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Comparative research on gravity load simulation devices for structural seismic tests based on FEA

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Abstract. Structural seismic tests usually need to simulate the gravity load borne by the structure, the gravity load application devices should keep the force value and direction unchanged, and can adapt to the structural deformation. At present, there are two main ways to simulate gravity load in laboratory: roller group and prestress. However, there are few differential analysis between these two ways in the existing experimental studies. In this paper, the simulation software ABAQUS is used to simulate the static pushover analysis of reinforced concrete column and frame, which are the most common models in structural seismic tests. The results show that the horizontal restoring force of the model using prestressed loading method is significantly greater than roller group, and the difference between the two will increase with the increase of the horizontal deformation. The reason for the difference is that the prestressed loading method does not take the adverse effects of gravity second-order effect (P-Delta effect) into account. Therefore, the restoring force obtained under prestressed loading method should be corrected and the additional shear force caused by P-Delta effect should be deducted. After correction, the difference of restoring force between the two gravity load application methods is significantly reduced (when storey-drift is 1/550, the relative error is within 1%; and when storey-drift is 1/50, the relative error is about 3%). The research results of this research can provide reference for the selection and data processing of gravity load simulation devices in structural seismic tests.

Keywords: error analysis; FEA; P-Delta effect; pushover analysis; structural seismic tests

1. Introduction

Structural seismic tests usually need to simulate the gravity load borne by the structure, the gravity load application device should keep the force value and direction unchanged, and can adapt to the structural deformation. JGJ/T 101 (2015) stipulates that jacks for vertical loading should have a stabilizing device to ensure that the vertical load of the specimen remains unchanged during the test process.

There are many types of vertical load application devices used in structural seismic tests, each with its own advantages and disadvantages. Lu *et al*. (2017) introduced four different design schemes for vertical load application devices and recommended vertical loading methods based on the size of the experimental site. According to relevant studies, many seismic performance tests

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conducted at home and abroad mainly use two types of gravity loading devices: roller group loading device and prestressed loading device. Liang *et al.* (2024) developed pseudo-static loading to research the behavior of large SCFST column with different confinement effects applying roller group vertical loading device; Zhang *et al.* (2022) developed quasi-static loading tests on high-strength recycled concrete shear walls with high-strength longitudinal reinforcement at the edges applying a roller group vertical loading device; Gu *et al*. (2022) experimentally investigates the seismic behavior of L-shaped precast superposed shear walls with castin-place boundary elements with roller group vertical loading device; Zhang *et al*. (2021) and Wu *et al*. (2022) conducted low cycle reciprocating loading tests on steel confined concrete columns and two shear walls using a roller group vertical loading device. Del Vecchio *et al*. (2022) developed pseudo-dynamic tests on full-scale two storeys RC frames with different infill-to-structure connections adopting prestressed gravity loading device; He *et al*. (2013) carried out pseudo-dynamic testing of hybrid frame with steel beams bolted to CFT columns using a prestressed loading device; Zhang *et al*. (2023) conducted quasi-static loading tests on a composite frame with irregular columns and buckling restrained steel plate shear walls using a prestressed loading device; Qian *et al*. (2017) carried out pseudo dynamic loading tests on a three storey prefabricated shear wall structure adopting a prestressed loading device; Fan *et al.* (2007) used a prestressed vertical loading device to complete pseudo dynamic loading on prefabricated concrete frame structures.

The above researches focus on structural systems and does not explore the differences between the two gravity loading devices. As an important means of studying structural systems, it is very important to scientifically select experimental equipment and data processing methods for structural research. To clarify the differences between the two types of gravity loading devices, this paper provides a detailed introduction to the composition and structural characteristics of the roller group and the prestressed vertical loading devices. The finite element software ABAQUS was used to develop static pushover simulations on the two models of reinforced concrete columns and reinforced concrete frame. The two models represent two typical deformation modes of bending and shear, and the differences caused by the two vertical loading methods were compared and analyzed, and this paper can provide reference for the selection of vertical loading devices for structural seismic tests.

2. Gravity load simulation devices

2.1 Roller group loading device

The main components of the roller group loading device include reaction floor, reaction wall, reaction frame, roller support, stabilizing jack, hinge support, actuator, load transducer, test piece, loading distribution girder, etc. Composition of static pushover test using roller group loading device for reinforced concrete column and frame are shown in Figs. 1 and 2, respectively.

From Figs. 1 and 2, it can be seen that the roller group loading device can strictly ensure that the gravity load direction is always vertical during the test loading process, which can reflect the actual loading situation.

2.2 Prestressed loading device

The main components of the prestressed loading device include reaction floor, reaction wall,

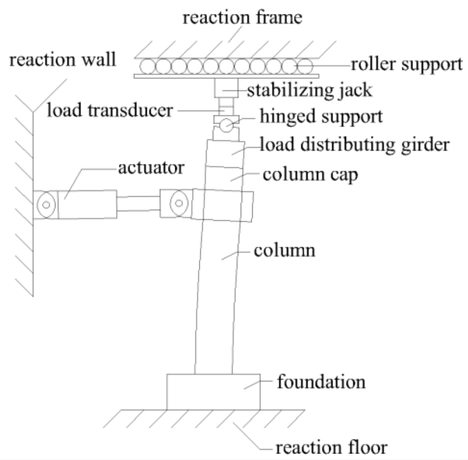


Fig. 1 The composition of static pushover test using roller group loading device for reinforced concrete column

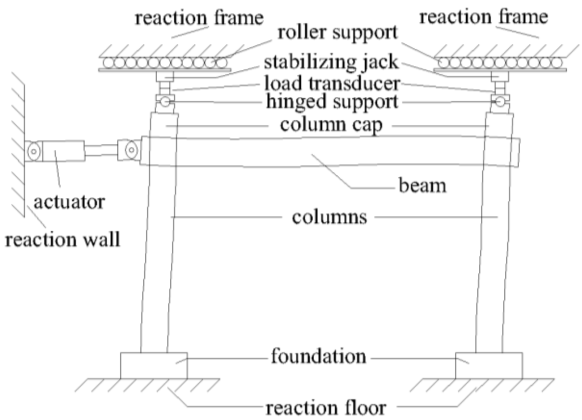


Fig. 2 The composition of static pushover test using roller group loading device for reinforced concrete frame

centre hole jack, hinge support, actuator, load transducer, test piece, loading distribution girder, etc. Composition of static pushover test using the prestressed loading device for reinforced concrete column and frame are shown in Figs. 3 and 4, respectively.

From Figs. 3 and 4, it can be seen that the prestressed loading device is difficult to ensure that the gravity load direction is vertically downward during the loading process, which resulting in changes in the actual vertical force borne by the structure.

3. Models design and simulation

Based on the loading characteristics of the two vertical loading devices mentioned above, a reinforced concrete column model and a reinforced concrete frame model were created using the

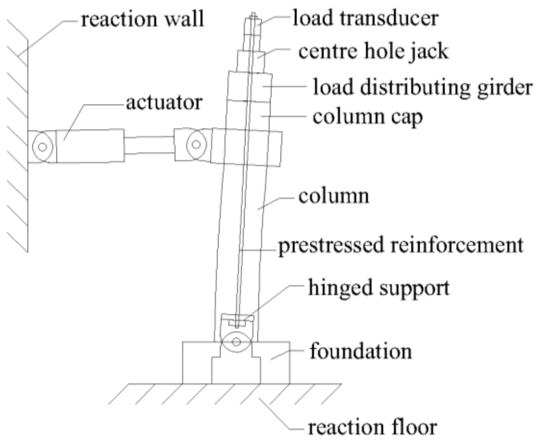


Fig. 3 The composition of static pushover test using prestressed loading device for reinforced concrete column

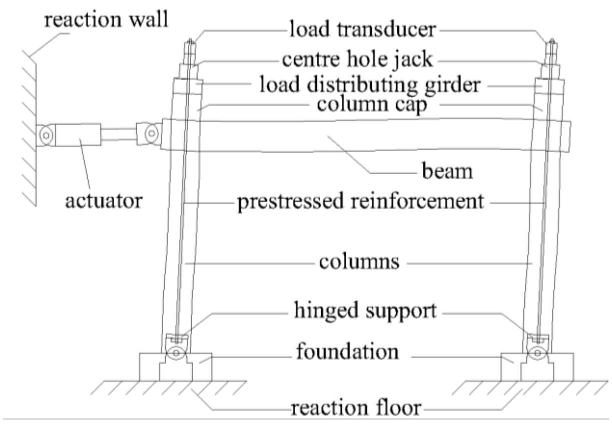


Fig. 4 The composition of static pushover test using prestressed loading device for reinforced concrete frame

general finite element software ABAQUS. Static pushover simulations were carried out to study the differences in horizontal restoring force caused by the two loading methods under bending deformation and shear deformation.

3.1 Models design

The first model is a reinforced concrete column with a bending deformation mode, the height is 1150 mm, the section size of column is 250 mm×180 mm. and the section size of foundation for column is 400 mm×250 mm. Both the diameter of column and foundation stirrups is 6 mm, the diameter of column longitudinal bars is 14 mm, and the longitudinal bars of foundation is 16 mm. Another model is a single span-layer reinforced concrete frame scaled model with shear deformation mode, the span of the framework is 3000 mm, the dimensions of the frame columns are consistent with the first model,and the height of columns is 1725 mm, the section size of frame beam is 250 mm×120 mm, and the section size of foundation is 400 mm×250 mm. The diameter of stirrups of foundation, frame columns and beam is 6 mm, the longitudinal bars of frame columns and beam is 14 mm, and the longitudinal bars of foundation is 16 mm. The concrete strength grade is C30.

3.2 Finite element modeling

3.2.1 Element type

This article uses the static general solution module of the finite element software ABAQUS for simulation analysis. During the simulation process, the concrete was modeled using three-dimensional solid element C3D8R. The modeling of longitudinal bars and stirrups adopts a two node element T3D2. Assuming there is no slip between the steel bars and concrete, the embedded method is used to simulate the interaction between solid elements and truss elements to achieve deformation coordination.

3.2.2 Constitutive model

In order to more accurately consider the behavior of concrete during tensile and compressive processes, this study adopts the Concrete Plastic Damage Model (CDP model). Lemaitre (1985) proposed damage evolution equation, the deterioration process of concrete with increasing deformation is described by the damage factor, which essentially reflects the relationship between the secant stiffness and initial elastic modulus of concrete. The concrete constitutive model adopts the stress-strain relationship of uniaxial tension and compression of concrete provided in Appendix C of GB 50010-2010 (2015).

Both longitudinal reinforcement and stirrups adopt plastic constitutive models.

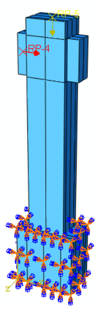
3.2.3 Load settings

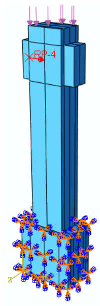
In the load application module of ABAQUS, the gravity application method using roller group loading device is to create a reference point and establish a coupling relationship with the top surface of the column, and then apply a vertically downward concentrated force on the reference point. The gravity application method using prestressed loading device is directly to apply a distributed force on the vertical surface at the top of the column. The horizontal direction adopts a displacement loading mode, and the maximum loading displacement is twice of the inelastic storey drift limit of the reinforced concrete frame specified in GB 50011 (2015). The concrete constitutive relation adopts elastic-plastic constitutive model, and the load applied to each column top of the two models is 150 kN. The load and boundary condition applying of column and frame are shown in Figs. 5 and 6, respectively.

4. Results comparison and analysis

4.1 Results comparison

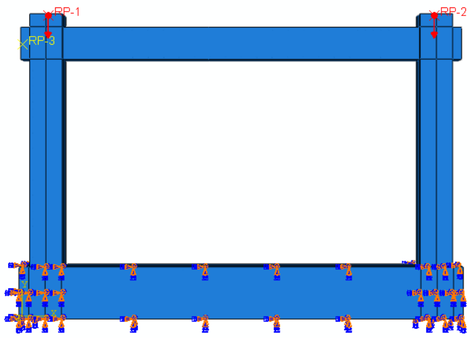
The restoring force obtained by finite element modeling for reinforced concrete column and frame applying gravity load by roller group and prestressed loading device, which are expressed



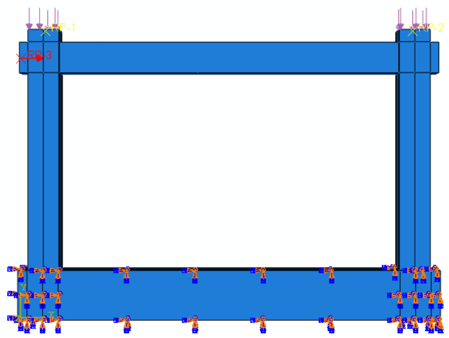


(a) The roller group loading device (b) The prestressed loading device

Fig. 5 The load and boundary condition applying of reinforced concrete



(a) The roller group loading device



(b) The prestressed loading device

Fig. 6 The load and boundary condition applying of reinforced concrete frame

by F_r, and F_p respectively. The comparison of restoring force-displacement curves of column and frame are shown in Figs. 7 and 8.

It can be seen from the comparison curves of the horizontal restoring force of the reinforced concrete column and the frame under the two gravity application methods that the restoring force obtained by the prestressed loading device method is obviously larger than that by the roller group, and the difference increases further with the increase of horizontal lateral displacement.

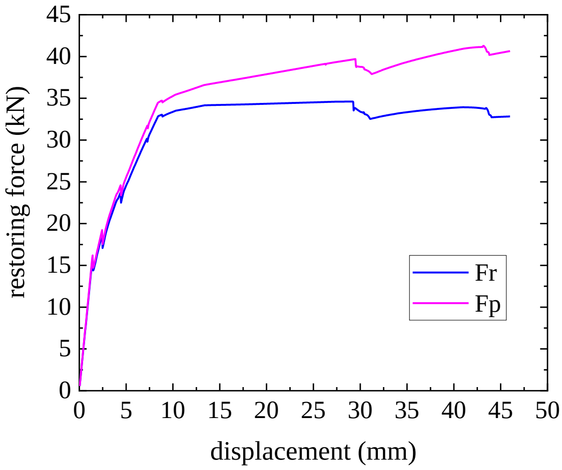


Fig. 7 The comparison of restoring force-displacement curves for reinforced concrete column

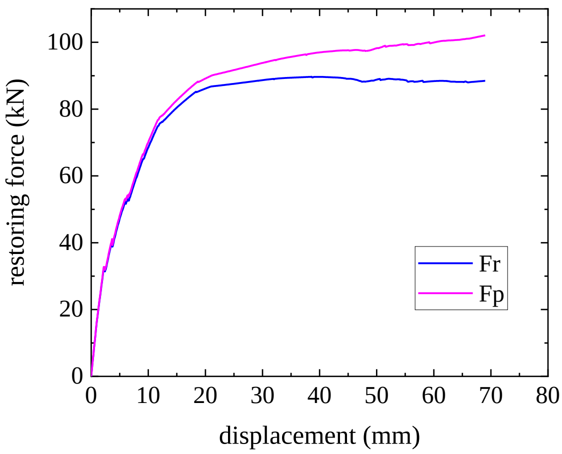


Fig. 8 The comparison of restoring force -displacement curves for reinforced concrete frame

4.2 Results analysis

The second order effect of gravity caused by the horizontal deformation of the structure, that is the P −Delta effect, makes the horizontal displacement and the horizontal shear nonlinear. Conduct force analysis on columns under two gravity loading methods. The Fig. 9 The second order effect of gravity caused by the horizontal deformation of the structure, that is the P −Delta effect, makes the horizontal displacement and the horizontal shear nonlinear. Conduct force analysis on columns under two gravity loading methods. The Fig. 9

In order to simplify the calculation, it is assumed that the material maintains a linear elastic state during loading, and the lateral stiffness of the column is K. Δ_1 consists of two parts, one is the lateral displacement caused by horizontal shear force, and the other is the lateral displacement caused by gravity second-order effect. The formula for Δ_1 is shown as follows

(a) The roller group loading method (b) The prestressed loading method

Fig. 9 Force analysis diagram

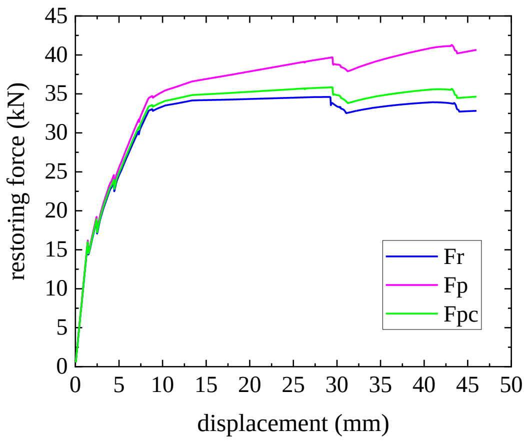


Fig. 10 The comparison of restoring force-displacement curves for reinforced concrete column

$$\Delta_1 = \frac{V}{K} + \frac{P\Delta_1}{hK} \tag{1}$$

The Δ_2 consists of three parts, the first part is caused by horizontal shear force, the second part is caused by P-Delta effect, and last part is caused by horizontal component force of *P*, The formula for Δ_2 is shown as follows

$$\Delta_2 = \frac{V}{K} + \frac{P\cos\theta_2\tan\theta_2}{K} - \frac{P\sin\theta_2}{K} \tag{2}$$

According to the trigonometric relationship, it can be concluded that $\cos\theta_2\tan\theta_2 - \sin\theta_2 = 0$, therefore, Eq. (2) becomes as follows

$$\Delta_2 = \frac{V}{K} \tag{3}$$

It can be seen from Eq. (3), using the prestressed loading device to simulate gravity does not take the adverse influence of the P-Delta effect into account, so that the structural restoring force

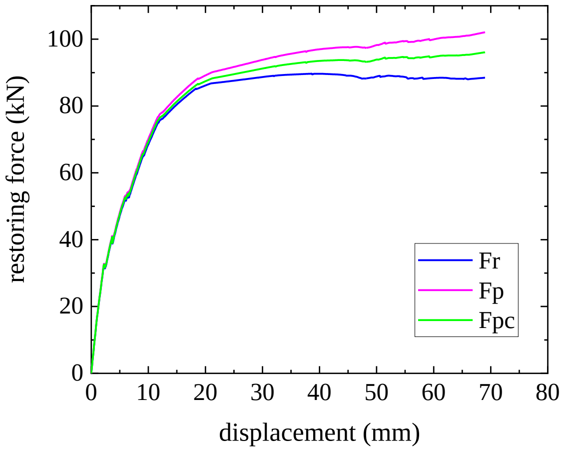


Fig. 11 The comparison of restoring force -displacement curves for reinforced concrete frame

Table 1 The comparison table of restoring force for reinforced concrete column

θ	F_p(kN)	F_{pc}(kN)	F_r(kN)	E(%)	E_c(%)
1/2000	6.63	6.55	6.49	2.16	0.90
1/1000	13.22	13.07	12.95	2.08	0.9
1/750	14.86	14.66	14.53	2.27	0.89
1/550*	17.71	17.43	17.27	2.55	0.93
1/250	24.06	23.49	23.20	3.71	1.25
1/100	35.88	34.38	33.75	6.31	1.87
1/50*	38.48	35.48	34.45	11.70	2.99
1/25	40.65	34.65	32.83	23.82	5.54

obtained is larger than the actual one. The result should be corrected and the additional shear caused by gravity second order effect should be deducted. The correction formula of F_p is as follows

$$F_{pc} = F_p - \frac{P\Delta_2}{h} \tag{4}$$

The F_{pc} is the corrected restoring force.

Add F_{pc} on the basis of Figs. 7 and 8 for further comparison, the model of reinforced concrete column and frame are shown in Figs. 10 and 11, respectively.

Select representative storey drift to compare and analyze the horizontal restoring force obtained by two gravity load application methods, and calculate the relative error according to the Eqs. (5) and (6). The summary of the comparison results for reinforced concrete column and frame is shown in Tables 1 and 2, respectively

$$E = 100\% \times (F_p - F_r)/F_r \tag{5}$$

Table 2 The comparison table of restoring force for reinforced concrete frame

θ	F_p(kN)	F_{pc}(kN)	F_r(kN)	E(%)	E_c(%)
1/2000	14.54	14.47	14.41	0.90	0.42
1/1000	26.49	26.34	26.18	1.18	0.61
1/750	32.42	32.22	32.09	1.03	0.41
1/550*	37.31	37.04	36.73	1.58	0.84
1/250	55.41	54.81	54.19	2.25	1.14
1/100	86.22	84.72	83.77	2.92	1.13
1/50*	95.49	92.49	89.36	6.86	3.50
1/25	102.08	96.08	88.47	15.38	8.60

*: 1/550 in Tables 1 and 2 is the elastic storey drift limit, and 1/50 is the inelastic storey drift limit

$$E_c = 100\% \times (F_{pc} - F_r)/F_r \tag{6}$$

It can be seen from Tables 1 and 2 that before the horizontal displacement reaches the elastic storey drift limit specified in GB 50011 (2010), the simulation results of the roller group loading method and the prestressed loading method are relatively close. Especially after modification, the relative error of the calculation results of the two loading methods is within 1%. When the horizontal displacement exceeds the inelastic storey drift limit, the relative error of the two loading methods of reinforced concrete column and frame increase significantly with the increase of the horizontal displacement. The relative error of reinforced concrete column exceeded 10%, while the reinforced concrete frames reached 6.87%, and the relative error significantly decreased to around 3% after correction.

5. Conclusions

This study analyzes the differences between the two most commonly used application methods for gravity load simulation in structural seismic tests, which are roller group and prestress, respectively. Based on the finite element software ABAQUS, static pushover was carried out on two models of reinforced concrete column and frame, and the restoring force of the structure was obtained.

• By comparing the horizontal restoring force calculated by two different gravity application methods, it was found that the restoring force obtained by using prestressed application method is significantly larger than that of roller group method, and the difference between the two further increases with the increase of horizontal deformation.

• Through the force analysis of two kinds of gravity loading methods, It can be found that the method of applying gravity load by prestress does not take the adverse influence of gravity second order effect (P-Delta effect) into account, causing that the restoring force is larger than the actual one. The result should be corrected and the additional shear caused by the P-Delta effect should be deducted. The correction of the results in this paper can significantly reduce the relative error. The simulation results of the two gravity load application methods are very close after correction: when storey drift is 1/550, the relative error is within 1%; and when storey drift is 1/50, the relative error is about 3%

• In seismic tests, especially when gravity load and horizontal displacement are large, priority should be given to using a roller group to simulate gravity load. When prestress is applied, the additional shear force caused by gravity second-order effect should be deducted from the measured horizontal restoring force to improve the accuracy of the test.

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