fig. 3(c) with Fig. 3(d). There are a lot of cracks between two loading points in the tensile area of concrete, but they don't run through the whole section of steel-concrete-steel composite beam. On both out sides of the two loading points, there are two shear cracks running through the whole section of composite beam, the steel plates are raised and stripped with concrete.

Table 2 shows the ultimate bearing capacity result of experiment and simulation, they are 186 KN and 201 KN respectively. For steel-concrete-steel composite beam, low strength interface exists between steel and concrete. The shear force is transmitted by shear connectors. Thus, the interface slip produces between steel and concrete, it limit ultimate load bearing capacity of composite beams. In this paper, the numerical model (Fig. 1) is calculated without low strength interface between steel and concrete. So the simulation result is more than experimental result. The deviation of experiment and simulation is 8.06%. The simulated results are in agreement with the experimental result.

5. Model of the part interaction steel-concrete-steel composite beam

In order to study the influence of the interface on the failure mode of steel-concrete-steel composite beam, the numerical model of part interaction composite beam is built, considering the interface of steel and concrete. The mechanical properties are listed in Table 3, and the model is plotted in Fig. 4.

Table 3 The contrast of ultimate bearing capacity

Mechanical properties	Steel	Concrete	Interface
Mean degree *m*	100	3	3
Young's modulus E_0 (GPa)	206	35.6	20
Tensile yield strength σ_0 (MPa)	375	146	100, 120, 160

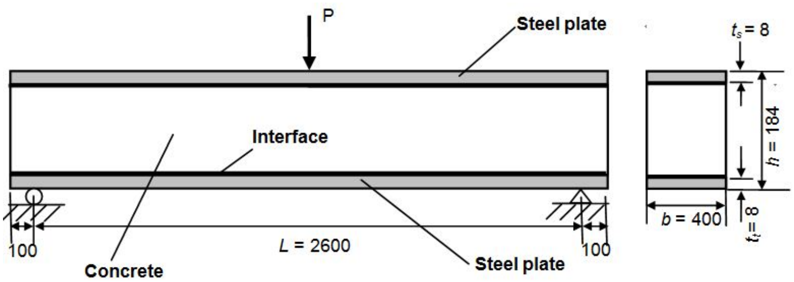
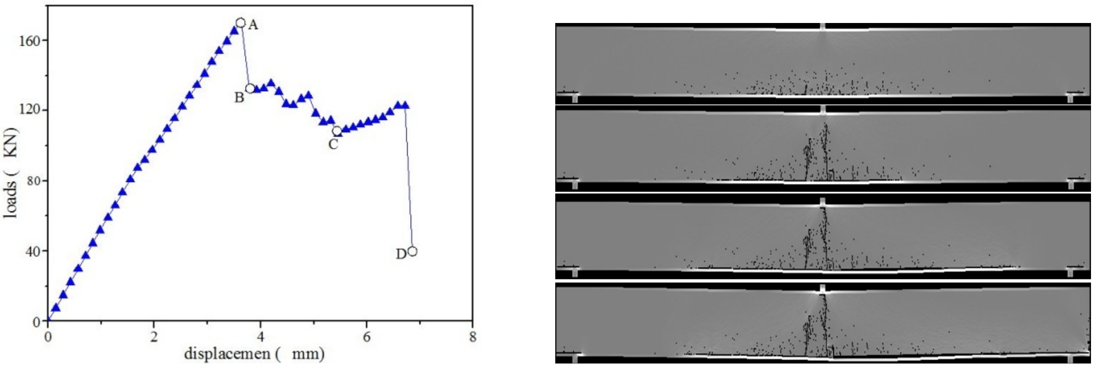


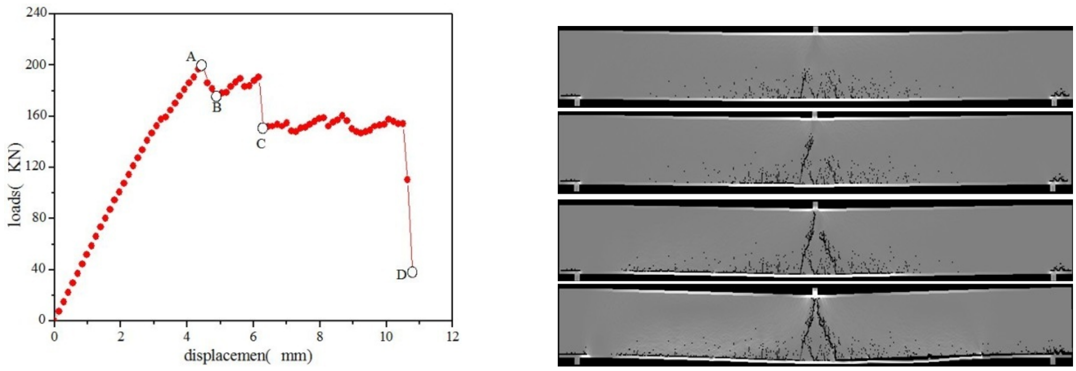
Fig. 4 Calculation model

6. Analysis the failure mechanism of part interaction steel-concrete-steel composite beam

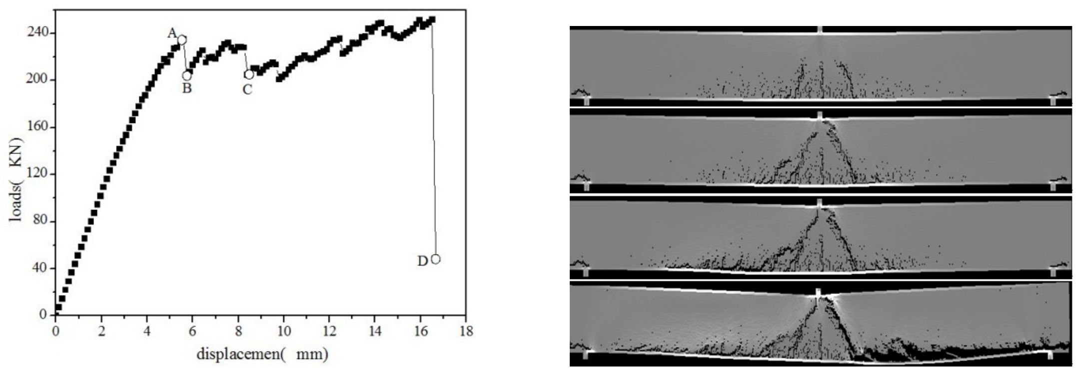
Fig. 5 shows the failure processes of the different interface strength. From Fig. 5, there are two failure modes: one is the stripping failure, when the interface strength is lower than the concrete, as Figs. 5(a) and (b); another is the cohesion failure, when the strength of the interface is higher, as Fig. 5(c).



(a) Average interface strength 100 MPa



(b) Average interface strength 120 MPa



(c) Average interface strength 160 MPa

Fig. 5 The composition of failure mode

When the first failure mode, the crack appears on the interface layer creates at midspan of steel-concrete-steel composite beam. When reaching the peak of the loading-displacement curve, the crack of concrete propagates rapidly to cross the whole section, the crack of interface layer ranges from the midspan to the end of the composite beam, the curve presents a small amplitude downward trend, the steel is stripping incompletely with concrete, bearing capacity of composite beam is still strong, and then the yield stage coming. When the crack propagation of interface layer reaches the end of beam, the steel plates are raised and stripped with concrete. The failure mode is the stripping failure of interface between steel plates and concrete.

The second, as Fig. 5(c), the crack of the concrete in the tensile area begins to appear. When reaching the peak of the loading-displacement curve, the crack of concrete propagates rapidly to cross the whole section, Meanwhile, the concrete is damaged because that the down edge of concrete occurs a lot of shear cracks from midspan to the end of the beam, and the steel plate is stripped with the down edge of concrete, bearing capacity of composite beam is still strong, and then the yield stage coming. When the down edge of steel plate of composite beam is damaged completely and the steel plates are raised and stripped with concrete, with phenomenon that the fragment of concrete dropping at the compression area, the cohesion failure of the beam happens.

Fig. 6 shows the loading-displacement curve of the different interface strength. In the beginning, three curves are coincident, when reaching the A point, three curves start separating. Comparing with the three curves, there are some conclusions: At the elastic stage, under the same loading, the relative minimum deformation happened when interface strength 160 Mpa, moreover, the relative maximum deformation is 100 MPa. When reaching the ultimate bearing capacity, the steel-concrete-steel composite beam still has a better ability of bearing capacity. The loading-displacement curve has a bit downtrend to reach the yield stage, the beam is good malleability. Ultimate bearing capacity of composite beam is enhanced with increasing interface strength, when the 100 MPa interface strength, the ultimate bearing capacity of the composite beams is 178 KN, when the 160 MPa interface strength, the ultimate bearing capacity of beam is 256 KN, up 43.82%. The plastic deformation increases with the enhanced interface strength. For the low interface strength of composite beams, belongs to low share connection, its bearing capacity and malleability is relative low, due to the stripping too early between the steel and the concrete, the tensile yield strength of steel does not work completely; For the high interface strength of the

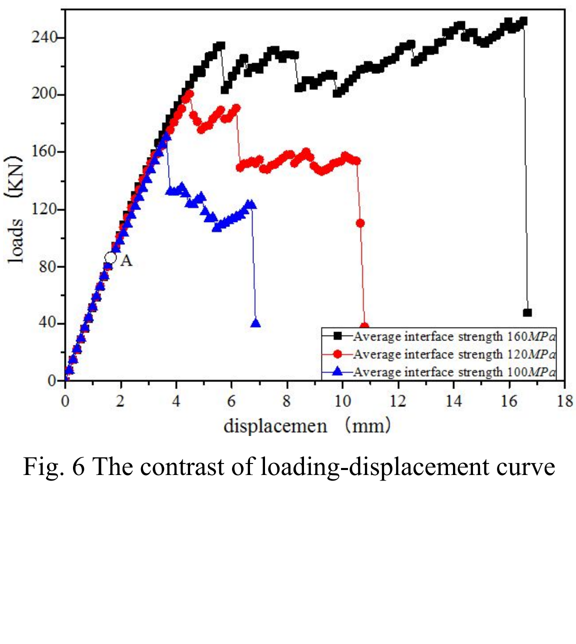


Fig. 6 The contrast of loading-displacement curve

composite beams, belongings to the high share connection, the steel plate happens cohesion failure with the concrete, its bearing capacity and malleability is relative higher, the tensile yield strength of steel can work completely.

7. Conclusions

Through numerical simulation, the full and part interaction steel-concrete-steel composite beam are studied. And some significant results obtained from the present work are summarized. The numerical model is built to study the failure process and failure mechanism of steel-concrete-steel composite beam. The simulated results are in agreement with the experimental result. When the strength of the interface is lower than that of the concrete, the failure happen at the interface layer of the steel and the concrete, failure mode is the stripping failure. When the strength of the interface is higher than that of concrete, the steel and the concrete are stripped because of the shear cracks at down edge of concrete, the failure modes is cohesion failure. The loading-displacement curve of steel-concrete-steel composite beam can be divided into three stages, i.e., elastic, inelastic and yield stage. The curve presents a small amplitude downward trend, and then into yield stage, bearing capacity of steel-concrete-steel composite beam is still good. Comparing the loading - displacement curves of different interface strength, the ultimate load bearing capacity, deformation and the malleability of steel-concrete-steel composite beam will be better with the enhanced interface strength.

Acknowledgments

The authors gratefully acknowledge the financial support of this study by the National Natural Science Foundation of Heilongjiang (No. KY10200150016).

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