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Experiment Performance of a Novel Precast Concrete Column-to-Column Connection Using Steel Plate Hoop with Bolts

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Abstract:

At present, precast concrete structures are developing rapidly in China, and the precast concrete column-column connection is the key part in the fabricated concrete structure. A new type of column-to-column connection using steel plate hoop with bolts is presented in this paper, which has the advantages of simple installation and fast construction speed. However, the moment transfer mode of this connection is unique, which is different from the traditional reinforced concrete column and the concrete filled steel tube column. In order to study the flexural performance and mechanism of this connection mode, six new type connection members and one cast-in-situ member were tested under static low-cycle unidirectional repeated loading. The experimental phenomena, failure modes and load-strain relationships were introduced. The test results showed that this type connection using steel plate hoop with bolts has the same flexural bearing capacity as the cast-in-place member. The bending moment mechanism of this type connection is analyzed, and the design formula of this connection is given. The theoretical results are in good agreement with the experimental results.

***Keywords**: Precast concrete column-to-column connection, Prefabricated joint, Steel plate hoop with bolts, Flexural bearing capacity, Bending mechanism.*

1. INTRODUCTION

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In order to solve the increasingly prominent problems faced by the construction industry, such as labor shortage, rising labor costs, environmental pollution, waste of water resources and large amount of construction waste, the Chinese government has formulated a series of policies and measures to support the development of construction industrialization [1]. Safety and construction convenience are the key factors for the application of assembled concrete structures, especially the connection between precast concrete columns. At present, the main connection modes of precast concrete columns are tenon connection [2,3], grouting-anchoring connection [4-7], insertion connection [8], column-beam-plate stacking joint [9] and so on. There are some problems in the actual construction site, such as complex assembly procedures and slow construction speed [10]. To solve this problem, a new type of column-to-column connection is proposed in this paper, which can be seen in Fig 1. Compared with the traditional connection method, the longitudinal bar connection between prefabricated columns is cancelled and replaced by steel plate hoop with bolts. This type connection can simplify the complex process of longitudinal bar connection in construction site and improve the assembly efficiency. This connection mode has a unique way to transfer bending moment, which is different from the traditional connection mode and the bending mechanism of concrete filled steel tube [11,12], and there are few related studies. Therefore, it is necessary to study the flexural performance of this kind connection.

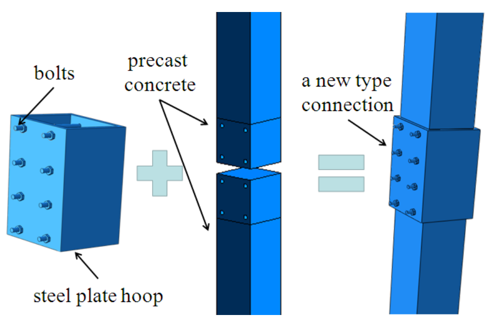

Fig 1: Steel tube with bolts connection

II. MATERIAL AND METHODS

2.1 Specimen Design

Seven full scale model specimens are designed in this test, where PRCB-00 is the cast-in-place beam and the others are the new type connection beams. The basic parameters of all specimens are shown in TABLE I. Size and reinforcement of specimens and the position of

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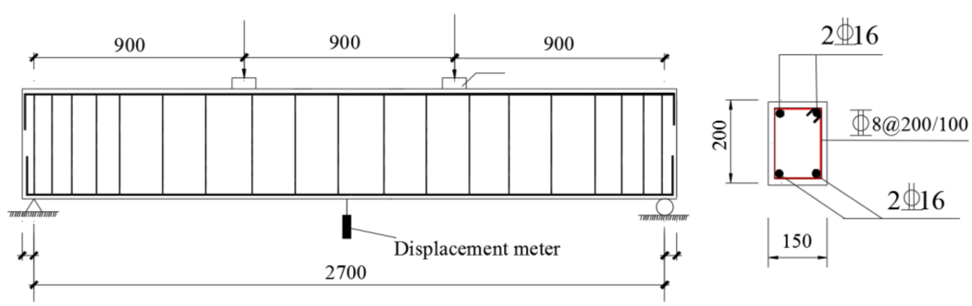
loading point are shown in Fig 2. In order to ensure tight connection, grout is filled in the gap between steel pipe and prefabricated member.

TABLE I. Details of specimens

Specimen	Strength of concrete	Thickness of steel plate hoop /mm	Length of steel plate hoop/mm	Bolts
PRCB-00	C30	---	---	---
PRCB-01	C30	8	400	4⏀22
PRCB-02	C30	8	500	4⏀22
PRCB-03	C30	8	400	---
PRCB-04	C30	8	500	---
PRCB-05	C30	5	400	---
PRCB-06	C30	5	500	---



(a) Size and reinforcement of PRCB-00 specimen

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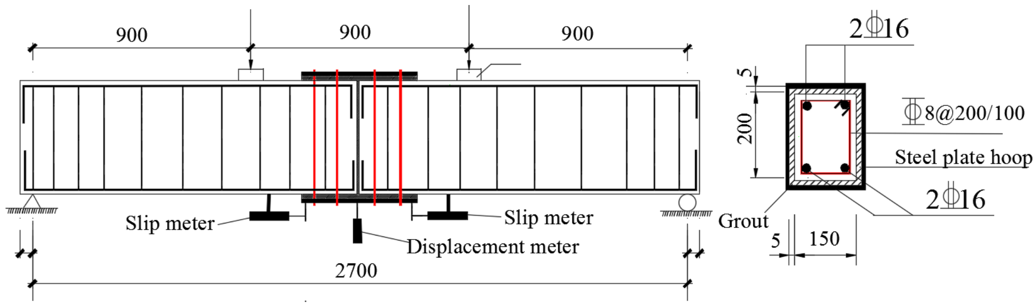
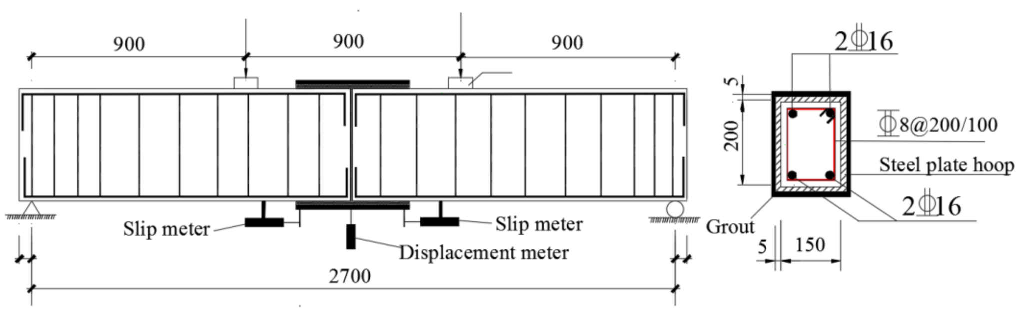


(b) Size and reinforcement of PRCB-01and PRCB-02 specimens



(c) Size and reinforcement of PRCB-03~ PRCB-06 specimens

Fig 2: Specific size and structure of specimen

2.2 Material Properties

The material properties tests of steel plate hoop and steel bars are shown in TABLE II. The compressive strength of the concrete cube in the precast concrete specimens and the cast-in-place specimen is 33 Mpa, and the axial compressive strength of grouting material used in the space between steel plate hoop and concrete specimens is 35 MPa.(GB/T 50081-2002)

TABLE II. Mechanical properties of steel

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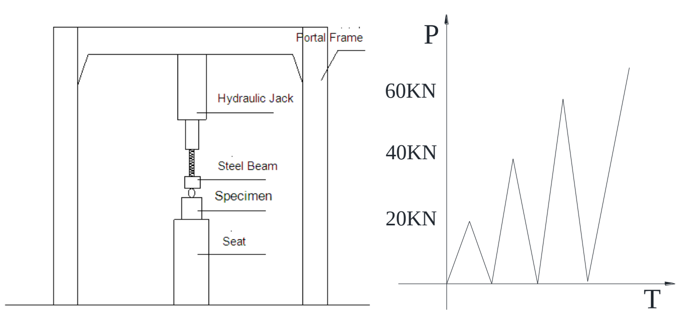
Reinforcement	Measured thickness/mm	f_y/MPa	f_u/MPa	f_v/MPa	$\varepsilon_y/10^{-6}$
Steel plate hoop	5 and 8	290	400	180	1524
Φ16 bar, Φ22 bolt	---	450	610	320	2250
Φ steel bar	---	520	720	---	---

III. TEST SETUP AND LOADING HISTORY

During the test, 1000 kN hydraulic jack was combined with portal frame to achieve three-section load through distributed steel beam, and a pure bending section was formed in the middle section. Three load-unload cycles were carried out during the loading process, and the cyclic load was loaded until the assembly specimen was damaged or failed. Load P and defection Δ are automatically collected by TDS-602 and the P-Δ hysteresis curve was drawn. The loading device and the loading history are shown in Fig 3.



(a) Test loading device (b) Loading history

Fig 3: Schematic diagram of test loading device and loading system

The static strain measuring instrument is used to measure the strain of steel bar and rectangular steel plates. The arrangement of the strain sheet on the steel bar and the steel tube is shown in Fig 4. Strain ε were automatically collected by TDS-602.

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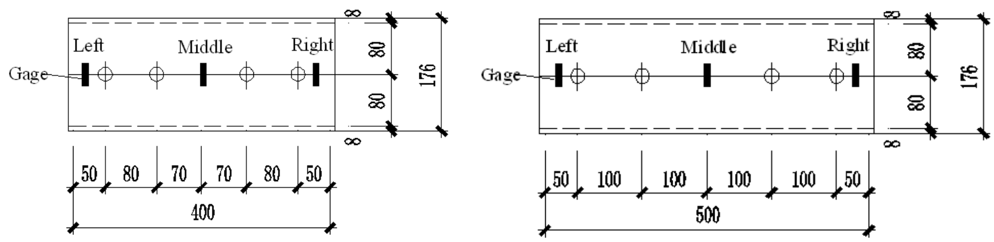
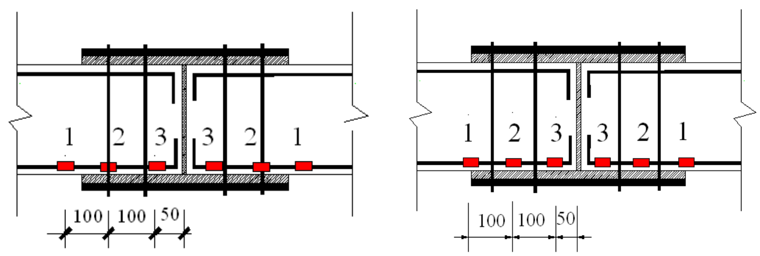


(a) The position of bolts and gage in PRCB-01 (b) The position of bolts and gage in PRCB-02



(c) The position of bars gage in PRCB-01 (d) The position of bars gage in PRCB-02

Fig 4: Strain gauge layout

IV. ANALYSIS ON TEST RESULTS

4.1 Experimental Phenomena and Failure Modes

Test failure modes can be classified into three categories, as shown in TABLE III and Fig 5.

TABLE III. Failure modes

Failure types	**Specimen**	**Damage phenomenon**
First type	PRCB-00	It is typical failure of ideally reinforced beam. Fig 5 (a), (b).

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	PRCB-01 PRCB-02	No slip and failure occurred in the steel bracer connection. The failure process is similar to bending failure of ideally reinforced beam. Fig 5 (c), (d).
Second type	PRCB-03 PRCB-04	The slippage is obvious between steel tube and concrete member. Compressive failure occurred in upper concrete. Fig 5 (e), (f).
Third type	PRCB-05 PRCB-06	Tearing failure occurred on the upper part of steel pipe, and there is a very serious slip phenomenon. Fig 5 (g), (h).

(a) PRCB-00 damage map (b) Local failure diagram

(c) PRCB-02 damage map (d) Local failure diagram

(e) PRCB-04 damage map (f) Local failure diagram

(g) PRCB-06 damage map (h) Tear failure of steel pipe

Fig 5: Failure modes of joints

4.2 Load-Deflection Skeleton Curve

The load deflection skeleton curves for all specimens are shown in Fig 6. The deflection and ultimate bearing capacity of PRCB-00 and PRCB-02 are almost the same. The ultimate bearing capacity of PRCB-01is slight lower. The ultimate strength of PRCB-03 and PRCB-04 decreases little and the deflection is large. The bearing capacity of PRCB-05 and PRCB-06 decreases obviously, and the deflection deformation is the largest. This indicates that the bolts, the length and the thickness of steel plate hoop are three important factors affecting the flexural capacity of the new type connection.

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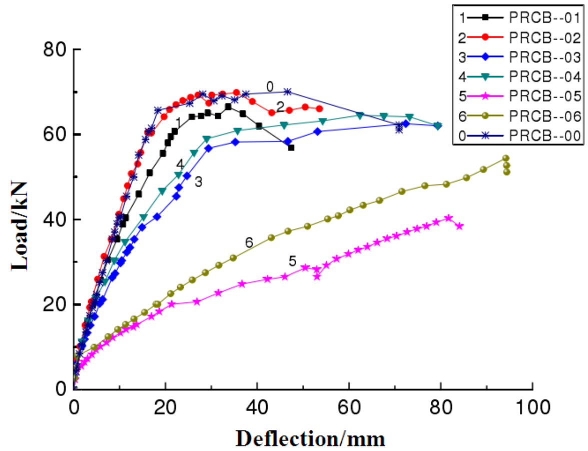
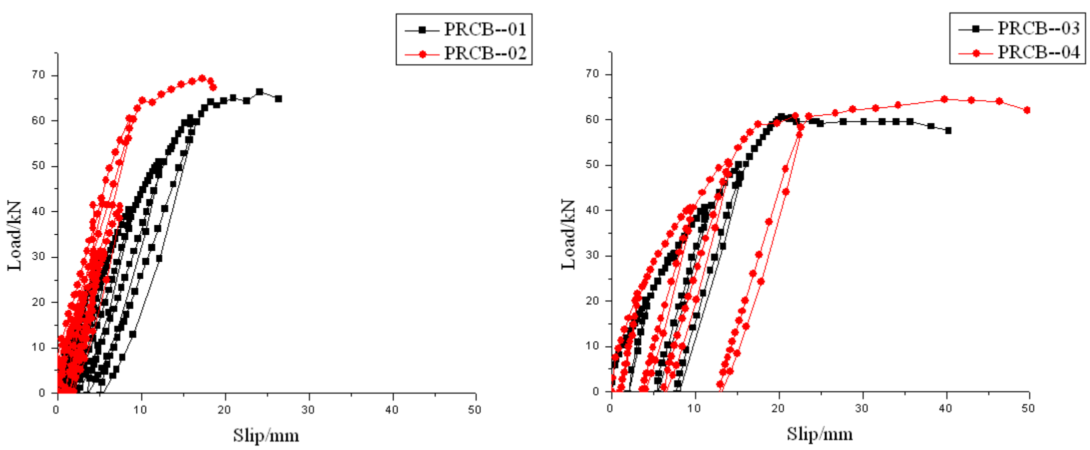


Fig 6: Load deflection curve

4.3 Load-Slip Curve

The load-slip curve of PRCB-01~PRCB-06 are shown in Fig 7. When unloading, the slip of connections without bolts would not disappear, and the joints with bolts have good slip resistance. This indicates that the bolts can effectively limit the slip, and which plays an important role in bending moment. It can also find that the longer and thicker steel pipe is helpful to control slip.



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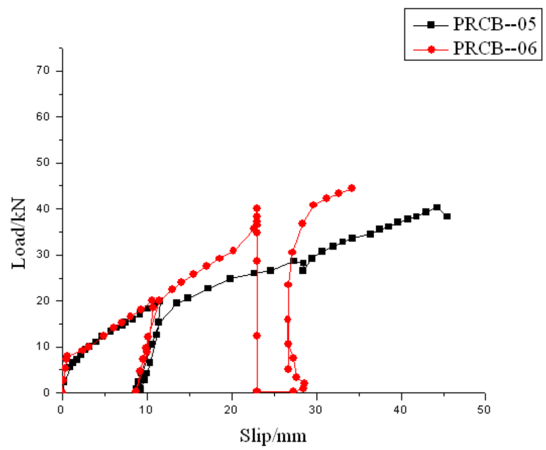

Fig 7: Load Slip Curve

4.3 Load - Strain Curve

Bolts:Tensile strains of bolts in PRCB-01 and PRCB-02 are shown in Fig 8. It indicates that the longer the length of the steel hoop, the smaller the tension of the bolt. However, tensile strain of bolts is far from yield strain, especially bolts in the PRCB-02, which indicates that the tensile strength of bolts plays little role in the new type joints.

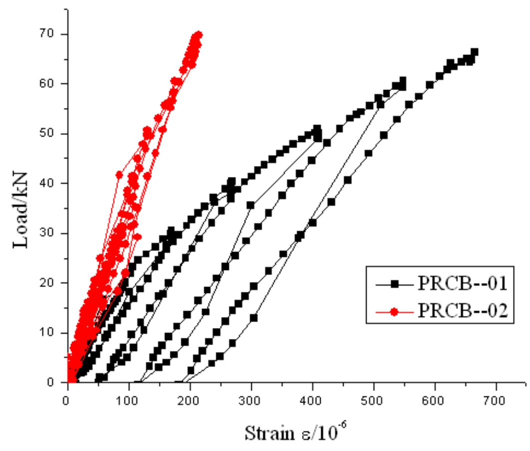

Fig 8: Load strain curve of bolts

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Steel plate hoop: The load-strain curves of the steel plate hoops in PRCB-01 and PRCB-02 are shown in Fig 9. The Left and Right of strain gauges are located on the outside of the bolts, and the Middle of strain gauge is on the middle of the steel hoop. The specific positions of Left, Right and Middle are shown in Fig 4. The maximum tensile strain occurs in the middle bottom of the steel plate hoop. And there is almost no tension strain right and left bottom of the steel tube. According to the position of the test as shown in Fig 4, it can be concluded that the bottom of steel plate hoop inside the bolts is pulled, while outside of the bolts in the bottom plate produce almost no pulling force. The maximum compressive strain occurs in the middle top of the steel plate hoop, but both sides are also involved in the compression.

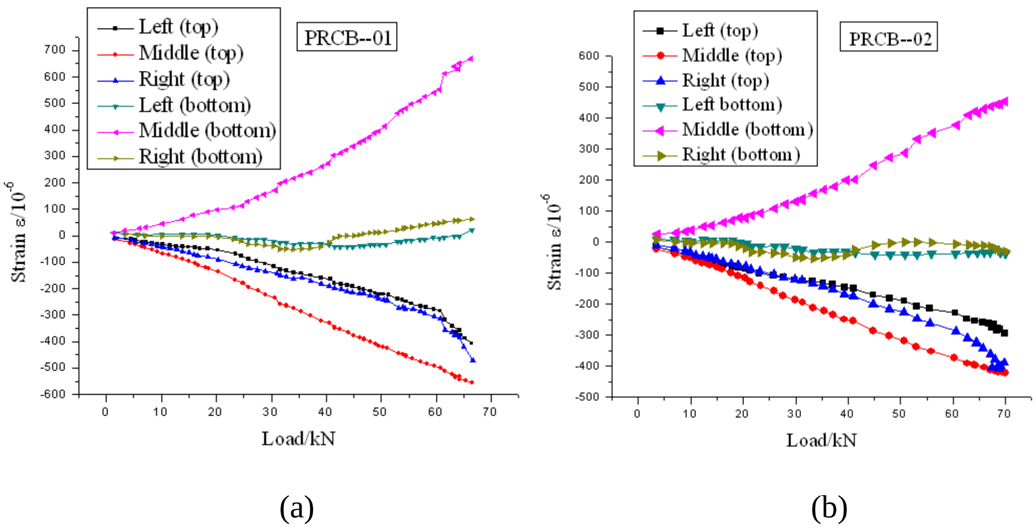

Fig 9: Load-strain curve of steel plate hoop top surface and bottom surface

Longitudinal reinforcement: The load-strain curves of Longitudinal reinforcement at NO.1, NO.2 and NO.3 in PRCB-01 and PRCB-02 are shown in Fig 10. The specific locations of No. 1, No. 2 and No. 3 are shown in Fig 4. No. 1 and No. 2 in the steel bar reach the yield strain, and the point 3 in the bar is far from yielding strain. According to the points of the bars as shown in Fig 4, the tensile force of the bottom reinforcement bars decreases gradually from the outside to the inside of the steel plate hoop.

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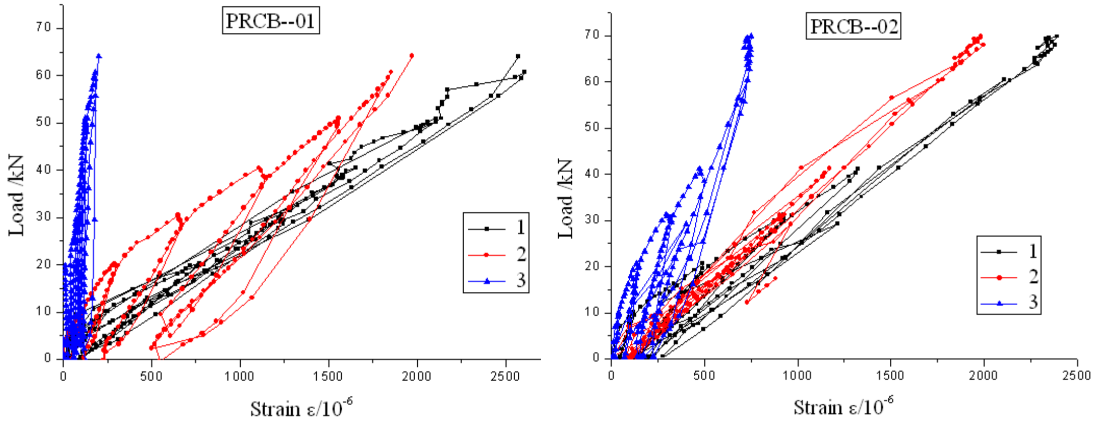


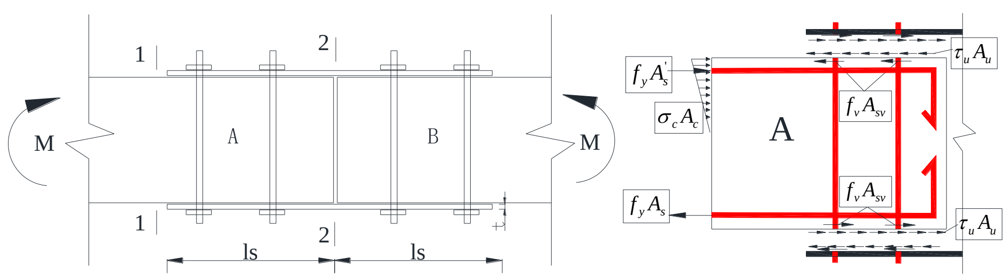
(a) (b)

Fig 10: Load strain curve of bars

The following conclusion can be obtained from the comprehensive analysis of bolts, steel plate hoops and longitudinal reinforcement. The tensile force is transmitted from the longitudinal reinforcement to the steel plate hoop through bolts. The shear capacity of bolts is the main way of tension transmission.

V. BENDING MECHANISM DISCUSSION

5.1 Analysis of Bolts



(a) Connection isolation (b) Condition of precast member A

Fig 11: Analysis of tension transmission path

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Fig 11 (a) shows the pure bending section of steel plate hoop with bolts, and Fig 11 (b) shows that the member between section 1-1 and section 2-2 is isolated. According to the analysis of the test results, the bottom longitudinal reinforcement in precast concrete members transfer the tension to bolts and concrete. Therefore, in Fig 11 (b), the tensile force of the bottom longitudinal reinforcement is transferred to the steel plate hoop through the shear force of the bolts and the bond force between the concrete and the steel plate. We can get the Formula (1).

$$f_y A_s = n f_v A_{sv} + \tau_u A_{su} \tag{1}$$

Where, f_y is the yield strength of steel bar, A_s is the sectional area of tension steel bar, n is the number of bolts, f_v is the shear strength of bolts, A_{sv} is the sectional area of a bolt, τ_u is the bonding power between concrete and steel plate hoop, A_{su} is the contact area of bonding power. In order to ensure that the bolts don't appear shear failure during loading, the following formula are needed.

$$n f_v A_{sv} \geq f_y A_s - \tau_u A_{su} \tag{2}$$

In formula 2, the parameters of longitudina reinforcement and bolts are easy to determine, but the bond strength between concrete and steel plate is difficult to determine. The bond strength of traditional concrete filled steel tubular is between 0.182 and 0.6 Mpa[13-15], and 0.38Mpa is chosen as the bond strength which is suitable for the materials used in this paper. So we can get the Formula (3).

$$n f_v A_{sv} \geq f_y A_s - 0.38 A_{su} \tag{3}$$

5.2 Analysis of Steel Plate Hoop

In order to study the influence of steel plate hoop on bending resistance, the pure bending section of the connection without bolts is isolated. Component A and B produce rotational tendency, as shown in Fig 12. Component A is isolated and its force situation is shown in Fig 13.

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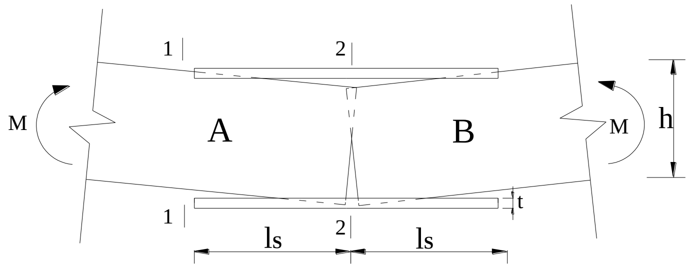

Fig 12:Deformation state

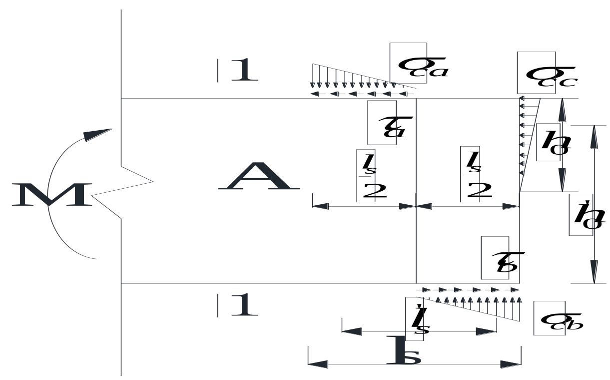

Fig 13: Stress state of component A

In Fig 13, the following formulas can be obtained from the mechanical equilibrium:

$$\int_0^{\frac{l_s}{2}} \tau_b \, bdx = \int_0^{\frac{l_s}{2}} \tau_a \, bdx + \int_0^{h_0} \sigma_{cc} \, bdx \tag{4}$$

$$\int_0^{\frac{l_s}{2}} \sigma_{cb}\,(\varepsilon_{cb})bdx = \int_0^{\frac{l_s}{2}} \sigma_{ca}\,(\varepsilon_{ca})bdx \tag{5}$$

$$M = \int_0^{\frac{l_s}{2}} \tau_b bdx \cdot h_0' + \int_0^{\frac{l_s}{2}} \sigma_{cb}\,(\varepsilon_{cb})bdx \cdot l_s' \tag{6}$$

σ_{ca},σ_{cb} are the compressive stresses between component A and the steel plate hoop, τ_a,τ_b are the bond stress between member A and steel plate. And the length of their force range is close to $\frac{1}{2}l_s$.σ_{cc} is the compressive stress between component A and B. The section width of the member A is b. h_0' is the distance between the upper point and bottom point of resulting force, and l_s' is the distance between the left point and right point of force points.

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From Eq. (4), it can be concluded that τ_b will reach the ultimate strength ahead of τ_b. So the slip will occur when τ_b reaches the ultimate strength.

In Eq. (5), σ_{ca},σ_{cb} can be obtained by strain-constitutive relation, and the constitutive relation of concrete is selected according to the code of reinforced concrete structure.

$$\sigma_c = \begin{cases} f_c\left[1-\left(1-\frac{\varepsilon_{cx}}{\varepsilon_0}\right)^n\right] & for \quad \varepsilon_c \le \varepsilon_0 \\ f_c & for \quad \varepsilon_c \ge \varepsilon_0 \end{cases} \text{(GB 50010-2010)} \tag{7}$$

where ε_0 is 0.002 ,ε_{cu} is 0.0033 and n is 2.

According to the integral result of σ_{ca} and σ_{cb}, the position of the resultant force point can be found, and we can get $l_s^{'}$ is $0.8l_s$.

In order to simplify the calculation and ensure the safety of the design, the lower limit of $h_0^{'}$ is taken as

$$h_0^{'} = \frac{5}{6}h \tag{8}$$

The above calculation results are substituted into Eq. (6), Eq. (9) can be obtained.

$$M = \left(0.319 + \frac{0.159}{f_c}\right) f_c b l_s^2 \tag{9}$$

If we want to ensure that the connection has sufficient moment bearing capacity, we can set the minimum length of the steel plate by Eq. (10).

$$l_s \ge \sqrt{\frac{M}{\left(0.319+\frac{0.159}{f_c}\right) f_c b}} \tag{10}$$

5.3 Thickness of Steel Plate Hoop

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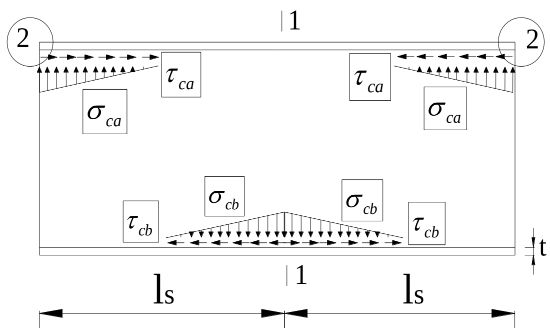

Fig 14: Force condition of steel plate hoop

The force situation about the steel plate hoop is shown in Fig 14. The 1-1 section in steel plate hoop is the weakest section in bending, and NO.2 is the weakest area in tension. The 1-1 section can be designed according to the formula in the steel structure code, and the following Eq. (11) is obtained.

$$\mathrm{M}_u \geq f_y W_x \qquad \text{(GB 50017-2017)} \tag{11}$$

Where M_u is the flexural strength of 1-1 section of steel tube, W_x is the section modulus of horizontal axis, and f_y is the tensile strength of steel tube.

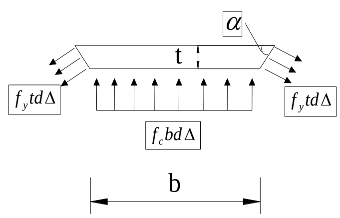

Fig 15: Stress situation of separating element

In the left edge of steel plate hoop, an infinitesimal segment with length $\mathrm{d}\Delta$ is taken. In this region, the compressive stress provided by concrete can be regarded as uniform distribution. Then the roof of steel plate hoop is isolated, and the force situation is shown in Fig 15. According to the mechanical equilibrium, Eq. (12) can be obtained. If the tearing failure of the steel plate is to be avoided, the thickness of the steel plate needs to satisfy Eq. (13).

$$2 f_u \mathrm{t} \cdot \mathrm{d}\Delta = f_c \mathrm{b} \cdot \mathrm{d}\Delta \tag{12}$$

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$$t \geq \frac{f_c}{2f_u} b \tag{13}$$

Where f_c is the compressive strength of concrete, t is the thickness of steel tube and b is the section width of steel tube.

5.4 Comparison of Theoretical Analysis and Experimental Results

In order to ensure the safety of the joints, the flexural capacity of the joints is required to be higher than the reinforced concrete members. Therefore, we can take the flexural capacity of reinforced concrete members as the design value of flexural capacity of joints. According to the reinforced concrete code (GB 50010-2010), the flexural capacity of cast-in-place beam can be calculated to be 65 kN · m. This calculation result is in accordance with the test results. Then the minimum thickness of steel plate (Eq.10) and the minimum length of steel pipe (Eq.13) can be calculated. According to the reinforcement of precast concrete members, the minimum section area of bolts can be calculated (Eq.2). The calculation results are shown in TABLE IV.

TABLE IV. Comparison between theoretical calculation and experimental results

Specimen number	Length of steel plate/mm	Thickness of steel plate /mm	Bolts sectional area /mm^2	Test failure value /kN · m
PRCB-01	400 (349)	8 (6.19)	760 (532)	65
PRCB-02	500 (349)	8 (6.19)	760 (532)	67
PRCB-03	400 (349)	8 (6.19)	——	60
PRCB-04	500 (349)	8 (6.19)	——	62
PRCB-05	400 (349)	5 (6.19)	——	42
PRCB-06	500 (349)	5 (6.19)	——	38

In TABLE IV., the values in brackets are calculated by theory and the values outside brackets are the actual values in test. It can find that PRCB-01 and PRCB-02 meet the requirements in bolts, thickness and length of steel plate hoop, so there was no joint failure.

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Bending failure of prefabricated members occurs. There are no bolts in the connections of PRCB-03 and PRCB-04, so the slip couldn't be recovered during the loading process, which caused the actual length of steel plate to decrease continuously. Therefore, according to the theoretical calculation, when the slip of PRCB-03 reached 26 mm and PRCB-04 reaches 75 mm, the damage would occur. This conclusion is in good agreement with PRCB-03, but not with PRCB-04. The main factor is that when the slip was large enough, the angle between the concrete member and the steel plate hoop also changed, which leads to the further reduction of the contact length between the concrete and the steel plate hoop. The thickness of steel plate in PRCB-05 and PRCB-06 is less than the calculated value, so the tearing failure of steel tube occurs during the second repeated loading. In summary, the calculated values are in good agreement with the experimental phenomena.

VI. CONCLUSIONS

1. Seven full scale model specimens were designed and tested in this paper, and the experimental phenomena and load-strain curves were introduced. The results show that this new type of connection with bolted steel plate hoop has the same flexural capacity as cast-in-place connections.

2. According to the experimental results, the mechanical mechanism of the new type joints is analyzed, and the design formulas for bolts, the thickness and length of steel plates are deduced theoretically. By comparing the calculated value with the experimental results, it is shown that the design formulas coincides with the experimental phenomena.

3. In this new type of connection, the longitudinal reinforcement between the two precast members is discontinuous, but reliable bending capacity is provided by steel plate hoops and bolts. However, the seismic performance and fire resistance of this connection are still unknown. We need to be further verified by new experiments.

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