Numerical investigation of beam-column connections using a new multi-axial-spring model

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Abstract

Precast concrete moment-resisting frame with hybrid beam-column connections, which is featured by inelastic deformation induced by opening and closing of the interface between precast beam and column, is emphasized in recent years, since it is capable of sustaining design basis earthquake with tiny damage. To explore the opening and closing behavior of the interface of hybrid beam-column connection, a new multi-axial-spring model with only two gap elements whose position and capacity is determined by simple advance section analysis method is proposed. The new multi-axial-spring model, which is obviously with high computational efficiency, is able to tracking accurately the change of compressive zone height of the interface between precast beam and column and count in “beam elongation effects”. The proposed numerical model analysis results are in good agreement with the experimental results.

Keywords: **Hybrid beam-column connection, Multi-axial-spring model, Compressive zone height, Precast concrete frame.**

Introduction

Compared with conventional monolithic concrete structures, precast concrete systems are advantageous in product quality, cost efficiency, and speed of construction. Precast concrete frame system with hybrid beam-column connections is widely used and commonly accepted in main design codes worldwide, for its capability of sustaining a design level earthquake with limited or negligible damage [1].

In precast frames with hybrid connections, the inelastic deformation demand is concentrated at and provided by opening and closing of the beam-column interface. A variety of numerical models, including macro-models, section analysis model, fiber model, lumped plasticity model, multi-axial-spring model and FEM model(Solid model), have been proposed to predict the behavior of hybrid connections with different level of complexity[1-4]. Fiber and lumped plasticity models are used widely with good accuracy and low computational cost, but for both models, it is difficult to simulation “beam elongation effect”.

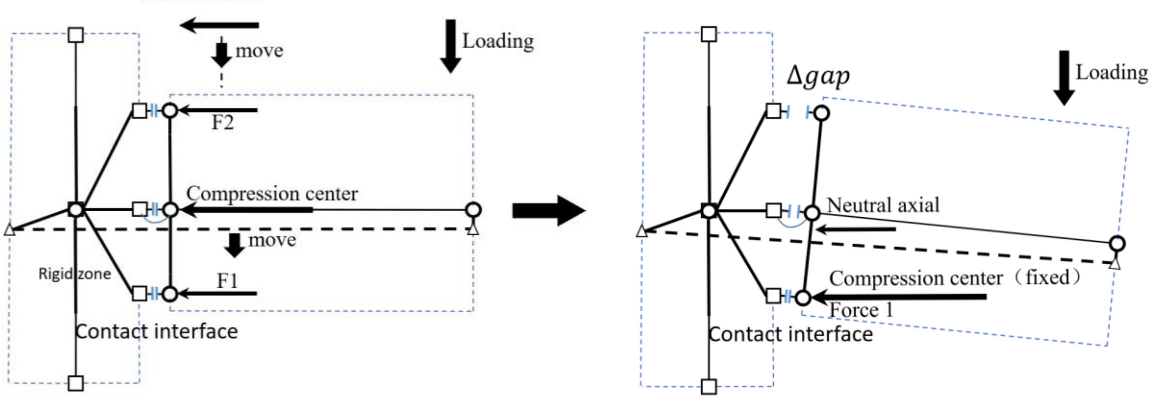
Multi-axial-spring model can be used to analyze the rocking behavior and capture the beam elongation effects, such an approach has been widely used to model the hybrid connections. In this model the joint itself was assumed to remain rigid, while beams and columns element are assumed to remain elastic. Inelastic action was supposed to concentrate in the grout(at the beam-column interface) and mild steel bars. Truss elements were used to model the reinforcing steel, while a prestressing element was used to prestress the joint together and 9 gap elements, which are evenly spaced along the height of the interface grout and each with the same area of grout, were used over each side to represent the grout behavior. Further details on the model as well as complete results on beam elongation effects from analytical investigations (using the computer program DRAIN-2DX) on multi-story frame systems can be found in Kim (2002) [5]. Carr, 2004 [6,7] has improved capabilities simulating the contact section interface with an increased number of gap elements. The gap elements is set up for 2 to 10 contact points, which are not evenly spaced along the height of the interface grout and each with the different area of grout. Two different integration schemes, namely, Gauss quadrature and Lobatto integration, can be used to optimize the position of gap elements and calculate their weighting.

In this paper, a new multi-axial-spring model with only two gap elements on half side of interface, which is obviously with better computational efficiency, is proposed and validated. Section analysis method is used to determine the distribution of the two gap elements and a representative area method is used to determine the mechanization property of the gap elements. In this investigation, the proposed model is used to simulate several tests including both hybrid connections and PPEFF beam-column connections [8]. Satisfactory agreement in aspects of overall mechanical property, mild reinforcement strain, prestressed tendon stress and compression center between the analytical and experimental results confirms the validity of the proposed model.

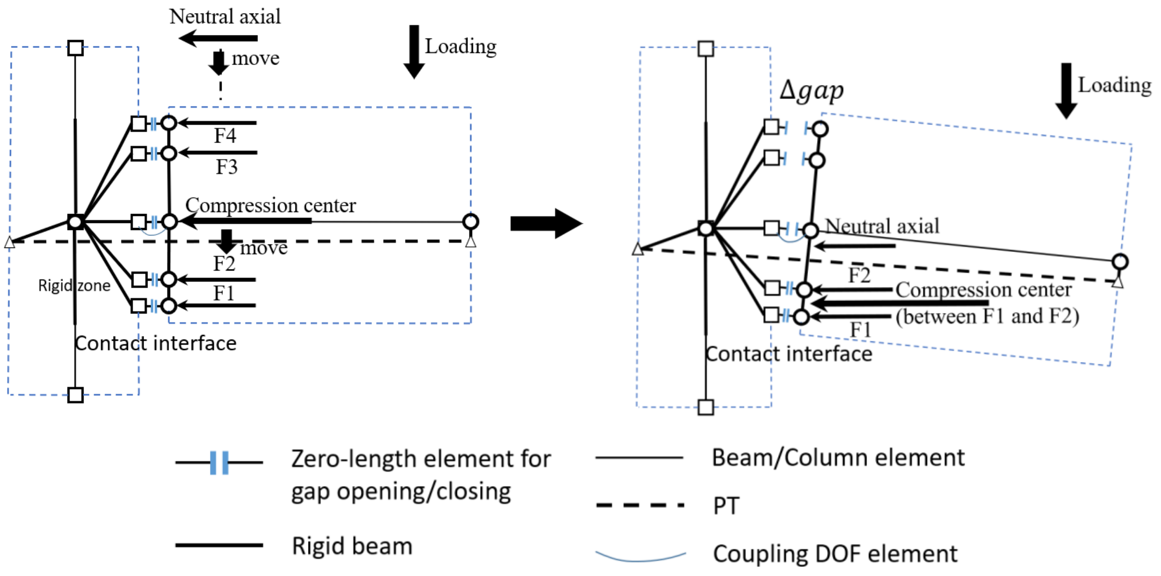
1 Methodology

1.1 Principle

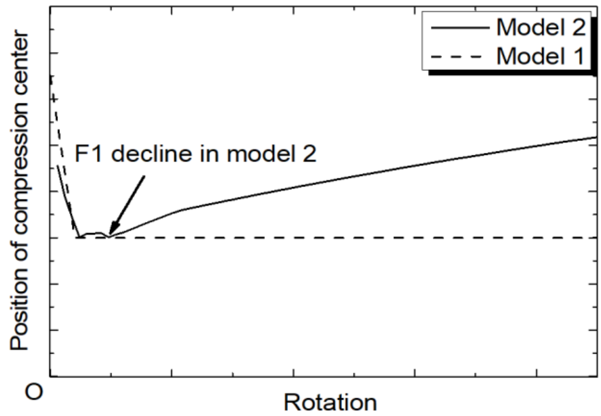
In case of the inelastic deformation of the connections induced by gap opening/closing of the contact interface the model should simulate accurately the local stress and strains in the contact area. The length of inner lever arm（distance from reinforcement to compression center）at the rocking section should be accurately simulated which is proportionate to the capacity of the rocking connection. With increase loading the neutral axis moves from infinity into the contact section and decreases in size with increasing gap opening, finally with the crushing of the edge concrete the compress zone increases in size. Figure 1 shows that two gap elements in compress area (model 2) can simulate the shift of the neutral axis more accurately than one gap element(model 1). In model 2, with suitable location and mechanical property gap elements, the simulate neutral axis firstly move from outside section into the section and the compress center move downward into the scope between F1 and F2, with the loading increasing the F1 begin to decline, the compress center begin to move upward (show in figure1c).



a) Model 1(one spring for compress zone)



b) Model 2(two springs for compression zone)



c) Position of compression center

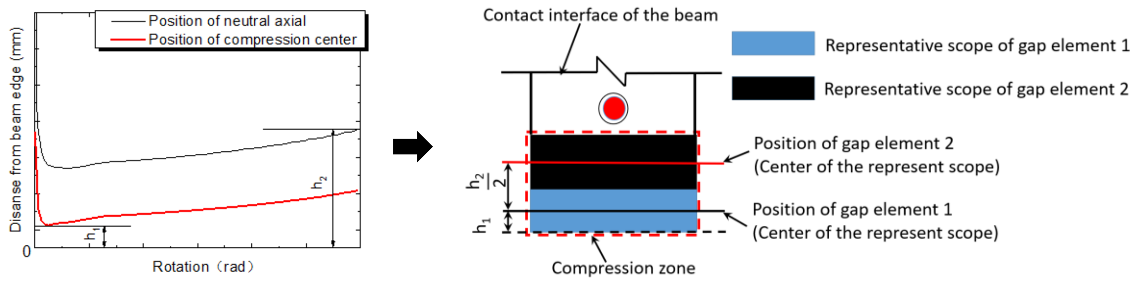
Figure 1 Shift of the compression center(numerical simulated)

1.2 Distribution and mechanical property of the gap elements

This paper proposes a new method to simulate the concrete in compressive zone with only two gap elements, and introduces the technique to determine the position and weighting of the two gap elements. To accurately simulated the shift of the neutral axis, the distribution of the gap elements is calculated by section analysis method [1]. We using the section analysis procedure proposed by reference [1] to simulated the contact interface of the beam column connection, and the position of the neutral axis and compression center can also be calculated (show in figure 2).

If the calculated position of the lowest point of compression center is h_1(from beam section edge), and the position of the neutral axis is h_2 at maximum rotation. We set the position of gap element 1 at the position of h_1 and the position of gap element 2 at the position of $h_1 + \frac{h_2 - h_1}{2}$ (show in the figure 2).

The mechanical property for each gap element is derived from the mechanical property of the scope of concrete it represent. Details of the model will be introduced in section 2.2.



a) Section analysis results b) Distribution of springs

Figure 2 Determine of the position of gap elements

1.3 Preliminary verification

Numerical simulation was conducted using the model presented in section 1.1 and 1.2. The proposed numerical model was developed using the Open System for Earthquake Engineering Simulation (OpenSees) [9]. Figure [3] shows the comparison between the numerical simulation and test result(O-P-Z4) of NISTIR[10], where good agreement is observed both of skeleton curve and hysteretic curve which confirm the validity of the proposed model.

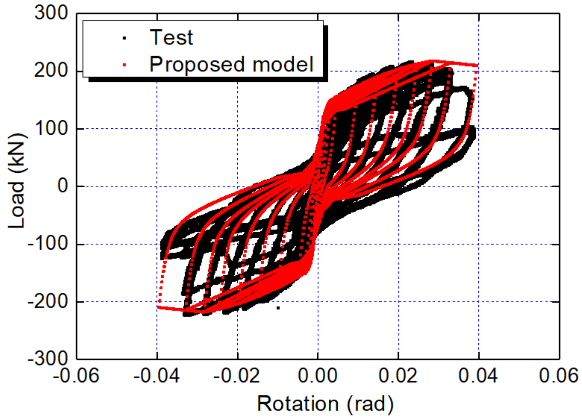


Figure 3 Comparisons of hysteretic behavior between numerical simulation and test

2 Experiment and numerical model

2.1 Experiment

Test were conducted on four specimens of PPEFF beam-column connections [8]: two exterior precast connections and two interior precast connections. The model is shown in Figure 4. Reinforcement information is in Table 1. Detailed information of the specimens are in reference [8]. Quasi-static tests were carried out to investigate the hysteretic behavior, stiffness, bearing capacity and deformation capacity of the beam-to-column dry connection assembled by post-tensioned tendons under slow reversed cycle loading. Experiment result shows PPEFF and hybrid beam-column connections is similarity in working and damage mechanism under low frequency cyclic loading, both of them is featured by inelastic deformation induced by opening and closing of the interface between precast beam and column, the PPEFF joint has slightly better performance [8].

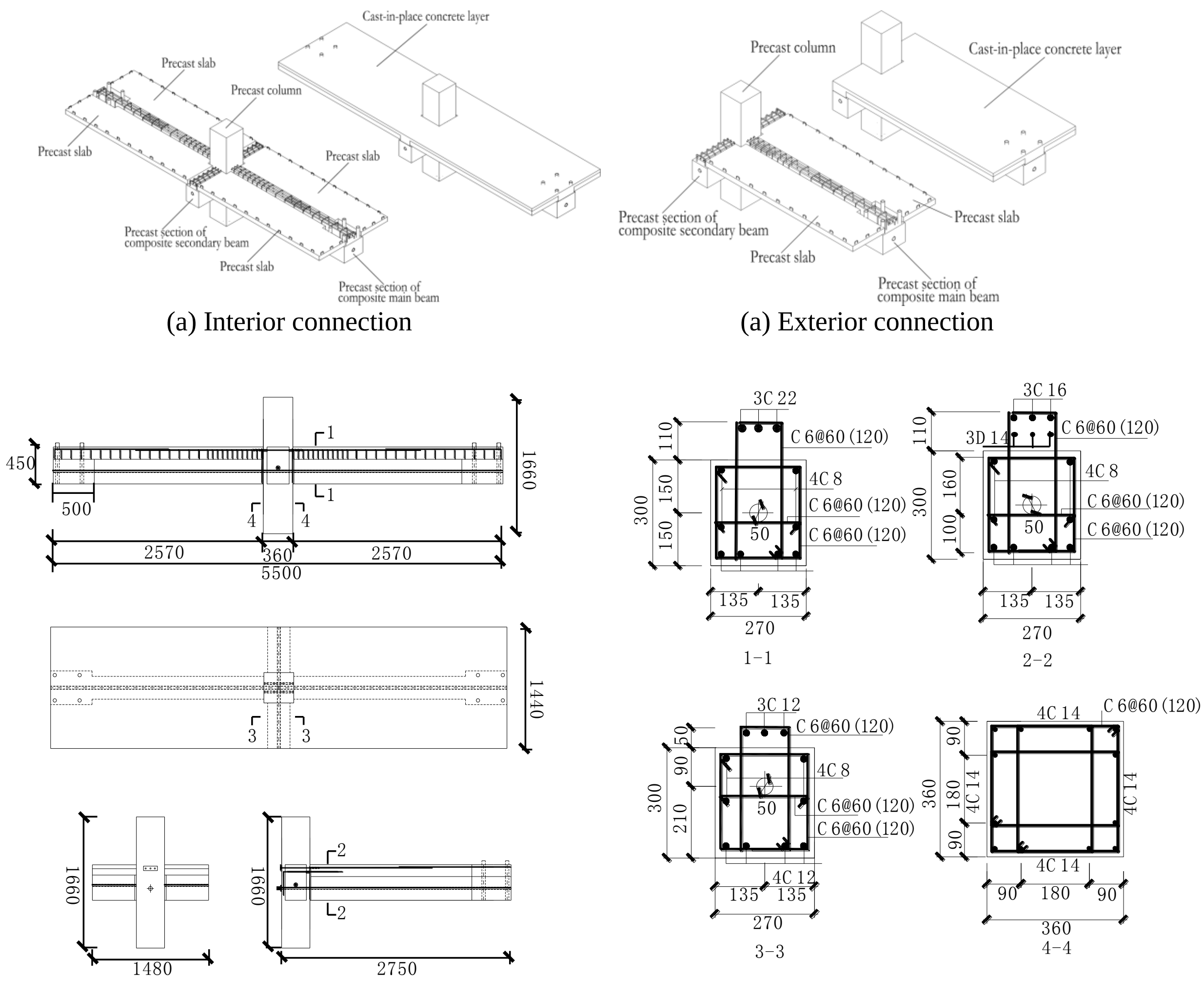


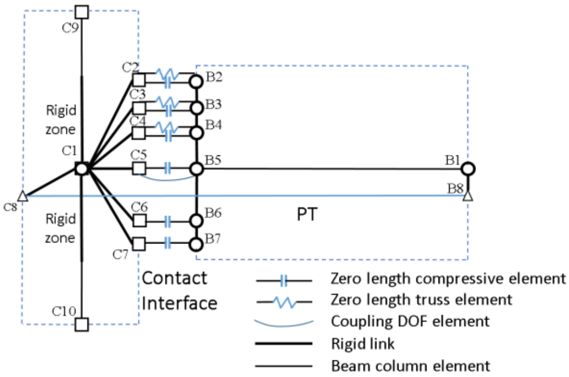
Figure 4 Connection specimens

Table 1 Test specimens

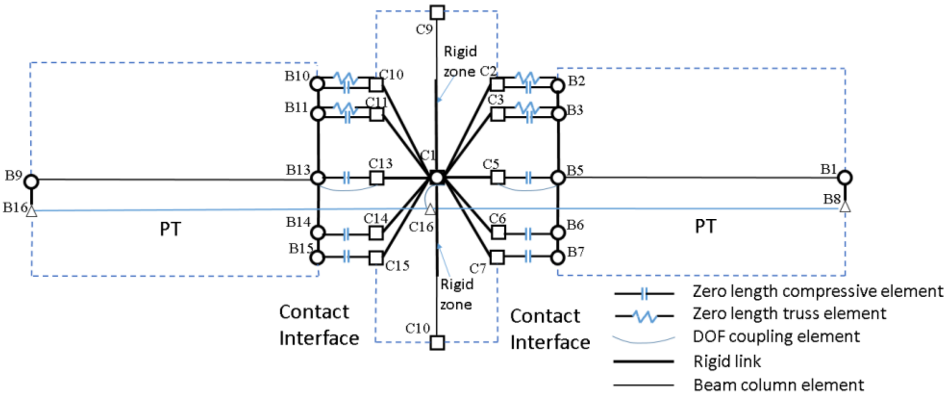
Connection type	Specimen Name	Slab steel	Bending steel	Shear steel	Length of unbonded mild steel(mm)	Unbonded PT
Interior	A2	12C6	3C22	--	360 (inside column)	4Φs15.2
	A3	12C6	3C22	--	120 (outside column)（10% weakened）	4Φs15.2
Exterior	B2	12C6	3C16	3C14	360 (inside column)	4Φs15.2
	B3	12C6	3C16	3C14	120 (outside column)（10% weakened）	4Φs15.2

2.2 Numerical model

The proposed numerical model was developed using OpenSees as shown in Figure 5.



a) Exterior Joint



b) Interior Joint

Figure 5 Numerical model

(1) Zero length elements with compression-only material properties (gap elements) are adopted to simulate the opening/closing behavior of the contact interface.
(2) Truss element with STEEL02[11] material (assigned initial strain), which takes isotropic hardening and Bauschinger effect into consideration, is used to simulate PT.
(3) Distribution reinforcement in slab, energy dissipation mild-steel are all simulated by zero length elements using STEEL02 material. CONCRETE02[12] material is used to simulate the concrete, transverse confinement effect is accounted for using the Mander model [13]. The length of truss element in this model (L_{model}) is different from the actual length of unbonded reinforcement in test (L_s), so the material properties and area of the elements require modification [5] using Formula (1).

$$A_1 = A_0 L_{model}/L_s \ , \ f_1 = f_0 L_s/L_{model} \tag{1}$$

Where A_1 、 f_1 are the area and yielding strength of the mild-steel in numerical model; A_0, f_0 are in test.
(4) Vertical coupling restraint is applied to limit the shear slip between C5 and B5, neglecting shear slip between precast beam and column.
(5) In the links of C2-B2 and C10-B10, two elements are used: one zero length element (assigned Concrete01 material with compression-only material properties) to simulate contact interface and one zero length element to simulate the behavior of rebar in slab.
(6) Two zero length elements are used to model the compressive behavior of the contact interface and mild energy dissipation steel for C3-B3 and C11-B11 links.
(7) Shear reinforcement in exterior connections is simulated by zero length element (assigned Hysteretic material) between C4 and B4. Noting that the bond length of shear reinforcement is 15d (d is the diameter of rebar), which is shorter than the anchorage length, the force-

displacement relation of zero length element is derived from bond-slip relation between concrete and rebar.

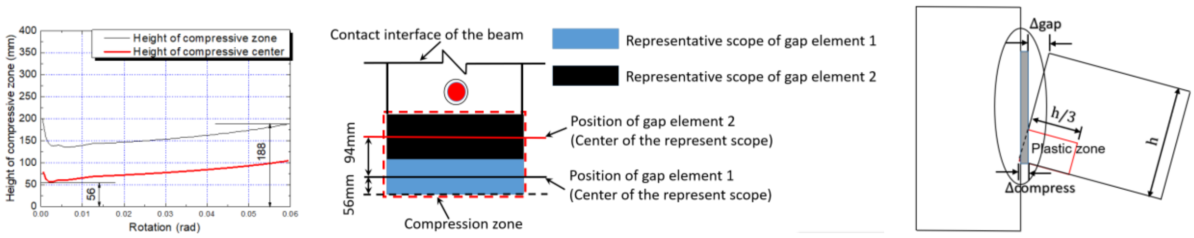
$$F=\pi d*\tau_0*15d=15\pi d^2*f(s) \tag{2}$$

Where s stands for slip displacement, $f(s)$ is the bond-slip relation between concrete and rebar[14].

(8) In the links of C6-B6, C14-B14, C7-B7 and C15-B15, zero length elements with compression-only material properties (gap elements) are used to simulated the contact interface. According to section analysis method, the minimum position of compression center is 56mm(take A3 for example), set gap element 1(Figure 6) at this position, which simulates the compressive zone with 112mm high at the bottom of the contact interface. (C6-B6, C14-B14) is designed to simulate the rest concrete when scope of the compressive zone exceeds the representative scope of gap element 1. For A3 the position of gap element 2 is (188-112)/2+112=150. Where 188mm is the calculated high of compression zone using section analysis method (show in figure 6). The mechanical property for C6-B6, C14-B14, C7-B7 and C15-B15 is derived from the mechanical property of the scope of representative concrete element with the length of h/3(the length of the plastic zone is h/3[15], where h is the beam section height). The length of truss element in this model (L_{cmodel}) is different from the actual length of plastic zone, so the material properties and area of gap elements require modification [5] using Formula (3).

$$A_c=3A_{c0}L_{cmodel}/h\ ,\ f_c(\varepsilon)=f_{c0}(\varepsilon)h/(3L_{cmodel}) \tag{3}$$

Where A_c 、 $f_c(\varepsilon)$ are the area and constitutive relationship of the concrete material in numerical model; A_{c0}, $f_{c0}(\varepsilon)$ are in test.



a) Section analysis results b) Distribution of gap elements c) Plastic zone

Figure 6 Position of the gap elements (C6-B6, C14-B14, C7-B7 and C15-B15)

(9) Figure 7 shows that the position of gap elements linking C2-B2, C10-B10, C3-B3 and C11-B11. The mechanical property of the gap elements is derived from the mechanical property of the representative concrete. The rest scope of the interface is simulated by the gap elements linking C5-B5 and C13-B13.

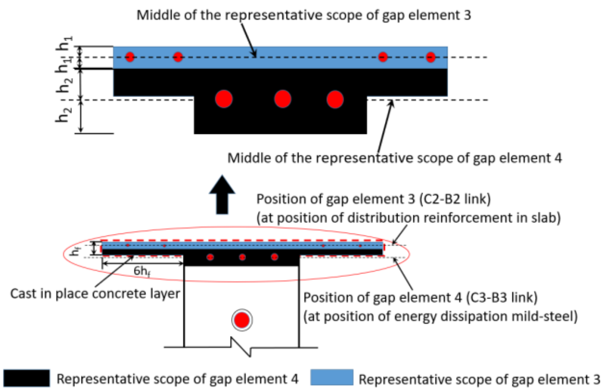
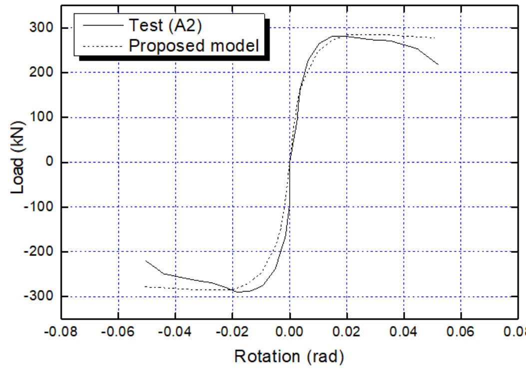


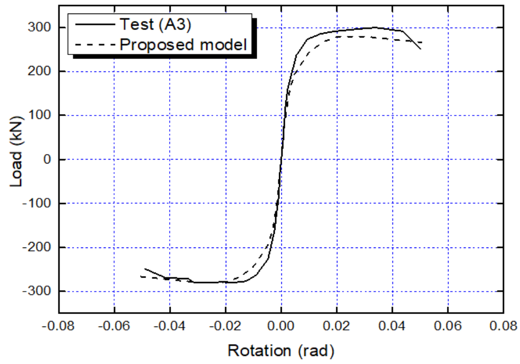
Figure 7 Position of the gap elements (C2-B2, C10-B10, C3-B3, C11-B11)

3 Experimental validation

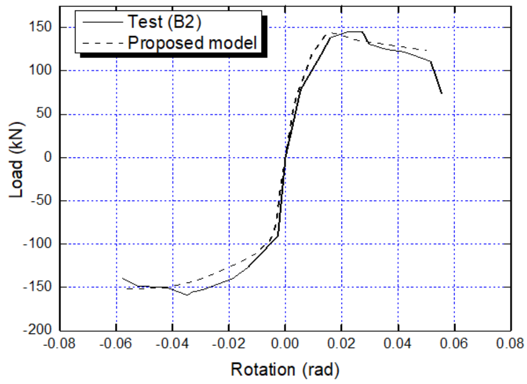
3.1 Validation of skeleton curves



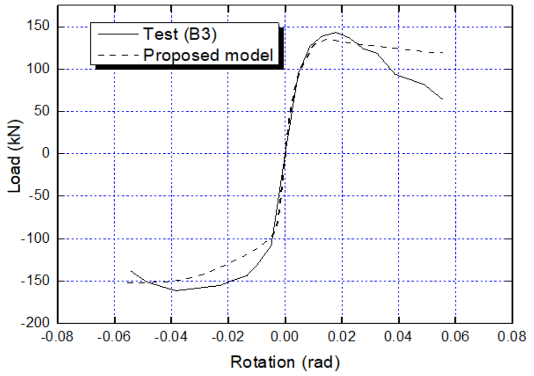
a) A2



b) A3



c) B2



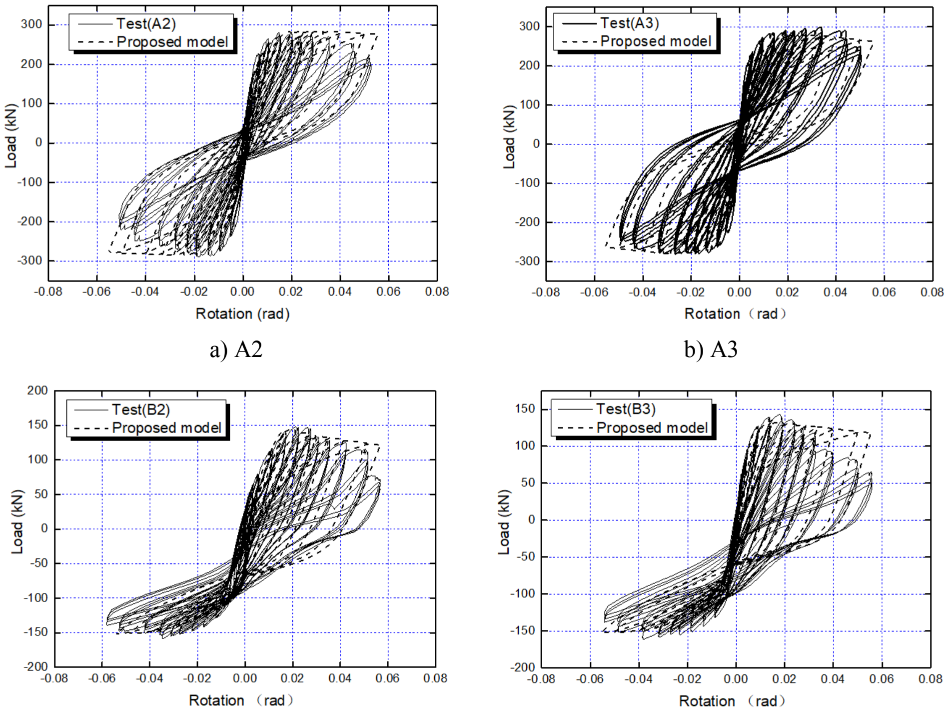
d) B3

Figure 8 Validation of the proposed model: skeleton curves

Dissymmetry in the skeleton curves of exterior connections, due to asymmetrical reinforcement through the beam-column contact interface, can be recognized in figure 8. For interior connection, the summation of bending capacity contributed by contact interface in either side of the column is symmetry, resulting in symmetrical skeleton and hysteretic curves. The experimental and simulation results of B2 and B3 show that, the contact interface remains elastic before cracking and the section stiffness declines after cracking. Under positive loading (mild steel in tension), the cracking moment is small because the prestressing tendons are at the mid lower portion of beam section, and due to mild steel and distribution steel in the slab, gradual instead of sharp stiffness decrease is observed before yielding of mild steel. Under negative loading (mild steel in compression), however, the cracking moment at the interface is larger and section stiffness decreases greatly as the neutral axis goes upward after cracking.

Under positive loading, the mild steel go gradually from elastic state into yielding and hardening stage as the moment rising, until the exterior concrete in compressive zone reaches its ultimate strength. Afterwards, the concrete at the edge of the contact interface crushed and the compression center moved upward, leading to decent of the bearing capacity. Under negative loading, the bearing capacity of the connection kept increasing under large deformation as the prestress tendon remains elastic and the slight damage of the compressive concrete due to slab. The connection bearing capacity decreased slightly after crushing failure of concrete.

3.2 Validation of hysteretic behavior



a) A2 b) A3

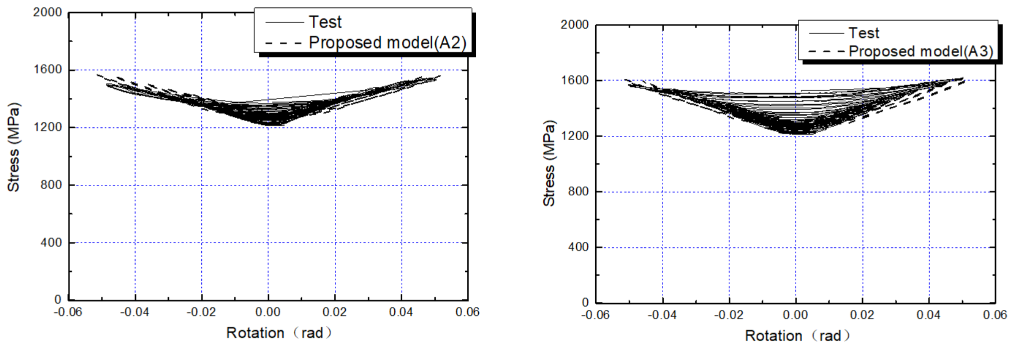
c) B2 d) B3

Figure 9 Validation of the proposed model: hysteretic behavior

Figure 9 shows the comparisons between the numerical simulation and test results, where the self-centering behavior and energy dissipation behavior are accurately replicated, implying the effectiveness of the proposed model for the behavior and mechanism of contact interface of the connections.

3.3 Validation of the stress of PT

Figure 10 shows the comparison of simulation and experimental results on stress of PT, where good agreement is observed.



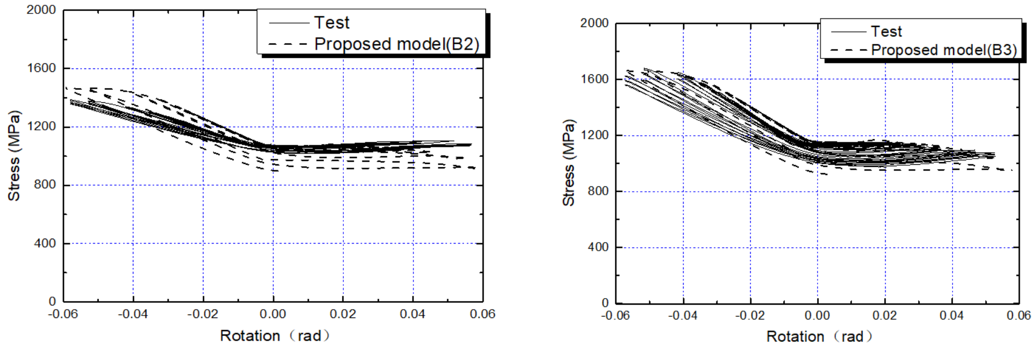


Figure 10 Validation of the proposed model: stress of prestressed tendon

3.4 Validation of the shift of compression center at contact interface

To further testify the accuracy of this model, the positions of compression center in simulation and test are compared for A3 and B3.

Using test data, including moment of the interface, stress of prestressed tendon and rotation of the interface, the position of compression center and stress of mild steel are calculated according to force equilibrium and moment equilibrium on the contact surface. The whole procedure can be summarized as follows.

① Impose a rotation θ, and get the moment M_0 based on test results

② Guess an initial neutral axis position c,

Calculate $\varepsilon_c = f(c)$, Evaluate corresponding compression force C, and calculate the position of compression center.

③ Calculate tensile force of prestressed tendon F_p according to section rotation and measured

④ Calculate tensile force of mild steel based on Section Equilibrium.

$$F_y = F_0 - F_p$$

⑤ Evaluate moment capacity.

$$M = F_y(C_0 + C_y) + F_p(C_0 + C_p)$$

C_y、C_p are the distances from the neutral axis to the mild steel and prestressed tendons, respectively.

⑥ If M = M_0

Yes, Go to Step 7

No, Revise neutral axis position and go to Step 2

⑦ End

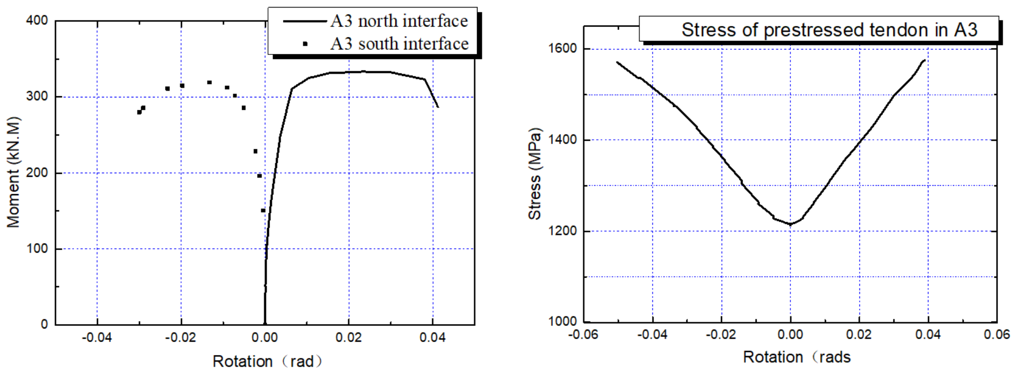


Figure 11 Rotation of contact interface and stress of PT (A3 test)

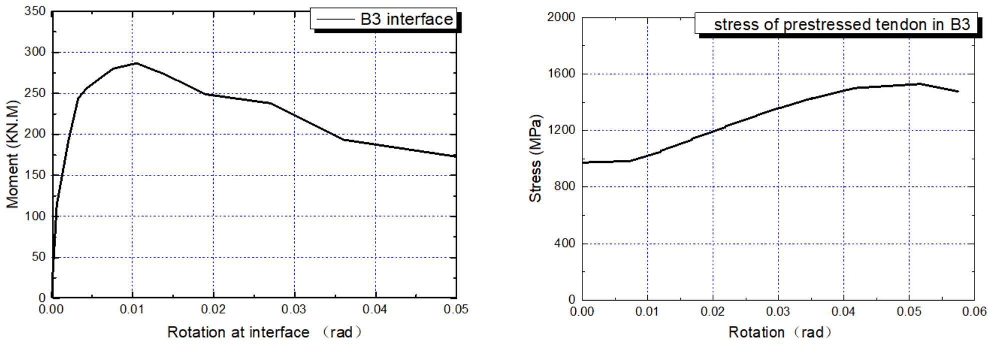
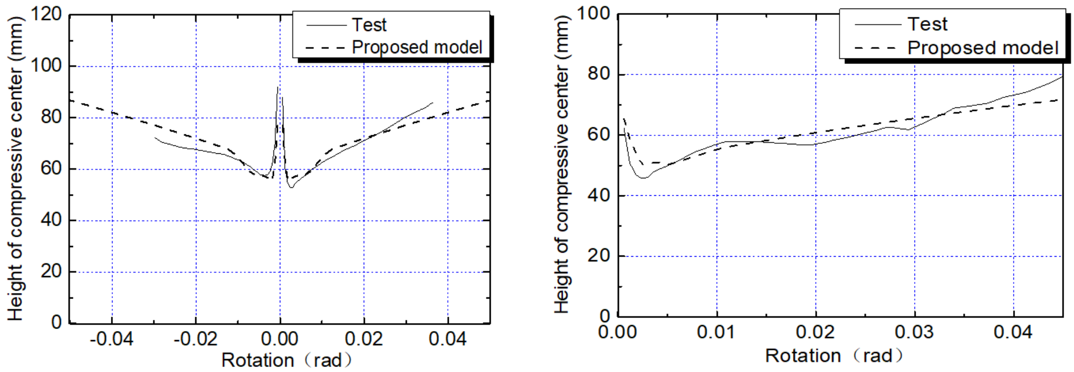


Figure 12 Rotation of contact interface and stress of PT (B3 test)

The shift of compression center calculated from the above procedure is shown in figure 13, using the test data in figure 11 and 12. The simulated compression center using proposed model is also given in figure 13 , which shows good agreement of the simulation and test results.



A3 **B3**

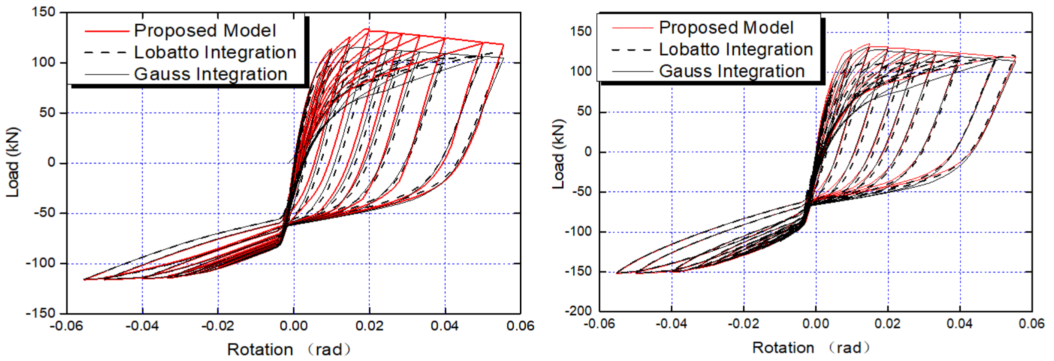
Figure 13 Comparison of compression center position between simulation and test

4 Study of gap elements distribution

Spieth 2004 proposed a multi-spring contact element using Lobatto Integration and Gauss integration to calculate the position of the springs and their weighting. In this paper the effect of different distribution of the springs is investigated. Figure 14 and 15 shows the simulation results by the models using Lobatto integration, Gauss integration and the proposed method in this paper to calculate the position of the gap elements (gap element 1 and 2 in figure 6) and their weighting(show in Table 2). Figure 16-18 show comparison of PT stress, steel stress and compression center position between proposed model and the model using Gauss integration.

Table 2 Position and weighting of the compression gap elements using numerical integration

Spring	Proposed model （A3）		Proposed model （B3）		Lobatto integration		Gauss integration	
	Position	weighting	Position	weighting	Position	weighting	Position	weighting
1	0.33	0.34	0.44	0.23	0.447	0.83	0.34	0.65
2	0.75	0.50	0.78	0.44	1	0.17	0.86	0.35



A3 B3

Figure 14 Comparison of the hysteretic behavior of A3(Beam end loading) and B3

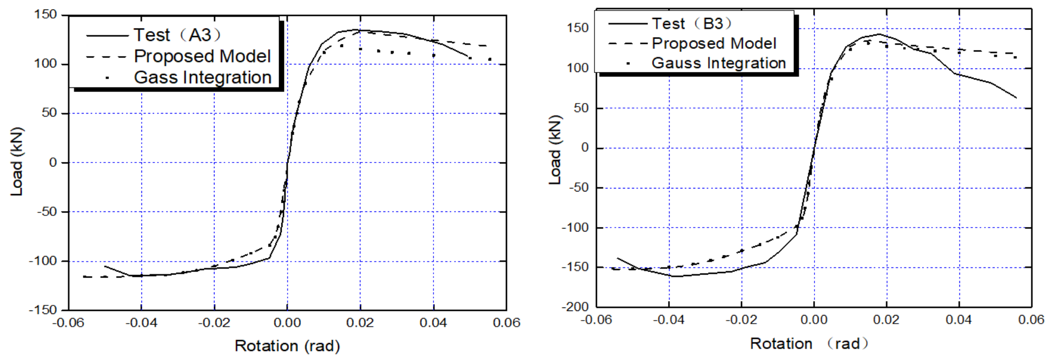
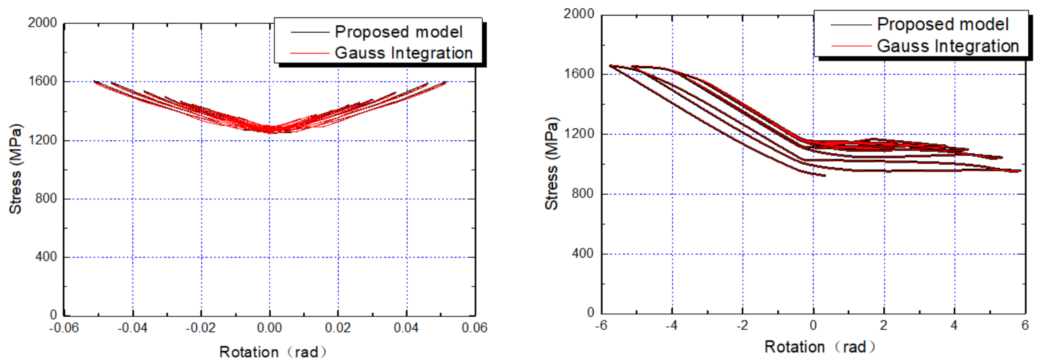
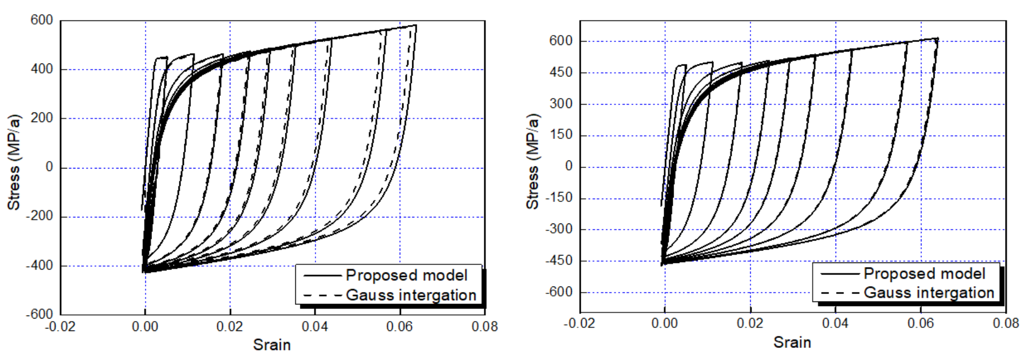


Figure 15 Comparison of the skeleton curves



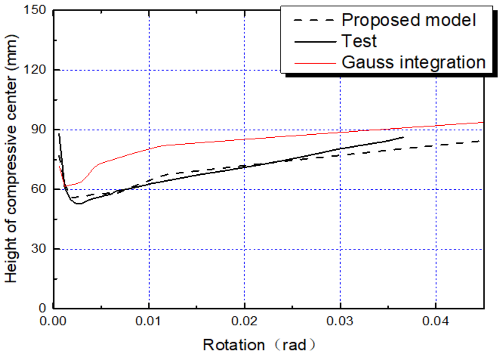
A3 B3

Figure 16 Comparison of stress of prestressed tendon of A3 and B3

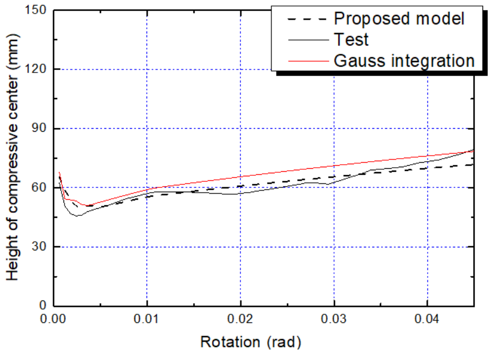


A3 B3

Figure 17 Comparison of steel stress of A3 and B3



A3



B3

Figure 18 Comparison of compression center of A3 and B3

The method proposed in this paper to determine the position and weight of gap elements takes into consideration the variation of compressive zone, calculated from section analysis procedure, caused by prestressed tendon's area and stress state, area of mild steel, geometry of the contact section, etc. Gauss integration and Lobatto integration, which merely calculates the position and weight of integration point mathematically but without clear physical significance, however, diverges from the actual situation and the simulation results are inferior to that of the proposed method.

5 Conclusions

Based on the comparison of the presented analysis and tests results, conclusions are drawn as follows:

(1) The new multi-axial-spring model, which is obviously with higher computational efficiency, is able to tracking accurately the change of compressive zone height of the interface between precast beam and column and count in "beam elongation effects".

(2) The new multi-axial-spring model is validated by several low-cycle loading tests including both hybrid connections and PPEFF beam-column connections and satisfactory agreements in aspects of skeleton curve, hysteretic curve, prestressed tendon stress and compression center are obtained between the analytical and experimental results.

(3) The new multi-axial-spring model is obviously with better computational efficiency than previous multi-spring models using Lobatto Integration and Gauss Integration since the new one is more accurate with the same number gap elements.

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