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Research on rotation capacity of the new precast concrete assemble beam-column joints

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Abstract. The joints of the new prefabricated concrete assemble beam-column joints are put together by the hybrid joints of inserting steel under post-tensioned and non-prestressed force and both beams and columns adopt prefabricated components. The low cyclic loading test has been performed on seven test specimens of beam-column joints. Based on the experimental result, the rotation capacity of the joints is studied and the M-θ relation curve is obtained. According to Eurocode 3: Design of steel structures and based on the initial rotational stiffness, the joints are divided into three types; by equivalent bending-resistant stiffness to the precast beam, the equivalent modulus of elasticity E_e is elicited with the superposition method; the beam length is figured out that satisfies the rigid joints and after meeting the requirements of application and safety, the new prefabricated concrete assemble beam-column joints can be regarded as the rigid joints; the design formula adopted by the standard of concrete joint classification is theoretically derived ,thereby providing a theoretical basis for the new prefabricated concrete structure.

Keywords: beam-column joint; rotation capacity; stiffness of equivalent bending-resistant; standard of concrete joint classification

1. Introduction

In recent years, the precast concrete structures has increasingly developed in China and the industrialization of construction and housing has also become a hot topic, and various industrialization modes of construction are the trends of industrial development (Cheok *et al*. 2015, Dhakal *et al*. 2005, Fu 2014, Lee *et al*. 2014, Kataoka *et al*. 2012, Korkmaz and Tankut 2005, Rodriguez and Torres-Matos 2013, Zhang 2013).

Several types of studies on precast concrete joints have been done in research centers around the world. In general, studies include the development of joints which provide high rigidity and easiness of implementation. In the research of Shariatmadar and Beydokhti (2011) was tested a joint between precast beam and column preformed without the use of corbel. The region which joins the elements was cast in situ. The improvement of the bending moment transfer to the column by the use of prestressed reinforcement was another way found by the researchers to

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improve the joints behavior. Hawileh (Hawileh *et al*. 2010) performed a numerical and experimental study of joints involving prestressed reinforcement. The authors compared both results and they concluded that computer simulation is an economical option to analyze the behavior of joints. Li (Li *et al*. 2006) proposed an innovative type of joint details for composite structures consisting of steel beams and reinforced concrete columns (RCS), and both experimental and analytical research was conducted to evaluate the seismic behavior of bolted end plate joints.

At present, internationally there are two commonly used classification methods of the node, by linearity M-ϕ curve and by nonlinearity M-ϕ curve. From the chapter of M-ϕ curve, the node's stiffness, strength and rotation capability can be obtained, and this is the main basis of the node's classification (Bjorhovde *et al*. 1990, Hasan *et al*. 1998).

The new prefabricated concrete structure in this paper adopts a total prefabricated assembly method, components made in the prefabricated field and shaped by lifting equipments on construction site. The key to the prefabricated concrete structure lies in its joint technique and the joint performance will have a direct effect on the whole structure's seismic performance. In the seismic damage investigation, the joint damage of the prefabricated structure is the most significant feature. When the joints of the buildings are damaged, the loading path of the structure can be changed or interrupted all of a sudden, resulting in the structural damage or collapse.

The joints in the fabricated structure are mainly divided into four types: beam-slab, beam-slab-column, slab-wall and slab-beam, among which the beam-column joint is the most important one, deciding the transfer mode of force. The performance of beam-column joints can be evaluated from bearing capacity, rotation capacity and so on. The rotation capacity of joints refers to the relative rotation capacity and shows the deformability of joints. This paper discusses the research on the rotation performance of the beam-column joints, and based on the Eurocode 3 (Eurocode3 2005), the equivalent modulus of elasticity E_e can be figured out; and then by modifying the classification standard of joints in the Eurocode 3, the proposed formula for the classification standard of the concrete joints is obtained.

2. The joint classification of the Eurocode3: design code for steel structure

According to the Eurocode 3 (2005), the joints of steel structures, the three key performance indexes of the beam-column joints are given: the flexural capacity $M_{j,Rd}$, the initial rotational stiffness $S_{j,ini}$ and rotation capacity θ_{Cd}. Moreover, according to the initial rotational stiffness, the joints are divided into three types: rigid joints, semi-rigid joints and hinged joints or nominally pinned (Fig. 1).

The rigid joints may be assumed to have sufficient rotational stiffness to justify analysis based on full continuity. The rigid joints are the ones with the stiffness of the beam-column joints large enough to guarantee the original angle of the joint from change and the beam-ends to pass all the shearing force and bending moment to the columns, which is applied to elastic analysis; the semi-rigid joints refer to the ones that when joints are bearing load, the beam-ends can pass not only the shearing force but also bending moment to the columns but the beam-column can produce the limited relative rotation; the hinged joints are those that the joints bearing load, the beam-ends can only transmit the shearing force to the columns, but not the bending moment and the free relative rotation can be produced from the beam-column joints.

Joints of steel structures may be classified by the following method in the Design of steel structures (Eurocode 3 2005):

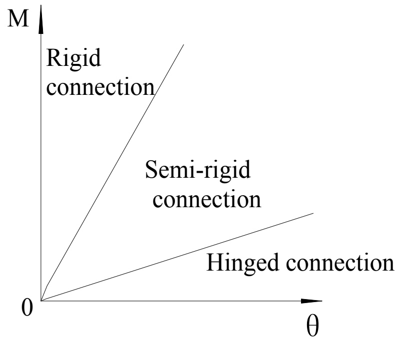


Fig. 1 Joint classification

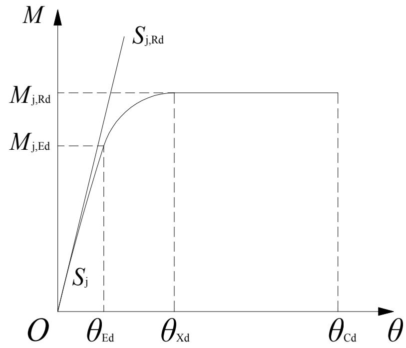


Fig. 2 *M*-*θ* curve

Rigid joint Eqs. (1)-(2)

$$S_{j,ini} \geq 25\frac{EI_b}{L_b}(\text{unbraced structure}) \tag{1}$$

$$S_{j,ini} \geq 8\frac{EI_b}{L_b}(\text{braced structure}) \tag{2}$$

Semi-rigid joint Eqs. (3)-(4)

$$\frac{1}{2}\frac{EI_b}{L_b} < S_{j,ini} < 25\frac{EI_b}{L_b}(\text{unbraced structure}) \tag{3}$$

$\frac{1}{2}\frac{EI_b}{L_b} < S_{j,ini} < 25\frac{EI_b}{L_b}$（unbraced structure）

$$\frac{1}{2}\frac{EI_b}{L_b} < S_{j,ini} < 8\frac{EI_b}{L_b}(\text{braced structure}) \tag{4}$$

Hinge joint Eq. (5)

$$S_{j,ini} \leq \frac{1}{2}\frac{EI_b}{L_b} \tag{5}$$

Where: E is the elasticity modulus of the steel beam, I_b is the inertia moment of reinforced concrete beam section, L_b is the span of a beam (centre-to-centre of columns), $S_{j,ini}$ is rotational stiffness of a joint. The semi-rigid joint has a good rotation capacity, benefiting anti-seismic but its relative rigidity is lower than rigid joint, and therefore, the bearing capacity of the steel can't be fully developed normally. In the design, the calculation and design of the bearing capacity can't be performed on the semi-rigid joints and it is necessary to be designed with the obvious nonlinear *M*-*θ* (Fig. 2) curve and as a result, it is not helpful to the project design.

3. Test program

The test includes seven concrete beam-column joint models, one cast-in-place joint RC-01 (Fig. 3) and six fabricated joints with numbers from PAN-03 to PAN-08 (Fig. 4), with beam cross-sections in the form of H-Section, among which the specimens PAN -03, PAN-04, PAN-05, and PAN-06 are used with dense spiral stirrup in the beam-end plastic hinge zone to confine the beam end concrete, to avoid compression on the beam end under the effect of the low cycle repeated load test that the concrete is collapsed and broken off. Reinforcement of specimens is shown in Table 1.

For the I-shaped cross section with the beam section size of 380 mm × 450 mm × 150 mm × 150 mm, the column section is 400 mm × 400 mm. The core range of the column node is covered by the steel plate hoops with the thickness of 4 mm, while the structural measures of welding steel are adopted inside in case sliding may happen.

The designed strength of the column concrete is C60 and high strength reinforcement is used as longitudinal reinforcement with the yield strength no lower than 600 MPa and the diameter is 22 mm. The designed strength of the beam concrete is C40 and the longitudinal reinforcement adopts

Table 1 Arrangement of reinforcement of specimens

Specimen	Strength of concrete	Shape	Size (mm)	Longitudinal reinforcement	Stirrup spacing (mm)	Stirrup encryption area (mm)
Beam	C60	Rectangle	400×400	16 ϕ 22 HRB600	50	30
RC-01	C60	Rectangle	450×380	12 ϕ 22 HRB600	50	30
PAN-03	C40	I-shaped	h = 450 b_f = 380 b = 110 h_f = 150	4 ϕ 25 HTH1080 8 ϕ 18 HRB400	50	30
PAN-04	C40	I-shaped			50	30
PAN-05	C40	I-shaped			50	30
PAN-06	C40	I-shaped			50	30
PAN-07	C40	I-shaped			50	30
PAN-08	C40	I-shaped			50	30

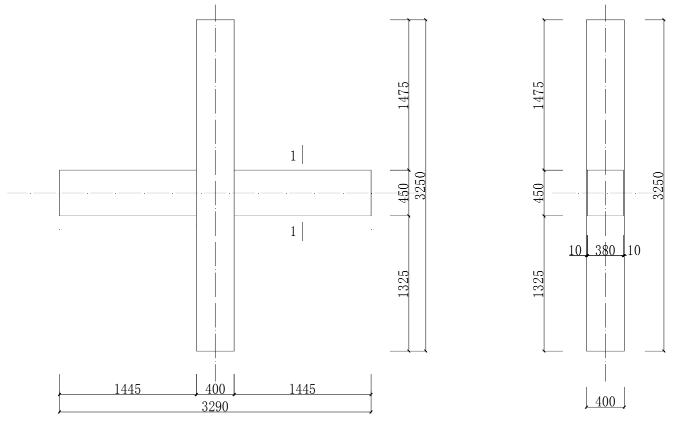


Fig. 3 Details of RC-01 (Unit: mm)

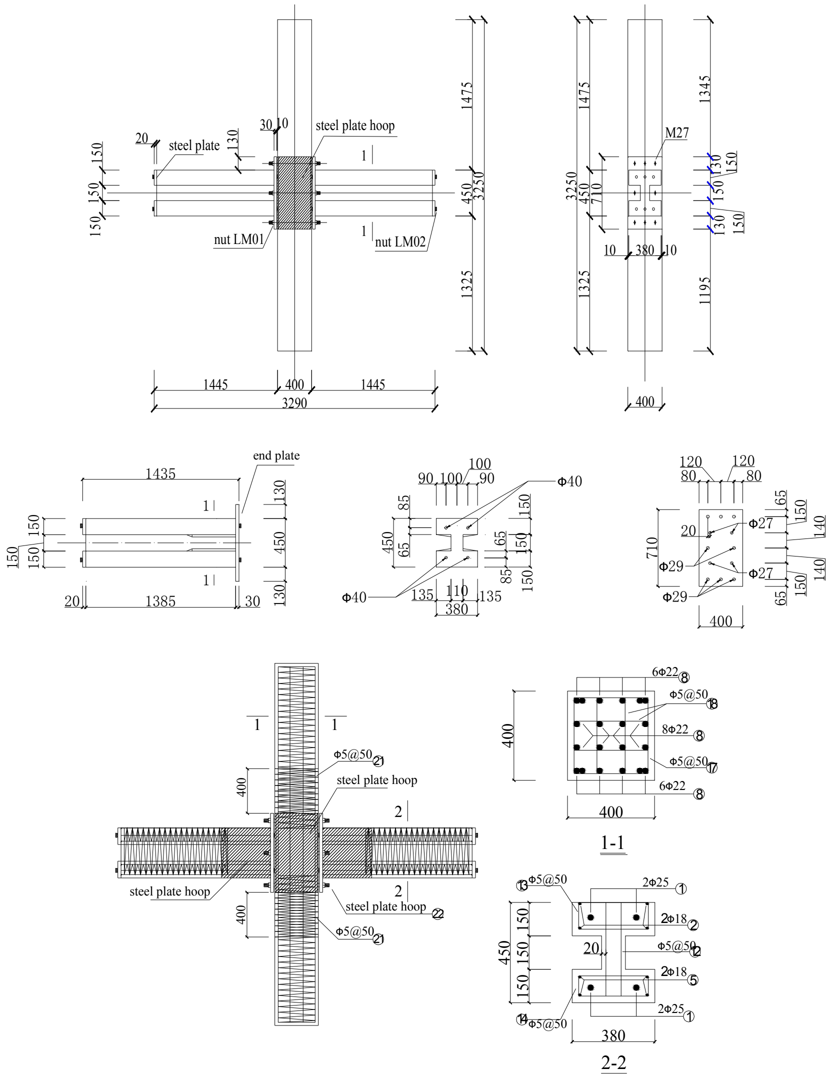


Fig. 4 Details of PAN-03 (Unit: mm)

HRB400, the diameter 18mm. All the stirrups are high-strength continuous composite spiral hoops with the yield strength no lower than 1100 MPa and the diameter 5 mm. The hoop reinforcement of the stirrup spacing area is 30 mm, and the non-densification region is 50 mm. The end plate is made of structural steel Q390, with high strength and low alloy and 32 mm in thickness with good weld ability to make sure that the beam's longitudinal bearing force reinforcement can have clear force transmission.

Two prestressed reinforcements are arranged in the beam's upper and lower flange with the yield strength; no lower than 970 MPa and 25 mm in diameter. The symmetrical reinforcement is arranged on the test specimen of the beam-column joint and the column's designed compression ratio is 0.27. Except PAN-03 (Fig. 4), the other specimens all use the method of welding the end-plates on both sides together externally with steel plate hoops (Fig. 5). The I-shaped steel plate

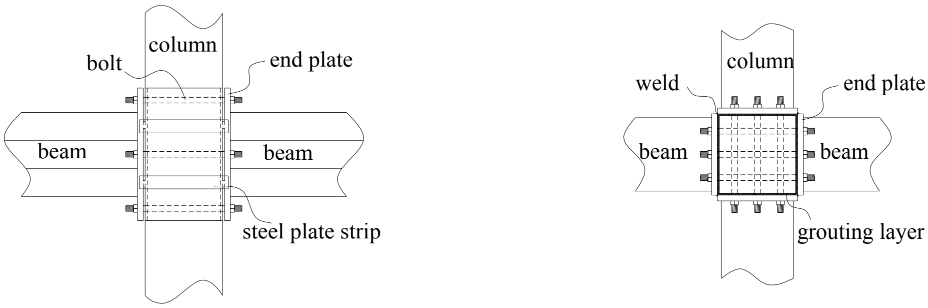


Fig. 5 External joints to enhance the bending capacity of the end plates

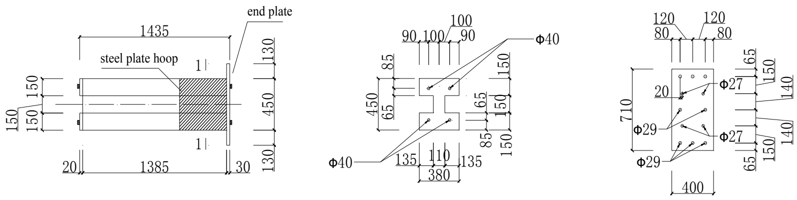
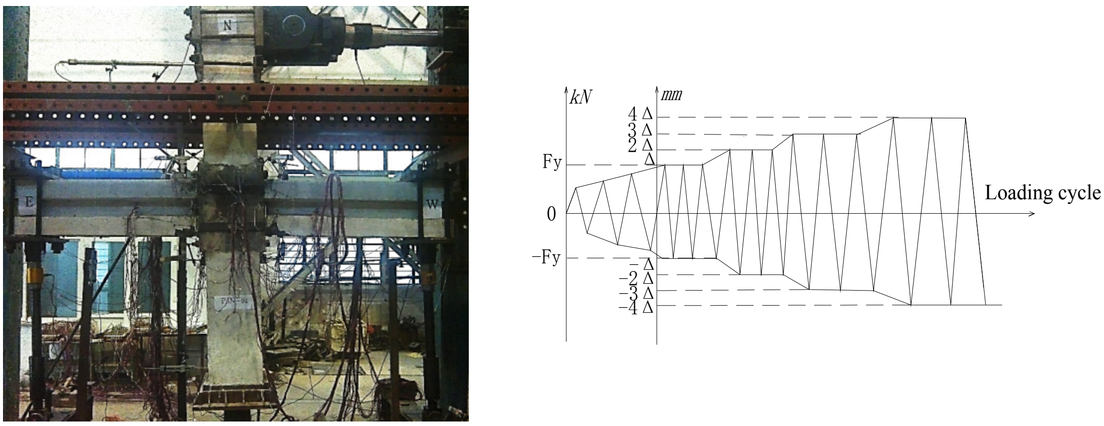


Fig. 6 Details of PAN-07's beam (Unit: mm)

hoops are set up in the beam's plastic hinge of the specimens, PAN-07 and PAN-08 without stirrup at the place of steel plate hoops (Fig. 6).

Because the thickness of the concrete flange results in the large distance between bolts, it is not good for the bending resistance of the end plate. By using the steel plates to connect the end plates on both sides externally, the bending capacity of end plate can be significantly enhanced. In the practical projects it is easy to use this method, because the joints in the practical projects are bidirectional ones, that is to say, there are end plates all around the columns and it only needs to weld four end plates after the joints are installed (Figs. 5-6) (Pampanin 2005, Psycharis *et al*. 2012).



(Note: 1 kN = 0.225 kips; LVDT is linear variable differential transformer)

Fig. 7 Test setup and loading history

Using low cyclic loading, the quasi-static test is performed on the specimens (Fig. 7), a load-displacement hybrid control program was applied, in which the lateral loading sequence was controlled by force for the initial loading cycles till the yielding initiation of the test specimen was observed. When the test specimen started yielding, the loading sequence was controlled by displacement. On the basis of the yield displacement, the target displacements for the cyclic loading were set as the multiple of the yield displacement; the cyclic loadings were repeated three times at each target displacement. Loading was terminated until the reaction force descended to about 85% of the maximum value. The loading process is shown in Fig. 7 (Im *et al*. 2013, Dhakal *et al*. 2014, Chen *et al*. 2012, Brunesi *et al*. 2015, Alizadeh *et al*. 2013, Pampanin 2005, Vidjeapriya *et al*. 2015, Xue *et al*. 2014).

4. Relation curve of *M-θ*

From the test, the relation curve of M-θ can be obtained and the relative rotation θ to the beam-column joints needs to be measured and by reference to the definition of Eurocode 3 (2005), the relative rotation θ can be figured out according to the following formula Eq. (6).

$$\theta = \frac{\Delta_1 - \Delta_2}{h + 2h'} \tag{6}$$

In the formula, Δ_1 and Δ_2 are the displacement increment derived by both top and bottom of the beam and recorded by the displacement meter on the surface of columns. h is the height of beam; h' is the height of the displacement meter to the surface of beam.

The bending moment M can be obtained by support reaction or horizontal thrust (Fan *et al*. 2011). The comparison of M-θ curve for the specimens can be seen from Fig. 8.

The maximum rotational angle (see Fig. 8) of PAN serial test specimens all reaches 0.04 rad, close to RC-01, showing good ductility of PAN serial test specimens. During the elastic stage, it is found that the M-θ curves of the test specimens overlaps basically, explaining the initial stiffness of the test specimens is approximate.

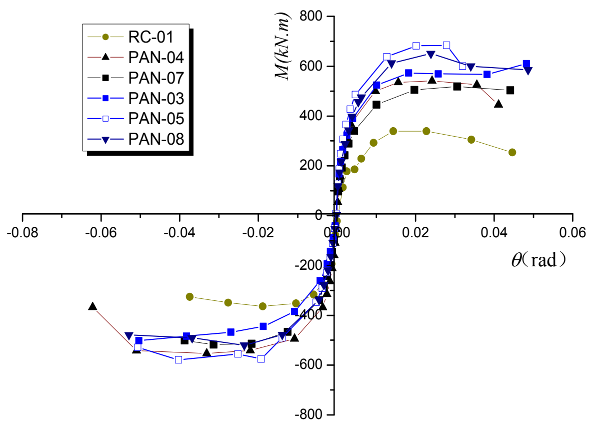


Fig. 8 M-θ curves for specimens

In bearing capacity, the bearing capacity of RC-01 test specimens is the smallest and this is because RC-01 test specimen is the shear failure in the core area of joint and both beams and columns are damaged so the bearing capacity is smaller. The reason why the bearing capacity of PAN-03 is inferior to the other test specimens of PAN series is that there is no steel plates used on the end-plates of columns' both sides, so the end-plates have severe deformation, causing the low rotational stiffness of joints in the plastic stage and joints' bearing capacity being unable to be improved.

However, because of the function of the end-plates' energy dissipation, the joints have better ductility and the arrival of loading limit in the test makes it impossible to damage the test specimen by loading.

5. Precast beam's stiffness of equivalent bending-resistant and bending rigidity of steel beam

In the Eurocode 3 (2005), the joint classification of the steel structure is based on the comparison between the initial rotational stiffness and the linear stiffness of steel-beam. But for the reinforced concrete beam, it can be assumed that section agrees with the assumption of plane section. So with reinforcement known, the equivalent elasticity modulus E_e of the section is elicited by using strain rapport. The superposition method is used here to deduce calculation formula of the equivalent elasticity modulus E_e.

The following formula Eq. (7) is the relationship between bending moment and the stress on any point of the section. Formula 7 is only applied to rectangular cross sections.

$$\sigma = \frac{My}{I_z} \tag{7}$$

Where σ-the normal stresses; y-the distance from the neutral surface; I_z-the centroidal moment of inertia of the section about z-z axis.

Thus gets the relationship Eq. (8) between bending moment M and the strain of the section's edge ε.

$$M = \frac{2\sigma I_z}{h} = \frac{2E\varepsilon I_z}{h} \tag{8}$$

Where h – the height of the beam.

Eq. (9) is the relationship between the elasticity modulus and the stain ratio of bending moment

$$E = \frac{Mh}{2I_z\varepsilon} \tag{9}$$

Because of the beam section's strain is linear change in the stage of elasticity; the bending moment's calculation of the reinforced concrete's elastic stage can be divided into two parts: concrete and rebar at different places, and then add two parts together. For this test, take PAN-03 for example and the equivalent modulus of elasticity E_e of the specific section can be calculated as follows (Fig. 9):

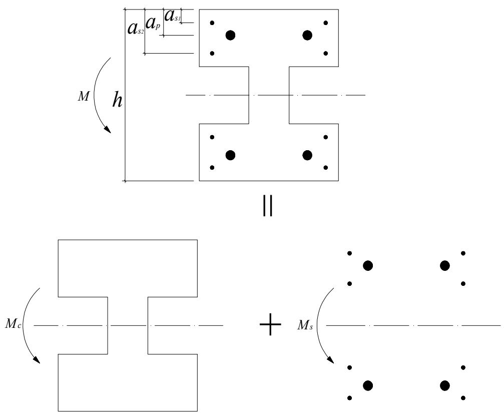


Fig. 9 the section is made up of two parts

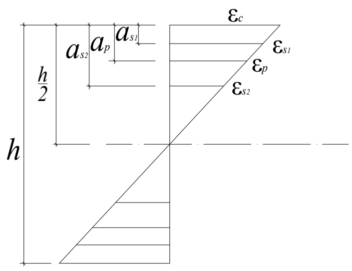


Fig. 10 the section's strain coordination

The concrete bending moment M_c borne is given by Eq. (10)

$$M_c = \frac{2I_z E_c \varepsilon_c}{h} \tag{10}$$

Where ε_c is the concrete strain.

The following relationship Eqs. (11)-(13) can be obtained by the section's strain coordination Fig. (10)

$$\varepsilon_{s1} = \left(1 - \frac{2a_{s1}}{h}\right)\varepsilon_c \tag{11}$$

$$\varepsilon_p = \left(1 - \frac{2a_p}{h}\right)\varepsilon_c \tag{12}$$

$$\varepsilon_{s2} = \left(1 - \frac{2a_{s2}}{h}\right)\varepsilon_c \tag{13}$$

Where

ε_{s1} - Reinforcement strain of the first layer;
ε_{s2} - Reinforcement strain of the second layer;
ε_p - The prestressed reinforcement strain;
a_{s1} - Distance from compression edge to the centroid of the first layer's reinforcement;
a_{s2} - Distance from compression edge to the centroid of the second layer's reinforcement;
a_p - Distance from extreme compression edge to the centroid of the prestressed reinforcement.

The bending moment borne by the rebar can be figured out according the following formula Eqs. (14)-(16)

$$M_{s1} = E_s \varepsilon_{s1} A_{s1}(h - 2a_{s1}) \tag{14}$$

$$M_p = E_p \varepsilon_p A_p (h - 2a_p) \tag{15}$$

$$M_{s2} = E_s \varepsilon_{s2} A_{s2} (h - 2a_{s2}) \tag{16}$$

Where

M_{s1} - Moment of the first layer's reinforcement;
M_{s2} - Moment of the second layer's reinforcement;
M_p - Moment of the prestressed einforcement;
A_{s1} - Area of the first layer's reinforcement;
A_{s2} - Area of the second layer's reinforcement;
A_p - Area of the prestressed reinforcement.

The total bending moment can be got by adding different parts together Eq. (17)

$$M = M_c + M_{s1} + M_p + M_{s2} \tag{17}$$

Put Eqs. (10), (14)-(16) into Eq. (17) and get the following Eq. (18)

$$\frac{Mh}{\varepsilon_c} = 2I_z E_c + E_s A_{s1}(h - 2a_{s1})^2 + E_p A_p (h - 2a_p)^2 + E_s A_{s2}(h - 2a_{s2})^2 \tag{18}$$

Put Eq. (18) into Eq. (9), and get the equivalent elasticity modulus of the section Eq. (19)

$$E_e = \frac{1}{2I_z}\left[2I_z E_c + E_s A_{s1}(h - 2a_{s1})^2 + E_p A_p (h - 2a_p)^2 + E_s A_{s2}(h - 2a_{s2})^2\right] \tag{19}$$

The equivalent bending stiffness of the section Eq. (20)

$$E_e I_z = \frac{1}{2}\left[2I_z E_c + E_s A_{s1}(h - 2a_{s1})^2 + E_p A_p (h - 2a_p)^2 + E_s A_{s2}(h - 2a_{s2})^2\right] \tag{20}$$

6. Discrimination of joint type

The beam's length in the test is 1.445 m, so it does not accord with the actual project. Besides, according to the joint classification standard of Eurocode 3 (2005), the beam's length is a key parameter. Here set the beam's length as an unknown quantity, then figure out the beam's length when the joint stiffness reaches the point where the rigid joint requires, just as Eq. (21)

$$L_b = 25\frac{EI_b}{S_{j,ini}} \tag{21}$$

Where L_b - the length of the beam; I_b - moment of inertia of beam.

The initial rotational stiffness $S_{j,ini}$ can be obtained according to the test curve of M-θ and results are as follows. From Table 2, it is clearly observed that the maximum of the beam length to

Table 2 Beam's length of rigid joint (unit: force/kN, length/m)

Specimen	$S_{j,ini}$	EI_b	L_b	$25EI_b/L_b$
RC-01	2.08E+05	1.01E+05	12.17	2.08E+05
PAN-03	1.88E+05	8.68E+04	11.55	1.88E+05
PAN-04	2.87E+05	8.68E+04	7.57	2.87E+05
PAN-05	2.59E+05	8.68E+04	8.37	2.59E+05
PAN-07	3.18E+05	8.68E+04	6.82	3.18E+05
PAN-08	5.64E+05	8.68E+04	3.84	5.64E+05

meet rigid joint is cast-in-place RC-01,whose span is 12.17 m, while the minimum is fabricated joint PAN-08 with the span of 3.84 m. Generally speaking, the cast-in-place joint is fully rigid. In the concrete code, the cast-in-place joint is regarded as rigid joint to design and it is proved in the practical projects that the assumption satisfies the requirement of application and safety. Therefore, the fabricated joint of PAN series can be regarded as rigid joint.

7. The classification method of concrete joint

By analyzing the data of the joint's initial stiffness in Table 2, it is obtained that the strength in the beam's bending linear rigidity and joint mode determines the initial rotation stiffness. In PAN series, the initial rotation stiffness of PAN-03 is minimum. The reason is that there is no steel bar to connect the end-plate outside the specimen, making the joint weakened and the initial rotation stiffness smaller.

The height of the concrete beam's section normally ranges from 1/12 to 1/18 of the girder span, of which the minimum for the height of 450 mm section is 5.4 m, the maximum 8.1 m. Both are smaller than 12.7 m, which shows the joint classification standard in Eurocode3 (2005) isn't suitable for the concrete structure. As is said above, regard the cast-in-place joint as rigid one with the beam's span of 5.4 m as the minimum beam length when the joint RC-01 meets the requirement of rigid joint, so the following inequality can be applied for the concrete joint classification standard:

Rigid joint (unbraced structure) Eq. (22)

$$S_{j,ini} \geq 11\frac{EI_b}{L_b} \tag{22}$$

Semi-rigid joint (unbraced structure) Eq. (23)

$$\frac{1}{2}\frac{EI_b}{L_b} < S_{j,ini} < 11\frac{EI_b}{L_b} \tag{23}$$

According to the standard above, the minimum beam length of the rigid concrete fabricated joint can be figured out and the result is shown in Table 3. As is seen in Table 3, PAN-03 needs a span of 5.08 m, PAN-08 1.69 m if the requirement of rigid joint must be met; showing that the way of the end-plate being connected outside can significantly enhance the initial rotation stiffness. As

Table 3 Beam's length of concrete rigid joint (unit: force/kN, length/m)

Specimen	$S_{j,ini}$	EI_b	L_b	$11EI_b/L_b$
PAN-03	1.88E+05	8.68E+04	5.08	1.88E+05
PAN-04	2.87E+05	8.68E+04	3.33	2.87E+05
PAN-05	2.59E+05	8.68E+04	3.68	2.59E+05
PAN-07	3.18E+05	8.68E+04	3.00	3.18E+05
PAN-08	5.64E+05	8.68E+04	1.69	5.64E+05

for the practical projects, the beam's span is over 5m, so the new fabricated joint meets the requirement of practical projects.

8. Conclusions

In this paper, the quasi-static test is performed on seven new fabricated column-beam joints and the rotation capacity of the column-beam joints is analyzed .The following conclusions can be drawn by theoretical derivation:

- Using the steel strip to connect the end-plates on both sides of column outside joints, it can make up the drawback resulting from too much bolt-space caused by the flange thickness and significantly enhances the initial rotation stiffness of joints.
- The bolted end plate joints adopted on the new fabricated column-beam joint can be designed based on rigid joint.
- The new fabricated column-beam joint satisfies both the span the rigid joint needs and the requirement of application and safety.
- The new fabricated column-beam joints can be classified by theoretical derivation, and this method can guarantee the safety of the practical projects.

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