Steel and Composite Structures, *Vol. 21, No. 5 (2016) 981-997*
DOI: http://dx.doi.org/10.12989/scs.2016.21.5.981

Cracking of a prefabricated steel truss-concrete composite beam with pre-embedded shear studs under hogging moment

Yanmei Gao [1,2a], Zhixiang Zhou [1,2b], Dong Liu [2] and Yinhui Wang [*3]

[1] *State Key Laboratory Cultivation Base of Mountain Bridge and Tunnel Engineering, Chongqing Jiaotong University, 400074, China*
[2] *College of Civil Engineering, Chongqing Jiaotong University, 400074, China*
[3] *Ningbo Institute of Technology, Zhejiang University, School of Civil Engineering and Architecture, 315100, China*

(*Received October 09, 2015, Revised March 06, 2016, Accepted July 02, 2016*)

Abstract. To avoid the cracks of cast-in-place concrete in shear pockets and seams in the traditional composite beam with precast decks, this paper proposed a new type of prefabricated steel truss-concrete composite beam (ab. PSTC beam) with pre-embedded shear studs (ab. PSS connector). To study the initial cracking load of concrete deck, the development and distribution laws of the cracks, 3 PSTC beams were tested under hogging moment. And the crack behavior of the deck was compared with traditional precast composite beam, which was assembled by shear pockets and cast-in-place joints. Results show that: (i) the initial crack appears on the deck, thus avoid the appearance of the cracks in the traditional shear pockets; (ii) the crack of the seam appears later than that of the deck, which verifies the reliability of epoxy cement mortar seam, thus solves the complex structure and easily crack behavior of the traditional cast-in-place joints; (iii) the development and the distribution laws of the cracks in PSTC beam are different from the conventional composite beam. Therefore, in the deduction of crack calculation theory, all the above factors should be considered.

Keywords: Prefabricated Steel Truss-Concrete Composite Beam (PSTC beam); precast deck; Pre-embedded Shear Studs (PSS Connector); epoxy cement mortar seam; deck crack test

1. Introduction

In order to reduce the work of concrete cast-in-place, speed up the construction progress, improve the quality of the construction, solve the shrinkage and creep problem of concrete cast-in-place, or make the replacement of the deteriorated concrete deck on the composite beam bridge more convenient, researchers have conducted a series of experimental and theoretical studies on the working performance of the composite beam with precast decks under hogging moment (El-Lobody and Lam 2002, Shim and Chang 2003, Ryu and Shim 2004, Ryu and Chang 2005, Nie *et al*. 2011, Chaudhary *et al*. 2009, Ryu 2010, Badie *et al*. 2011, Su *et al*. 2012a, b, Sun *et al*. 2014, Joergensen and Hoang 2013, 2015, Joergensen 2014), and the results have been widely applied to

∗Corresponding author, Ph.D., E-mail: wangyh7244@nit.zju.edu.cn
[a] Ph.D. Student, Lecturer, E-mail: lg2346@163.com
[b] Ph.D., E-mail: zhixiangzhou@cqjtu.edu.cn

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

some composite bridges (Ju *et al*. 2009, Shim *et al*. 2010) both at home and abroad.

Nie *et al*. (2011) has conducted comparative tests on two kinds of composite beams, i.e., one with full-depth precast decks, the other combined with full-depth precast decks, the other combined with half-depth precast decks and concrete cast-in-place. Results showed that their mechanical behaviors under positive moment are nearly the same, whereas under negative moment are significantly different. When the precast reinforced concrete deck of composite beams cracked, the crack width cannot be availably controlled, the section stiffness decreases dramatically, and then reaches the ultimate strength shortly.

Sun *et al*. (2014) conducted tests on the concrete crack resistance of composite beams. They proved that the prestress could improve the crack resistance of composite beam in the hogging moment region effectively though it was not aimed at the composite beam with precast decks.

Analytical and experimental studies were performed by Shim and Chang (2003) for precast pre stressed decks composite beams with shear pockets and female-to-female epoxy mortar joints. The result shows that the longitudinal prestress can effectively prevent the emergence of cracks in the deck joint under hogging moment. The cracks in the deck are firstly appeared around the shear pockets, and they appeared earlier than the deck joints, which indicated that the crack resistance was not weaker than the decks cast-in-place if the joints are carefully designed.

In order to explore the control of the cracks of prefabricated decks with shear pockets and overlap of loops joints between decks. A two-span continuous composite beam was tested by Ryu and Shim (2004), and a simple support composite beam was tested by Ryu and Chang (2005).The result shows the initial crack of the concrete deck emerged nearby the overlap of loops joints and shear pockets, which suggested that the structure of overlap of loops joints should be strengthened and cleaned clearly.

Su *et al*. (2012a, b) conducted the experiments of continuous composite beam with precast prestressed concrete deck, and the results verified that the efficiency of prestress and the cracking moment increased significantly by using precast prestressed concrete deck in the hogging moment regions. The initial concrete cracking load and serviceability limit state load are 3.16 times and 2.61 times than those of common continuous composite girder respectively. Besides, our research team (Xiang and Zhou 2012) did a variety of experiments and theoretical analysis on steel box-precast prestressed concrete decks composite beam with shear pockets, the mechanical behavior and analytical theory during the loading process are established. It has been concluded that the initial crack occurs mainly around the shear pockets.

Tests and theoretical work of loop connections were conducted by Joergensen (Joergensen and Hoang 2013, 2015, Joergensen 2014) for precast composite beam. The results show that the overlapping length of the U-bars, the spacing between adjacent U-bars and the amount of transverse reinforcement would influence the ultimate load of precast composite beam. A load-carrying capacity was obtained that was governed by yielding of the looped reinforcing bars (i.e., the U-bars) but not by fracture of the joint concrete.

Previous studies were mainly based on the composite beams with precast prestressed concrete deck, while the structure is constituted with shear pockets and cast-in-place joints between decks. The results proved that prestress and cast-in-place joints are comparatively effective. The ultimate strength of such kind of composite beam is no less than that of normal composite beam and with higher initial cracking load. It has also proved that it’s feasible that the steel beam and precast concrete deck are connected by shear connectors to carry load together for composite beam. However, the initial crack of this composite beam usually appears at the corners of shear pockets, which becomes a weak part and therefore influences the durability of the structure. The reason mainly lies in the fact that the remained pre stress in shear pockets is few and the local stress is concentrated. In some experiments, the initial crack appears on the joints between decks, which is closely related to the quality of joints and whether the prestress of decks is sufficient. The authors hold that female-to-female epoxy mortar joints or overlap of loops joints between decks make the structure more complicated, which leads to age difference of concrete between precast deck and cast-in-place joints.

Researchers have conducted some experimental and theoretical studies, in order to reduce the work of concrete cast-in-place, simplify the structure of joints, and reduce the crack caused by age difference between the precast deck and shear pockets or cast-in-place joints. Aimed at the steel-precast decks composite beam with through-bolt shear connectors, static push tests have been performed by Chen *et al*. (2014). The results showed that the ultimate shear loads are achieved with through-bolts similar to those observed for conventional shear studs. At the same time, Papastergiou and Lebet (2014) conducted the fatigue and static experiment on the composite beam with an innovative shear connection by adhesion, interlocking and friction. The interfaces include a steel-cement grout interface and a rough concrete-cement grout interface. The results showed that the damage on such type of connections was expressed by the development of a small residual slip in the interface that adopted the appropriate design stabilize with the number of cycles. Finally the composite beam was statically loaded up to failure since it had subjected to cyclic loading and did not present apparent damage after five million cycles. However, the preceding researchers focused on the working performance of the new sheer connector, while few attentions were paid on the structure behavior of this kind of composite beam.

On the basis of the existing study, this paper put forward a kind of prefabricated steel truss-concrete (PSTC) composite beam (Fig. 1), aiming to achieve a new kind of shear connection between precast deck and steel truss chord without cast-in-place concrete. It proposed a new way that pre-embed shear studs (PSS connector) into precast concrete deck firstly, then weld the steel truss and concrete deck together by PSS connector.

The assembling process of PSTC composite beam are as follows: (i) shear connectors is embedded in the concrete deck before it is precast. At the same time, the steel truss is constructed;

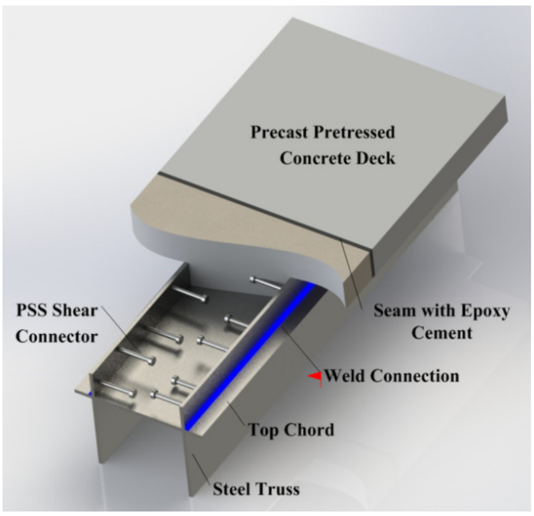


Fig. 1 Prefabricated steel truss-concrete composite beam

(ii) the precast concrete decks are installed on the steel truss; (iii) the epoxy cement mortar is smeared in the joints between decks, and then (iv) prestress steel tensions, finally (v) connect the precast concrete deck with the steel truss chord by welding ultimately. There have no need for cast-in-place joints between decks and no need for shear pockets either.

There has been no study on the mechanical and structural behavior of Prefabricated Steel Truss-Concrete (PSTC in short) Composite Beam with PSS connectors. Therefore, 3 PSTC composite beams with PSS connector and epoxy mortar joint are manufactured to explore the crack resistance under hogging moment. The prestress degrees of the 3 specimens are different. Under different load, the crack occurrence, crack development, crack space and crack width of PSTC composite beams, and the working performance of PSS connector in PSTC composite beams are studied in the experiment.

2. Experimental works

2.1 Test specimens

In Figs. 2 and 3, the parameters of the specimens named as PSTC-1, PSTC-2 and PSTC-3 are as follows: (i) the total length is 7160 mm; (ii) the calculation span is 7000 mm; (iii) the total height is 770 mm; (iv) the height of steel truss is 630 mm; (v) the upper and lower chords of steel truss are made of "Π" section, while the slant rod and the vertical stick are made of "[" section. In order to save the costs, the steel truss of the specimen is planned to use circularly. After each test, the concrete decks are demolished and the steel truss is remained. If the steel truss members show obvious change of mechanical behavior or deformation, they are replaced with new members before the next test.

The section of dwarf ribbed deck type is applied to the concrete deck, with the height of 140 mm and top width of 500 mm. The decks are divided into seven blocks to be prefabricated independently, and the standard length is 1000 mm per block. There are 5 post-tensioned straight pre stressed tendons through all the decks longitudinally (Figs. 3(a), (d), (e)). The effective pre-stress of PSTC-1, PSTC-2 and PSTC-3 are 10.6 MPa, 12.2 MPa and 12.6 MPa, respectively. Layout of reinforcement of per precast deck, as shown in Figs. 3(a)-(c), (e): the diameters of the longitudinal reinforcement are Φ8 and Φ6, and the diameter of the transverse reinforcement is Φ6, just being constructional reinforcement.

PSS connector, a new type of shear connector, is proposed by our research team on the basis of existing research, and the push test for this kind of connector has been conducted (Li *et al*. 2015).

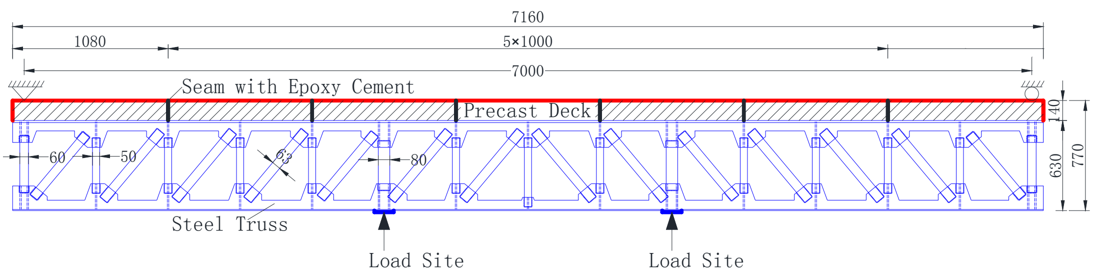
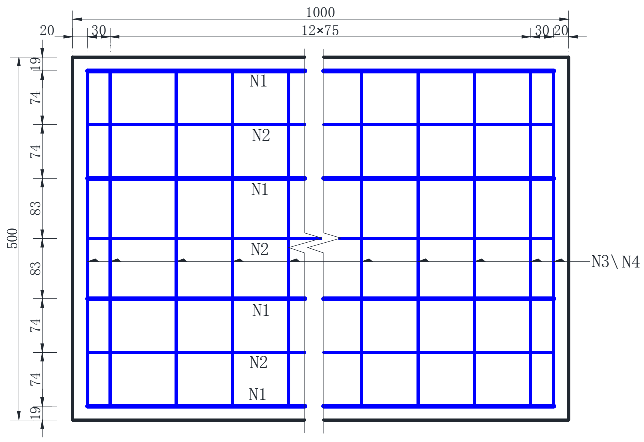
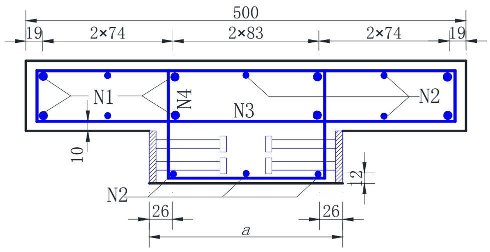


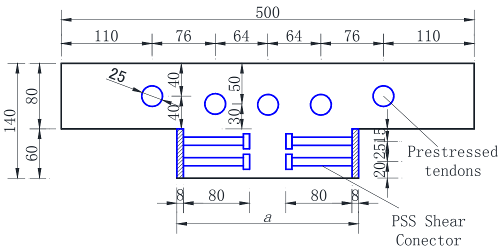
Fig. 2 Elevation layout of the PSTC beam (Unit: mm)



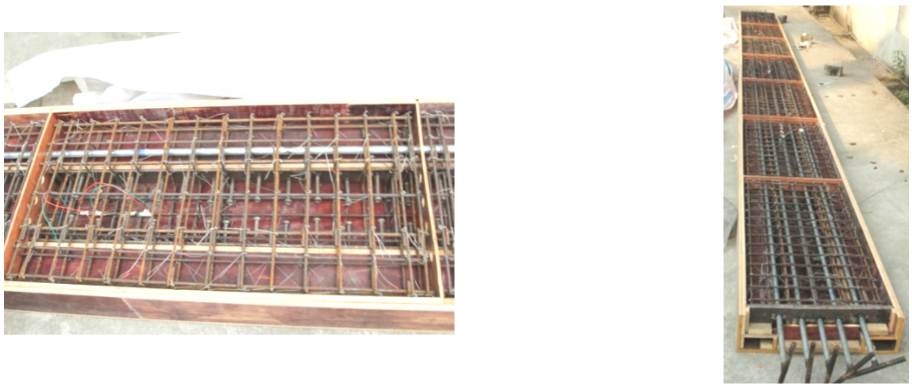
(a) General section (b) Plan of the reinforcement (Only one standard precast deck)



(c) Layout of the reinforcement



(d) Layout of the pre-stressed tendons



(e) Construction of reinforcement framework

Fig. 3 Standard section of PSTC beam (Unit: mm)

To achieve full shear connection, the cup head welding nails (Φ10×80 mm) are used with the material properties of ML15. In the PSTC-1 to PSTC-3, the numbers of studs are the same, while only the transverse spacing is different (Figs. 4-5). The vertical plate of shear connector is welded to the top flange of the steel truss (Fig. 5). The static and fatigue of welded joint are designed in accordance with the current specification (GB50017 2003).

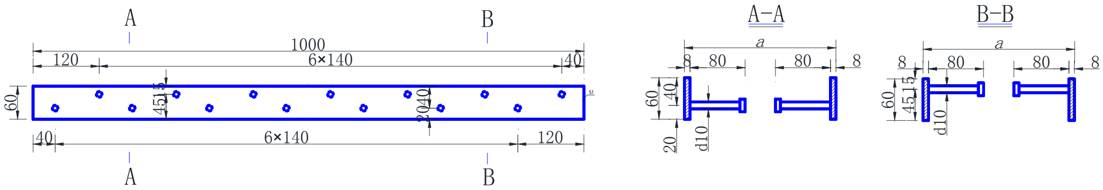


Fig. 4 Layout of the PSS connector in a standard deck (Unit: mm)

(a) (b)

Fig. 5 Layout of the PSS connector and the welded joint

2.2 Construction procedures

The construction procedures of PSTC composite beam are as follows: (i) precast the concrete decks (at the meantime pre-embedded the PSS connectors in the concrete deck), while fabricated the steel truss in factory at the same time. (ii) Install the concrete decks on the steel truss, smear the epoxy cement mortar in the seams between decks. (iii) Pre-stressed high strength tendons to concrete decks. Meanwhile, the strain rings between the anchorage and the anchor plate, are installed to measure the tendons' strain. Dial gauge is also installed to measure the macro-strain on the top of mid-span deck. Thus, the effective pre-stressed strain of deck and the pre-stress loss of high strength tendons are obtained. Then grout the pre-stressed duct. (iv) Weld the vertical steel plate of shear connector and the flange of the upper chord together. So the steel truss and concrete decks are assembled together to be a composite beam.

After all construction procedures are done, the whole construction process of composite beam is finished.

Table 1 Concrete properties

Test Beams	Average $f_{cu,k}$/MPa	Average f_{tk}/MPa	Average modulus of elasticity/MPa
PSTC-1	39.0	2.4	3.63×10^4
PSTC-2	36.9	2.3	3.59×10^4
PSTC-3	35.8	2.3	3.61×10^4

Table 2 Steel properties

	Modulus of elasticity(MPa)	Yield strength (MPa)	Ultimate strength (MPa)
Q345	2.04×10^5	357.0	456.0
Shear Studs	1.80×10^5	362.7	477.0

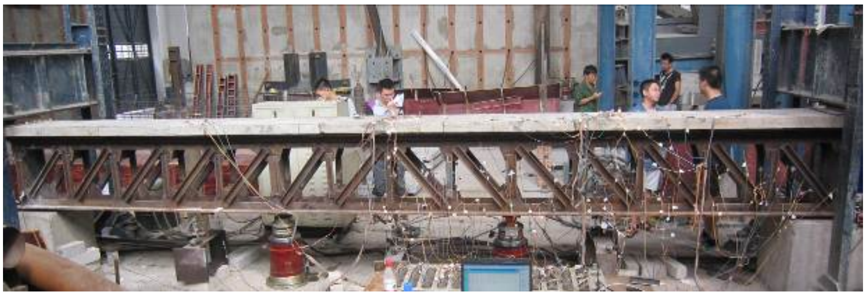


Fig. 6 Diagram of loading method

2.3 Material properties

The material properties of the specimens, such as steel and concrete, are shown in Tables 1-2, respectively.

The diameter of prestressed strand (Fig. 3) is $1\times\Phi^s15.2$ mm, and the standard strength is $f_{pk} \geq$ 1860 MPa, the cross sectional area is A = 140 mm^2, and the elastic modulus is $E_p = 1.95\times10^5$ MPa.

2.4 Loading method and scheme

2.4.1 Loading method

The simply-supported PSTC beam was loaded symmetrically at two points within the span. In this test arrangement, the pure bending of the specimens can be obtained between the two loading points without the presence of shear forces. The distance was 2000 mm between the two loading points (Figs. 2 and 6).

The test of each specimen is divided into three loading stages, i.e., elastic stage, cracking stage and failure stage:

(i) In the serviceability limit loading test, the static cyclic loading tests are conducted under 1~1.05 times of service load, which is 180 kN. It will be studied whether the steel truss and the precast concrete deck work well together.

(ii) Cracking test: increase the load until the initial crack of the deck appears. It will be obtained the data of the cracking loading, the crack's closure and reopen, the composite beam's strain and deformation, and the collaborative working conditions of steel beams and concrete deck.

(iii) The failure stage of loading tests: in order to save costs, steel truss are recycled. The PSTC-1 beam is loaded until the crack width of deck reaches 0.3 mm, then the deck of beam could be assumed as out of work as individual blocks, while the stress of longitudinal prestressed strands exceed the limit of its design strength and the stress of steel chords exceed the yield strength of 345 MPa. The PSTC-2 and PSTC-3 beams loaded gradually until the composite beams were significant damaged or buckled.

Then the strain and deformation of the test beams in the whole loading process, the experimental data of crack width, the spacing and length distribution, the failure model and the failure load of the specimens are obtained completely. After each test, the concrete decks of the damaged beams are dismantled. And if the steel truss members exhibit obvious change of

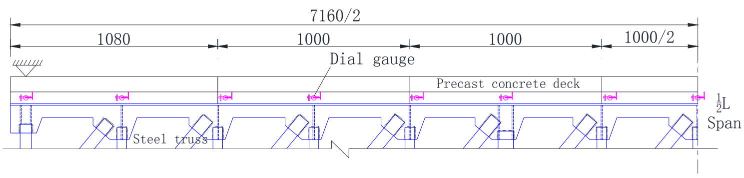


Fig. 7 Dial gauges layout for *L*/2

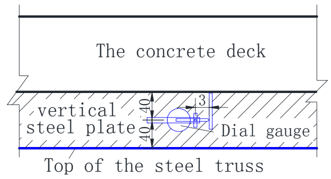


Fig. 8 Example for installation

Fig. 9 Dial gauges for measuring PSS connector slip

mechanical behavior or deformation, they are replaced with new members before the next test. Then the next loading test would be continued.

2.4.2 The slip measurement

To measure the PSS connector slip, dial gauges are installed between the vertical steel plate and the bottom flange of the concrete deck, which are corresponded to each node of steel truss (Fig. 7). Installation steps are as follows: first, organic glass is vertical pasted under the bottom flange of the deck; then dial gauge is installed on the central axial of the vertical steel plate (Figs. 8-9).

3. Test results

3.1 Initial cracking

3.1.1 Initial crack characteristics of the decks

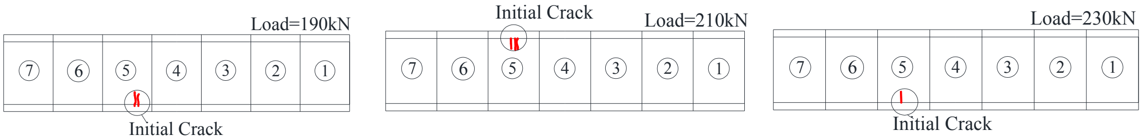
The judgment method of initial crack is: we can judge if it is the first crack under hogging moment from the position, the length, the direction and the width of crack, when the first crack is observed.

So, when the PSTC-1, PSTC-2 and PSTC-3 beams are loaded to 190 kN, 210 kN, and 230 kN respectively, the initial transverse crack appears at the edge of the deck, which is close to the loading point (Fig. 10 and Table 3). The length of the crack is 1~2.5 cm, the width is 0.002~0.003 mm and the direction is transverse. And with the load getting large, the crack becomes longer. Then the beams are unloaded. Later in the second loading round, the crack appears earlier than before. Such as PSTC-2, crack 1# appears again under the load of 144 kN, and the crack length is the same as that of the first load, namely 1.5 cm. When the load increases to 210 kN, a new crack appears. After unloading, all these cracks are closed. During this stage, no crack is found in the epoxy cement joint between the decks. And it shows that the prestress can effectively delay the cracking time of precast concrete deck. And the greater the prestress is, the latter the crack appears.

Table 3 Cracking load of the decks

Items	PSTC-1	PSTC-2	PSTC-3
Prestressed stress (MPa)	10.6	12.2	12.6
Cracking load, P_1 (kN)	190	210	230
ω_{max} = 0.1 mm, P_2 (kN)	350	380	450
P_1/P_u		0.32	0.36
P_2/P_u		0.57	0.71

*P_u: The ultimate strength of the beams



(a) PSTC-1 (b) PSTC-2 (c) PSTC-3

Fig. 10 Initial crack on the deck

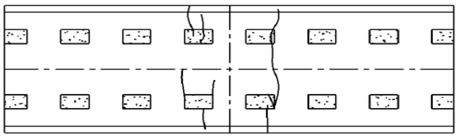


Fig. 11 Initial crack of the traditional precast deck with shear pockets (Su *et al*. 2012b)

The initial transverse cracks of PSTC-1, PSTC-2 and PSTC-3 beams are mostly originated on the edge of the deck which is close to the loading point. This is mainly because the members of steel truss close to the loading point are reinforced locally and the stiffness is relatively higher, so the stress is concentrated. The initial cracks of the traditional precast deck with shear pockets are almost originated in the corner of pockets (Su *et al*. 2012b) (Fig. 11). This is because the post pouring concrete in pockets has not enough prestress reserved and the stress is concentrated at the corner. However, the PSTC composite beam has no such phenomenon.

3.1.2 The initial crack between precast decks

On the PSTC-1, PSTC-2 and PSTC-3 beams, the initial crack of epoxy cement seam appears under the load of 310 kN, 280 kN and 330 kN respectively (Fig. 12).

Tables 3 and 4 show that the cracking load of decks is about 0.35P_u, and the cracking load of seam is 0.47P_u. The cracking load of epoxy cement mortar is greater than that of concrete deck, which shows that when the decks lost all their prestress, the epoxy cement mortar can play a role in tensile resistance, and this is a reliable means of splicing.

For the precast composite beams with female-to-female epoxy mortar joints or overlap of loops joints, the initial crack may appear earlier than the crack in the deck (Fig. 13). This is determined by the quality of jointing mortar and whether the pre-pressure is existed (Ryu and Shim 2004) or large enough (Ryu and Chang 2005). So, the deck joint of PSTC composite beam is simpler, easier to control with enough pre-pressure, and not affected by the quality of cast-in-place mortar.

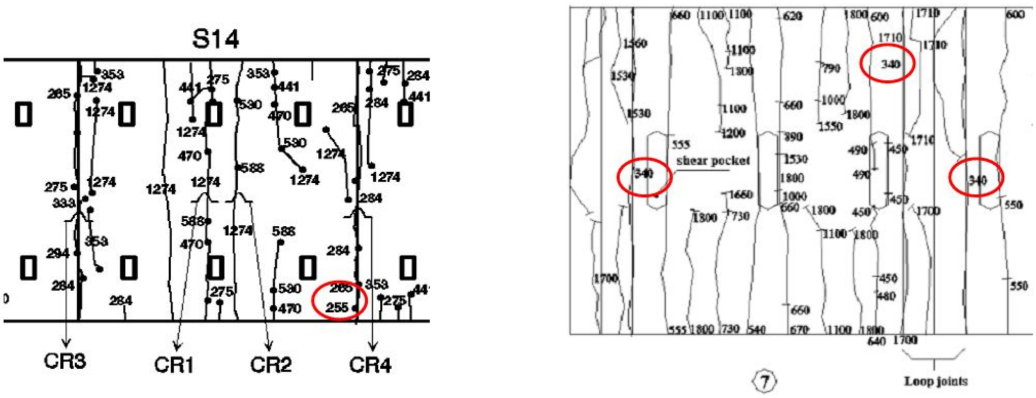
(a) PSTC-1 (b) PSTC-2 (c) PSTC-3

Fig. 12 Initial crack in the seam

Table 4 Cracking load of the seams

Items	PSTC-1	PSTC-2	PSTC-3
Pre-stressed stress (MPa)	10.6	12.2	12.6
Cracking Load, P_1 (kN)	310	280	330
$\omega_{\max}$ = 0.2 mm, P_2 (kN)	350	380	370
$\omega_{\max}$ = 0.3 mm,P_3 (kN)	390	480	410
P_1/P_u		0.42	0.52
P_2/P_u		0.57	0.58
P_3/P_u		0.73	0.64

*P_u: The ultimate strength of the beams



(a) Crack distribution of precast composite beam with female-to-female epoxy mortar joints (Ryu and Shim 2004)

(b) Crack distribution of precast composite beam with overlap of loops joints (Ryu and Chang 2005)

Fig. 13 Crack of precast composite beam with cast-in-place joints

3.2 Crack characteristic

3.2.1 Crack length

During the loading process of PSTC-1, PSTC-2 and PSTC-3, before the seam's crack appears between decks, the cracks in the deck develop fast, then widen and lengthen gradually. Also with new cracks appear constantly. When PSTC-1 and PSTC-2 are loaded respectively to 290 kN and

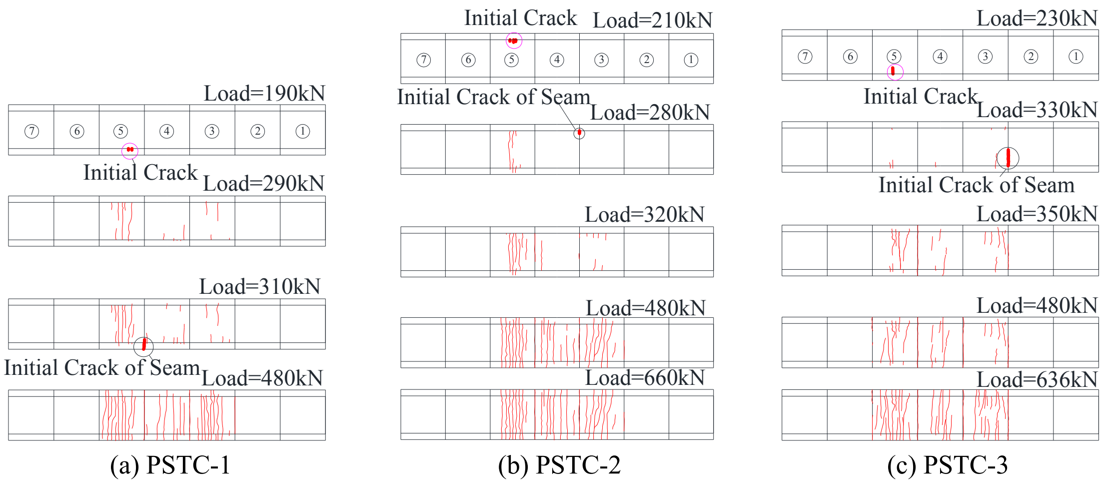


Fig. 14 Crack distribution of PSTC-1 to PSTC-3

280 kN, the transverse penetrating crack (as shown is Fig. 14) appears on the top of the deck. Once a crack of seam appears, its development will be the dominant one in all cracks. Its length growing rapidly, and simultaneously, the length of the cracks in the decks continue to increase, but with a slowing-down speed.

When PSTC-3 is loaded to 350 kN, a transverse penetrating crack appears on the top of the deck (Fig. 14). The loading tonnage is relatively bigger, and the cracks appear later than that of PSTC-1 and PSTC-2. This mainly because the cracks of seam (when the load is 330 kN) appear earlier than the penetrating crack of inter-deck, so the only strength transferring facility is the longitudinal pretressed strand, and the forces between the decks is uneven, so it delays the showing time of penetrating crack in the PSTC-3's deck.

As shown in Fig. 14, when PSTC-1, PSTC-2 and PSTC-3 are loaded to 350 kN, 380 kN and 350 kN respectively, the cracks of seam are through transversely. Increasing the load to 390 kN, 480 kN and 410 kN respectively, the transverse cracks are cut-through the cross section of the beam. The beam decks break into individual blocks and out of work.

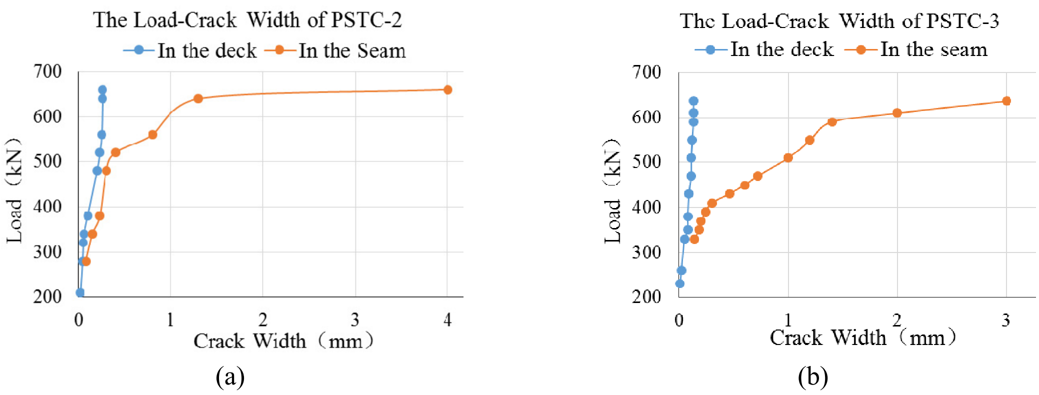


Fig. 15 Crack width comparisons between the slab and seam

3.2.2 Crack width

Tables 3 and 4 show that when the crack width in the deck is up to 0.1 mm, the load is about $0.64P_u$. When the crack width in the seam is up to 0.2 mm, the load is about $0.57P_u$, which indicates that the bearing capacity of the composite beam is enough. When the crack width in the seam is up to 0.3 mm, the load is about $0.7P_{u,}$ the steel truss has enough bearing capacity and the composite beam will not fail due to the cracks of deck. The design of the whole structure is reasonable.

Figs. 14 and 15 show that for the PSTC composite beams under hogging moment, the development of precast deck crack can be divided into the following two processes.

(i) The cracks in the deck are dominant: In this stage, the cracks in the deck develop quickly in the transverse direction, widen and lengthen gradually, until through the deck's surface. During this process, more and more new cracks are found. The development of the cracks in the deck is linear.

(ii) The cracks in the seam are dominant: Once the cracks in the seam appear, they soon become the main part. Their width and length are increasing much faster than that of the cracks in the decks.

There are three stages during the development of the seam's crack: the stage of slow growth in linear elastic state, the stage of fast growth in plasticity state, and the stage of free growth after failure stage.

For the first stage, during the load from 280 kN to 480 kN for PSTC-2, and from 410 kN to 590 kN for PSTC-3, the cracks appear in the seam. The cracking seam section with steel truss carry the load simultaneously. The width of cracks increased linearly with a relatively slow rate.

For the second stage, the load from 480 kN to 630 kN for PSTC-2, and the load from 410 kN to 590 kN for PSTC-3, the steel truss turns into yield state, and the cracks in the seam spread on the full cross section, then the decks become out of work. The composite section of strands and steel truss bear the force together. The crack width increased with faster rate.

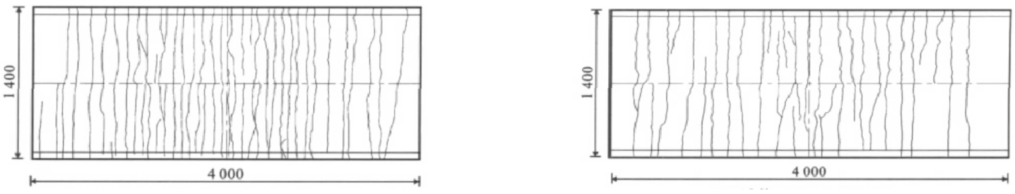
For the third stage, as PSTC-2 is loaded from 630 kN, and PSTC-3 is loaded from 590 kN, the beams composed by high strength strands and steel truss turn into yield state. In this stage, it is unable to increase the loading, and the crack width in the seam changes freely after the steel truss yields.

While for the precast decks with cast-in-place joints, cracks in the joints and in the deck develop simultaneously, the PSTC beam with significant difference. So it should be considered in the theoretical analysis process of crack calculation.

3.3 Crack distribution and spacing

It can be concluded from Fig. 14 that for the PSTC composite beams under hogging moment, the distribution of cracks mostly concentrate near the two loading points and the ③, ④, ⑤ decks, and there is no crack on the decks ①, ②, ⑥, ⑦. This is because the uneven stress between the decks, so the crack distribution is relatively concentrated. The decks near the supports are almost no cracks, and this phenomenon is very different from the crack distribution of cast-in-place concrete composite beam, whose stress distribution is more even (Su *et al*. 2012a) (Fig. 16).

To study the cracks distribution properties of deck, the adjacent cracks spacing on the edge of decks are shown in Table 5 statistically. For PSTC-1, the average cracking space on deck ③ and ⑤ is 75 mm, 82 mm respectively, and it is the same as the spacing of transverse reinforcement



(a) NSN-1 (p = 975 kN) (b) NSN-2 (p = 807 kN)

Fig. 16 The crack distribution of the cast-in-place composite beam (Su *et al*. 2012a)

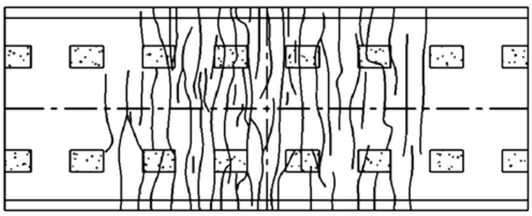
Table 5 Statistics of crack spacing in the deck (Unit: mm)

PSTC	Maximum spacing	Minimum spacing	Average spacing		
			③	④	⑤
1	225	46	75	126	82
2	185	49	115	108	81
3	153	28	90	94	86

(75 mm). The main reason is that the stress is concentrated near the loading point, so deck ③ and ⑤ crack firstly and get full development before the appearance of the seam crack. So the spacing is same as that of the transverse reinforcement. But the crack spacing of deck ④ is 126 mm, greater than that of transverse reinforcement. This is because the deck ④ cracks appears until the load is up to 290 kN, and then the initial crack in the seam appears. Thus from deck ③ to deck ④, or from deck ⑤ to deck ④, the stress can only transmit by high strength strands, the decks ④ bear uneven and less stress.

Once the cracks in the seam appeared, the length, width of cracks will increase in a large speed, and it will restrict the development of the deck crack adjacently. So the space between the seam crack and the nearest deck crack is bigger, and this is different from transverse reinforcement spacing (Table 6). And this cracks distribution is different from the precast deck with cast-in-place joints, whose distribution of crack in the decks is relatively uniform (Su *et al*. 2012b) (Fig. 17).

The crack in the decks distribution feature of PSTC-3 is different from PSTC-1 and PSTC-2. In deck ③, ④, ⑤, the average spacing is close to 90 cm, slightly larger than the transverse reinforcement spacing that is mainly because the appearance time of the crack in the seam is earlier than the inter-deck penetrating crack. So the development of crack in the deck is restrained, making the crack spacing larger.

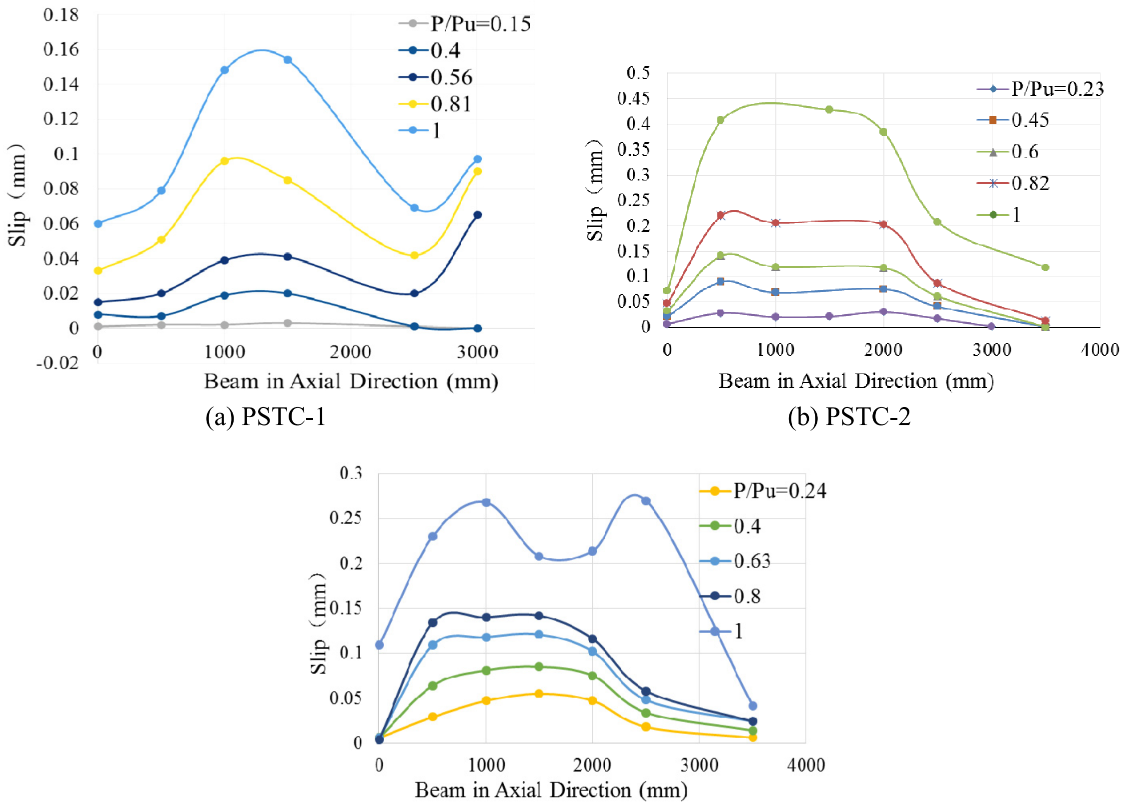


f NCN-2 , 1 000 kN

Fig. 17 The crack distribution of the precast composite beam with cast-in-place joints (Su *et al*. 2012b)

3.4 Slip characteristics of PSS connector

It can be seen from Fig. 18 that the slippage of the PSS connector at the support is about 0, and the maximum slippage is about 1500 mm away from the beam supports.



(a) PSTC-1 (b) PSTC-2

(c) PSTC-3

Fig. 18 Slip curve of bridge in axial direction

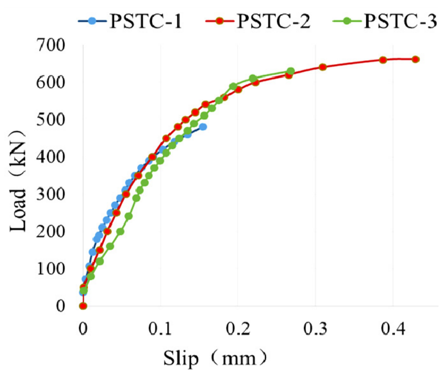


Fig. 19 Load-Slip curve of a position 1500 mm away from beam supports

Fig. 19 shows that the slippage increasing with the increasing of load. The initial load and slippage are in a linear relationship, and turns into nonlinear when the composite beams became plastic. In the whole process, the PSS connector worked in good condition.

For the PSTC beam, the slip effects exist, although this beam is designed for full-composite action. This is because the concrete deck of PSTC beam would obtain enough pre-stress before assembled. The concrete deck must balance out the pre-pressure which is produced by pre-stressing high strength tendons, then produce tensile stress. The slip for PSS connector is obvious at this time. So in the analysis process of bearing capacity, stiffness and crack, the slip effect should be considered.

4. Conclusions

For the conventional precast composite beam, to avoid the appearance of crack nearby the shear pockets or in the cast-in-place joints, a fully prefabricated steel truss-concrete (PSTC in short) composite beam with PSS connector is proposed in the paper. In order to investigate the initial cracking load, the crack development and the distribution characteristics, 3 tests on PSTC composite beam are carried out. In addition, the crack behavior of the deck in PSTC beam is compared with traditional precast composite beam. The results can be summarized as follows:

- Compared with the conventional composite beam, the PSTC composite beam adopts 2 key details: (i) pre-embedded Shear Studs (PSS in short), namely pre-embedded stud connectors in precast concrete deck, which are welded with steel truss to form a composite beam; (ii) Precast pre-stressed concrete deck is jointed in straight seam way with the epoxy cement mortar, replacing the female-to-female concrete joints or overlap of loops concrete joints between decks.
- Unlike the composite beams with shear pockets, the initial cracks of PSTC composite beam appear in the edge of deck near the loading points. It avoids the defect that the initial cracks are likely to appear on the corner of conventional shear pockets. The cracking load of seams is about $0.47P_u$, which is greater than the cracking load $0.35P_u$ of deck, solving the problems that the structure of conventional cast-in-place joint is complex and it's difficult to control the quality of joints. Besides, the straight seam with epoxy cement mortar is proved to be an effective and reliable splicing method.
- The development and the distribution laws of the cracks in PSTC beam are different from the conventional composite beam in the following facts. (i) For the precast composite beam with cast-in-place joints, the cracks in the deck develop with the crack in the joints simultaneously. However, for the PSTC beam, the cracks in the seam develop more quickly than the crack in the deck. (ii) The crack distribution of PSTC beam is relatively concentrated in the mid-span, which is unlike relatively uniform distribution of cast-in-place concrete composite beams. (iii) The crack spacing of PSTC beam between the seam and the closest crack in the deck is wider, compared with the relatively uniform crack distribution of precast deck composite beam with the cast-in-place joints. All should be considered in the theoretical derivation process of crack calculation.
- In the process of the whole test, the maximum slippage of the PSS connector is about 1500 mm away from the beam supports. And the slip characteristics are first elastic and later plastic. So when analyze the bearing capacity, the stiffness and the crack of PSTC composite beams, the influence of the slip should all be taken into consideration.

Acknowledgments

The research is supported by Ministry of Transport of the People's Republic of China (MOT) for funding of the present research (2013 319 814 040). The authors would like to thank the National Natural Science Foundation of China (Project No: 51308571) for the financial support for this research project.

References

Badie, S., Morgan Girgis, A.F., Tadros, M.K. and Sriboonma, K. (2011), "Full-scale testing for composite slab/beam systems made with extended stud spacing", *J. Bridge Eng.*, **16**(5), 653-661.

Chaudhary, S., Pendharkar, U. and Nagpal, A. (2009), "Control of creep and shrinkage effects in steel concrete composite bridges with precast decks", *J. Bridge Eng.*, **14**(5), 336-345.

Chen, Y.-T., Zhao, Y., West, J.S. and Walbridge, S. (2014), "Behavior of steel–precast composite girders with through-bolt shear connectors under static loading", *J. Construct. Steel Res.*, **103**, 168-178.

El-Lobody, E. and Lam, D. (2002), "Modelling of headed stud in steel-precast composite beams", *Steel Compos. Struct., Int. J.*, **2**(5), 355-378.

GB50017 (2003), "Code for design steel structures", Ministry Housing and Urban-Rural Development of the People's Republic of China, Beijing, China.

Joergensen, H.B. (2014), "Strength of loop connections between precast concrete elements", Ph.D. Thesis; University of Southern Denmark, Denmark.

Joergensen, H.B. and Hoang, L.C. (2013), "Tests and limit analysis of loop connections between precast concrete elements loaded in tension", *Eng. Struct.*, **52**, 558-569.

Joergensen, H.B. and Hoang, L.C. (2015), "Strength of loop connections between precast bridge decks loaded in combined tension and bending", *Struct. Eng. Int.*, **25**(1), pp. 71-80.

Ju, Y., Chun, S. and Kim, S. (2009), "Flexural test of a composite beam using asymmetric steel section with web openings", *J. Struct. Eng.*, **135**(4), 448-458.

Li, C., Zhou, Z., Su, C. and Fan, L. (2015), "Experimental study of prefabricated composite shear studs", *Bridge Construct.*, **45**(5), 60-65.

Nie, J. (2005), *The Structure of Steel-Concrete Composite Beam*, Science Press, Beijing, China.

Nie, J., Li, F., Fan, J., Zhang, X. and Diao, S. (2011), "Experimental study on flexural behavior of composite beams with different styles of concrete flange different styles of concrete flange", *J. Highway Transport. Res. Develop.*, (English Ed.), **5**, 30-35.

Papastergiou, D. and Lebet, J.P. (2014), "Design and experimental verification of an innovative steel–concrete composite beam", *J. Construct. Steel Res.*, **93**, 9-19.

Ryu, S.H. (2010), "Study on behavior of T-section modular composite profiled beams", *Steel Compos. Struct., Int. J.*, **10**(5), 457-473.

Ryu, H.K. and Chang, S.P. (2005), "Crack control of a steel and concrete composite plate girder with prefabricated slabs under hogging moments", *Eng. Struct.*, **27**(11), 1613-1624.

Ryu, H.K. and Shim, C.S. (2004), "Inelastic behavior of externally prestressed continuous composite box-girder bridge with prefabricated slabs", *J. Construct. Steel Res.*, **60**(7), 989-1005.

Shim, C.-S. and Chang, S.-P. (2003), "Cracking of continuous composite beams with precast decks", *J. Construct. Steel Res.*, **59**(2), 201-214.

Shim, C.S., Chung, C.H., Kim, I.K. and Kim, Y.J. (2010), "Development and application of precast slabs for composite bridges", *Struct. Eng. Int.*, **20**(2), 126-133.

Su, Q., Yang, G. and Wu, C. (2012a), "Experiments on concrete cracking of steel-concrete composite box girder", *China J. Highway Transport*, **5**(9), 74-81.

Su, Q., Yang, G. and Wu, C. (2012b), "Experimental study on mechanical behavior of continuous composite girder with prefabricate prestressed concrete slab", *J. Tongji Univ.* (*Natural Science*), **7**(7), 997-1002.

Sun, Q., Yang, Y., Fan, J., Zhang, Y. and Bai, Y. (2014), "Effect of longitudinal reinforcement and prestressing on stiffness of composite beams under hogging moments", *J. Construct. Steel Res.*, **100**, 1-11.
Xiang, H. and Zhou, Z. (2012), "Performance experiment and design theory research of fabricated steel box–prestressed concrete composite beams", *Chongqing Jiaotong University*.

CC