Seismic performance analysis of sleeve beam-column nodes under different reinforcement conditions based on Abaqus

Xiao Shuoting [1,*], *Nikita* Fomin[1], *Irina* Maltseva[1], and *Wang* Houyan[2]

[1]Ural Ural Federal University named after the First President of Russia B. N. Yeltsin, Yekaterinburg, Russia
[2]Ningbo Youzao Construction Technology Company, Ningbo, Zhejiang, China

Abstract. This study investigates the effect of different reinforcement designs on the seismic performance of RC columns with beam-column joints connected using grouted sleeves. Through finite element analysis using ABAQUS software, various reinforcement configurations were simulated and their seismic performance was evaluated. 3 reinforcement configurations were simulated and their seismic performance was evaluated through finite element analysis using ABAQUS software. The results showed that the use of grouted sleeve connections with additional installed reinforcement and composite hoop configurations were effective in improving the seismic performance of prefabricated columns with grouted sleeve beam-column connection nodes. The stiffness reduction and displacement ductility of the specimens were analyzed, and it was found that the longitudinal reinforcement diameter had a negligible effect on the stiffness reduction, while the use of composite hoops was more effective in improving the displacement ductility compared to parallel hoops. These findings help to understand the behavior of beam-column connections and provide a reference for the design of seismic-resistant structures and future research.

1 Introduction

In the rapidly evolving landscape of construction, prefabricated and modular structures have emerged at the forefront, chiefly due to their potential for swift construction, cost-effectiveness, environmental friendliness, and consistency in quality [1-4]. These merits align seamlessly with the construction industry's aspirations for sustainable development, marking a shift from traditional building methods to more advanced, eco-friendly practices. Beam-column joints in prefabricated reinforced concrete structures are critical joints. The failure of beam-column joints is often brittle in nature. Beam-column joints are susceptible to failure during an earthquake due to the high shear forces developed within the join [5]. In past earthquakes, the failure of beam-column joints, especially corner joints, has played a crucial role in building collapses [6].

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[*] Corresponding author: shuotingxiao@gmail.com

These joints have traditionally been reinforced using the lap method, but due to the ever-changing construction requirements, there has been a significant shift in reinforcement methods. Grouted sleeve connections are an alternative method that has emerged in contemporary times with potential advantages such as improved stress distribution and ease of construction. However, the effect of different reinforcement designs on the seismic performance of beam-column connections using such grouted sleeve connections remains largely unknown. The effectiveness and robustness of such connections, especially under cyclic seismic loading, are of paramount importance for modern infrastructures. The purpose of this work is to establish finite element models of different reinforcement designs through ABAQUS, to calculate, simulate and study the effect on the seismic performance of RC columns connected with reinforced grouting sleeves, with the aim of guiding structural engineers in designing for enhanced seismic capacity, and providing ideas and a basis for subsequent research.

2 Finite element modeling

2.1 Specimen design

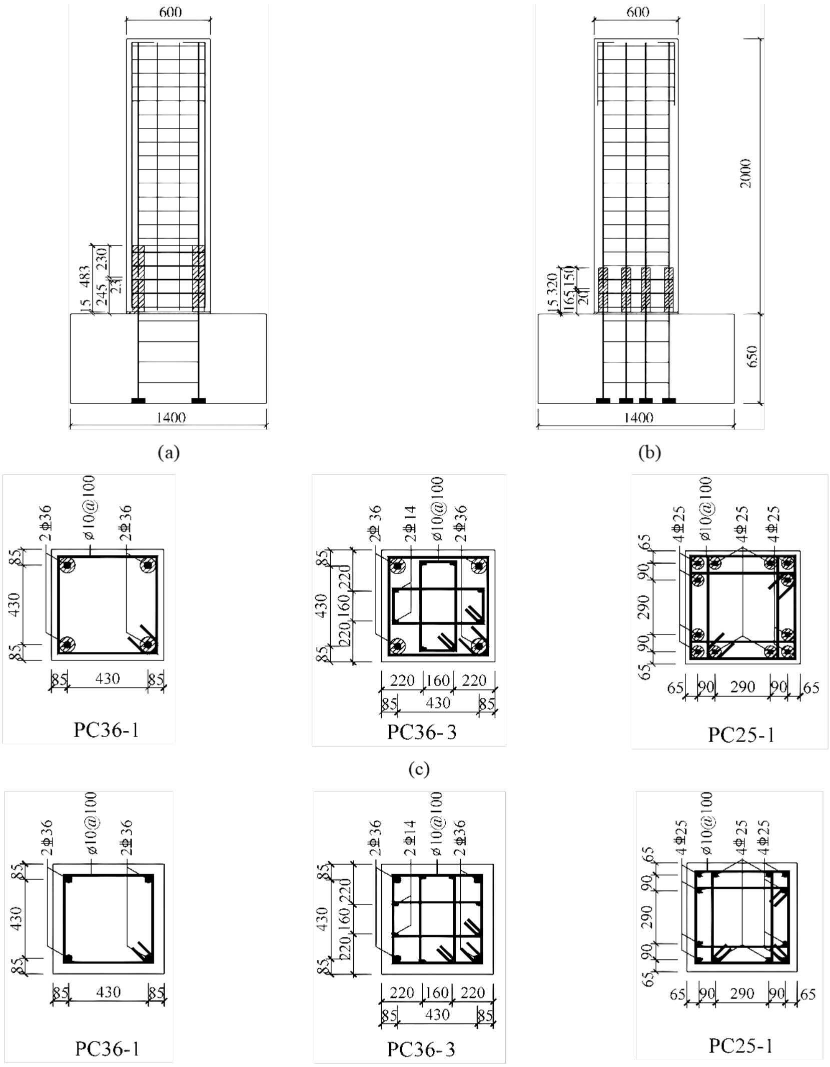
Three prefabricated columns with reinforcement sleeves for grouting were designed in this work. All the specimens had a cross-sectional dimension of 600 × 600 mm and a height of 2000 mm. The main parameters of the specimens are shown in Table 1, and the specific geometrical dimensions and reinforcement information are shown (Fig. 1). The longitudinal and circumferential reinforcement installed in the specimens were HBR500 rebars [7]. The thickness of the joints at the root of the specimens was 15 mm. The grout layer used was 325 mm and the measured compressive strength at standard service - 97 MPa.

Table 1. Main parameters of the experiment.

№	$\boldsymbol{n}$	$\boldsymbol{f_{cu}}$(МПа)	$\boldsymbol{f_c}$(МПа)	$\boldsymbol{c_1}$(мм)	$\boldsymbol{c_2}$(мм)	$\boldsymbol{\rho_s}$(%)	$\boldsymbol{\rho_v}$(%)
PC36-1	0,5	64	46	35	60	0,57	1,12
PC36-3	0,50	60	44	35	60	0,57	1,12
PC25-1	0,25	63	46	25	45	0,55	1,12

Notice, n - the experimental axial compression coefficient, $n = P/(f_c A_c)$*, N - the axial pressure,* A_c *- the cross-sectional area of the column. For frame structure columns, the design value of the axial pressure coefficient is approximately twice the experimental axial pressure coefficient.* f_{cu} *- the compressive strength of a cubic specimen with a side length of 150 mm cured under the same conditions as the specimen,* f_c *- the axial compressive strength of concrete obtained from* f_{cu} *according to GB 50010-2010 «Code for design of concrete structures» [8],* c_1 *- the thickness of the protective layer of concrete hoop reinforcement in the sleeve zone,* c_2 *- the thickness of the protective layer of hoop reinforcement of the upper column,* ρ_s *- the percentage of longitudinal reinforcement,* ρ_v *- the percentage of volumetric reinforcement.*

The test was carried out by the outrigger loading method with a horizontal distance from the point of force imposition to the bottom surface of the post of 1800 mm. A 3000 kN horizontal actuator loaded the specimen with a horizontal circular load of low frequency cycle. Each cyclic level was loaded 2 times.



(a) (b)

(c)

(d)

Fig. 1. Schematic representation of the specimen design: (a) test specimen PC36-3; (b) test specimen PC25-1; (c) drawing of bushing zone reinforcement; (d) drawing of column top reinforcement.

2.2 Constitutive relations of concrete

The plastic damage model of Abaqus is used to simulate the stress-strain behavior of concrete structures under cyclic low-frequency loading [9]. The elastic behavior of the building material is assumed to be isotropic and linearly coupled, while the mechanical behavior of the plastic component after damage is assumed to be damage plasticity. Therefore the plastic damage model of concrete is used in this work. The evolution of the surface on which plastic deformation or fracture occurs is mainly limited by the equivalent plastic tensile and compressive strains $\tilde{\varepsilon}_t^{pl}$ and $\tilde{\varepsilon}_c^{pl}$ [10].

If E_0 is used to describe the elastic strength of a material in the undestroyed state, the stress-strain of concrete in tension and compression can be described as follows:

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{\sim pl}) \tag{1}$$

$$\sigma_c = (1 - d_c)E_0(\varepsilon_t - \varepsilon_t^{\sim pl}) \tag{2}$$

The relationship between the equivalent plastic tensile strain $\varepsilon_t^{\sim pl}$ and the inelastic strain $\varepsilon_t^{\sim ck}$can be described as follows:

$$\varepsilon_t^{\sim pl} = \varepsilon_t^{\sim ck} + \varepsilon_{0t}^{el} - \varepsilon_t^{el} \tag{3}$$

$$\varepsilon_t^{\sim pl} = \varepsilon_t^{\sim ck} - \frac{d_t}{1-d_t} \cdot \frac{\sigma_t}{E_0} \tag{4}$$

Similarly, in the compression of concrete:

$$\varepsilon_t^{\sim pl} = \varepsilon_c^{\sim in} - \frac{d_c}{1-d_c} \cdot \frac{\sigma_c}{E_0} \tag{5}$$

The stiffness recovery effect is one of the most important characteristics of concrete under cyclic loading [11]. This feature is particularly pronounced after the load transition from tensile to extrusion, because the cracks formed during concrete tensile cracking can be re-closed after the application of force, resulting in the recovery of concrete compressive strength. In modeling the damage and ductility of concrete, it can be assumed that the elastic modulus E after failure is a function of the damage parameter d and the initial elastic modulus E_0:

$$E = (1 - d)E_0 \tag{6}$$

In ABAQUS, assume that:

$$(1 - d) = (1 - s_t d_c)(1 - s_c d_t) \tag{7}$$

When assigning material properties to a model, the ABAQUS software requires the input of concrete stress-strain data in addition to the tensile damage parameter d_t and compressive damage parameter d_t, which can be measured experimentally or obtained using the Sidiroff energy equivalence principle. In this work, we derive the damage parameter d by applying the Sidiroff energy equivalence principle [12].

2.3 Steel constitutive relations

In this work, a typical ABAQUS modeling of steel ductility is used. The model includes the Bauschinger effect and uses the Mises yield strain rule. The model uses ideal ductility, in which the stress does not change with ductility after zone service. The steel material model uses an ideal bipartite model.

2.4 Meshing and selection of element types for models in ABAQUS

When creating the model mesh in ABAQUS. For the precast concrete column detail, a hexagonal mesh with a global mesh size of 40 mm was used and the mesh type was set to C3D8R. Generally, C3D8R hexagonal meshes are a good choice for solving displacement modeling problems, they are not prone to shear self-locking under bending loads, and if the mesh is distorted, the resolution accuracy does not suffer much. A global mesh size of 10 mm is used to mesh the reinforcement and grout sleeves, and the mesh type for the reinforcement is T3D2 cells. The global mesh size for the concrete grid of the foundation footing is 100 mm. The meshing of the elements is shown (Fig. 2).

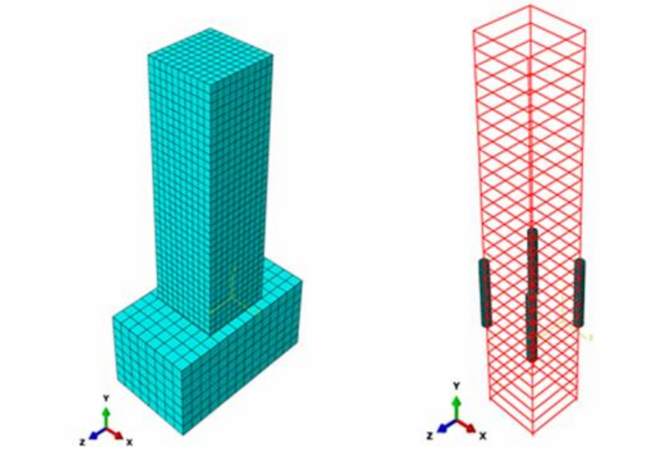
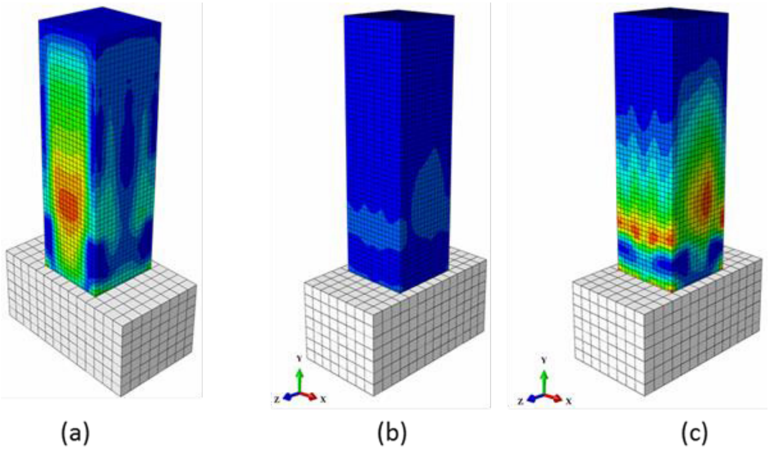


Fig. 2. Specimen meshing.

3 Finite element analysis results

The Figure 3 shows the results of the numerical simulation of the column test by ABAQUS. Comparison of simulation results is shown.



(a) (b) (c)

Fig. 3. Comparison of finite element modeling results: (a) PC36-1; (b) PC25-1; (c) PC36-3.

Damage to the concrete elements of the columns resulted in the formation of fracture surfaces mainly at the lower corners of the columns and in the concrete around the cement sleeve assemblies. Among the damage to each specimen, PC36-1 has severe damage to the protective concrete layer of the column body in the area near the top of its cement sleeve, with cracks in the column ribs extending diagonally downward toward the center axis. Specimens PC36-3 and PC25-1 showed less concrete failure. Specimen PC36-3 showed failure of the protective layer of concrete in the vicinity of the cement sleeve and some concrete failure at the top of the cement sleeve. The direction of cracking in specimen PC25-1 was diagonally downward from the corners to the center axis.

The next Figure (Fig. 4) shows a comparison of the model curves for the load-displacement axial compression results. Comparing specimens PC36-3 and PC25-1, it can be seen that the effect of the longitudinal bar diameter on the stiffness reduction of the specimen is negligible; comparing specimens PC36-1 and PC36-3, it can be seen that the displacement ductility of specimen PC36-1 is poorer, which suggests that the use of composite hoops is more effective in improving the displacement ductility of the specimen than the use of parallel hoops. Therefore, it can be concluded that the seismic performance of prefabricated columns with grouting sleeve can be ensured by using additional mounting reinforcement and composite hoop configurations. Considering the performance of the members and the ease of installation, it is recommended that PC36-3 shaped hoops are preferred for this type of structure.

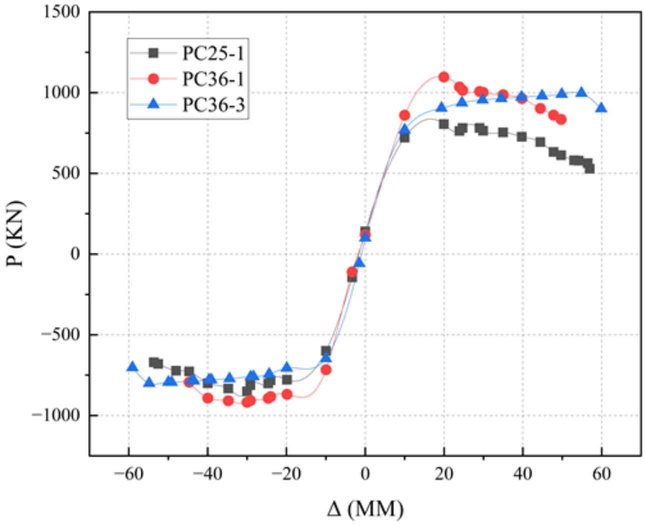


Fig. 4. Comparison of model curves for load-displacement axial compression results.

4 Conclusion

This study investigated the effect of different reinforcement designs on the seismic performance of RC columns with beam-column joints connected using grouted sleeves. Three reinforcement configurations were investigated and their seismic performance was evaluated through finite element analysis and simulation using ABAQUS software.

The results of the analysis revealed important insights into the behavior of beam-column joints in prefabricated reinforced concrete structures. It was observed that the use of grouted sleeve connections with additional mounting reinforcement and composite hoop configurations can significantly improve the seismic performance of such structures. Specifically, the stiffness reduction and displacement ductility of the specimens were analyzed, and it was found that the longitudinal bar diameter had a negligible effect on the stiffness reduction. On the other hand, the use of composite hoops proved to be more effective in improving displacement ductility compared to parallel hoops. These findings contribute to the understanding of beam-column joint behavior and provide valuable insights for the design and construction of seismic-resistant structures.

By optimizing the reinforcement design, the structural integrity and seismic resistance of buildings can be improved, leading to safer and more sustainable building practices. It is hoped that the results of this study will provide some reference value for further research or other studies. Further studies can be carried out in future research to explore more reinforcement designs and investigate their effects on the seismic behavior of beam-column connections.

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