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Research on Pseudo Dynamic Test of Reinforced Concrete Frame Industrial Foundation

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Abstract: Large industrial buildings often use frame structure as the basis of various industrial equipment. The safety and stability of equipment operation are closely related to the seismic performance of equipment foundation. Therefore, it is necessary to conduct a comprehensive assessment of the seismic performance of the industrial foundation frame. There are many kinds of experimental methods for seismic analysis, among which the pseudo-dynamic test is simple and the test results are obvious. In this paper, the pseudo-dynamic test method is used to study the frame foundation of large industrial buildings. The test mainly measures the restoring force time history, roof displacement time history, steel bar strain time history, crack location, crack width, hysteresis curve, etc., and evaluates the seismic performance of the whole structure.

Keywords: Pseudo-Dynamic; Earthquake Resistance; Framework Foundation; Strain Analysis; Fracture Analysis

1. Introduction

Large industrial plants, such as casting plant, forging plant, iron and steel metallurgy plant, electric plant, ship plant, chemical plant, etc., must have sufficient overall seismic capacity to ensure the safety and stability of the equipment when subjected to earthquake damage. A good seismic structure requires reasonable force and force transmission path, as much redundancy as possible, as well as sufficient strength, stiffness, ductility, etc., to ensure that the whole structure has good seismic capacity.

The industrial frame has become the first choice for large industrial buildings because of its large weight bearing and high flexibility. At the same time, with the development of industrial technology, the shape of industrial building structure becomes more complex and diverse, and the complex shape of the structure also makes the structure more complex, which brings a lot of challenges to the overall seismic resistance of the structure. Therefore, it is necessary to study the seismic performance of large industrial buildings. [1,2]

Pseudo-static test, seismic simulation shaking table test and pseudo-dynamic test are the three most commonly used test methods for structural seismic performance research at home and abroad.

The quasi-static test method is to use a certain load or displacement as the control value to perform low-cycle reciprocating loading on the specimen to obtain the nonlinear load-deformation characteristics of the structure. This method can measure the bearing capacity, stiffness, deformation capacity, energy dissipation capacity and damage characteristics of the structure. However, this method cannot simulate the response of the specimen under actual seismic load.

The shaking table of earthquake simulation can most directly and truly reproduce the dynamic characteristics and dynamic response of the model structure under the action of earthquake. The construction of the shaking table is constantly developing in the direction of high precision and multi degree of freedom. However, the seismic simulation shaking table equipment is complex and the investment is large, and the scale of the test model is limited by the size and bearing capacity of the shaking table. In addition, it is difficult to observe the structural damage during the test because the shaking table simulation of the seismic action process is a true reproduction, the experience time is short, and there is a certain safety hazard.

The pseudo-dynamic test is based on the characteristics of the pseudo-static test and the seismic simulation shaking table test. The computer and the testing machine are used to carry out the structural test. The structure experiences the seismic action at a lower loading rate. The inertia force of the structure in the earthquake is converted into a static force by calculation and applied to the structure to simulate the actual seismic response of the structure.

The pseudo-dynamic test does not need to make any assumptions about the restoring force characteristics of the structure when performing numerical analysis, which is particularly beneficial for the analysis of nonlinear system performance.[3] For structures with complex restoring force characteristics, the actual seismic response can also be reproduced according to the test results. [4] At the same time, because the time period of pseudo-dynamic test loading is almost static, the tester is given enough time to observe the process of structural performance change and damage, so as to obtain more detailed data. For some large-scale or large-scale models, the test on the seismic simulation vibration table will be limited by the technical conditions of the equipment or similar conditions that cannot be met. Under such test conditions, the pseudo-dynamic test can be used. The computer-controlled and electro-hydraulic servo loader directly performs seismic simulation loading on the component.

2. Experiment Overview

In this experiment, the 1: 10 scale model of the frame structure industrial plant is taken as the research object [5]. The pseudo-dynamic test method is used to apply the 6 degree rare earthquake, and the corresponding structural deformation, bearing capacity, strain time history, and structural damage are analyzed to evaluate the seismic performance of the structure.

2.1 Test Principle

The basic idea of pseudo-dynamic test is based on the numerical calculation process of structural dynamic equation. The structure is simplified as a discrete multi degree of freedom, and the displacement of each degree of freedom is controlled by an actuator in the test. [6] The equation of motion can be expressed as that:

$$Ma+Cv+Kd=f \tag{1}$$

where M, C and K are the mass matrix, damping matrix and stiffness matrix of the structure, respectively. f is the seismic action vector; a, v and d represent the relative acceleration, velocity and displacement, respectively. In order to solve the dynamic equation, it is necessary to discretize the continuous time in the dynamic equation. The differential equation is transformed into a difference equation, and the time step is set to Δt. Then the discrete time dynamic equation of ti at a certain time is that

$$Ma_i + Cv_i + Kd_i = f_i \tag{2}$$

For the solution of the above discrete functions, most of the current experiments use the central difference method because of its stable conditions and simple calculation. The velocity and acceleration of the time in the central difference method are that:

$$v_i = \frac{d_{i+1} - d_{i-1}}{2\Delta t} \tag{3}$$

$$a_i = \frac{d_{i+1} - 2d_i + d_{i-1}}{\Delta t^2} \tag{4}$$

Bring Equations (3) and (4) into the discrete equation (2) and let $Kd_i = r_i$, we can get:

$$d_{i+1} = (M + \frac{\Delta t}{2}C)^{-1}[2Md_i + (\frac{\Delta t}{2}C - M)d_{i-1} - \Delta t^2(r_i - f_i)] \tag{5}$$

It can be seen from Equation (5) that the displacement di+1 is calculated by measuring the displacement di and measuring the recovery ri. After di+1 is determined, the computer applies instructions to the actuator, and the actuator causes the model to produce displacement di+1. The force sensor on the actuator measures the recovery force ri+1 and repeats the above steps to measure the structural response time history under earthquake action.

2.2 Similar Relations

Table 1. Model Similitude

Name	Ratio of similitude
Geometrical dimension	$C_l = L_m/L_r = 1{:}10$
Density	$C_\rho = \rho_m/\rho_r = 1{:}1$
Quality	$C_M = M_m/M_r = 1{:}1000$
Dynamic magnification factor	$C_\beta = 1$
Elastic modulus	$C_E = E_m/E_r = 1{:}1$

In order to restore the main stress characteristics of large industrial plants, the model is designed at a ratio of 1: 10, and the same material is used for production. The same type of concrete and steel bars and the same reinforcement ratio are used to ensure that the stress-strain relationship curve of the model is similar to the original structure, which can reflect the mechanical properties of the actual plant structure. The following Table 1 is the similarity relationship of the physical quantities of the model.

2.3 Experimental Model

After completing the construction of the model, the cast iron is used to simulate the weight of the equipment, and the cast iron is arranged at the corresponding position of the model according to the similarity between the installation position of the equipment and the model, as shown in Figure 1.

Figure 1. Foundation Construction

In order to study the stress characteristics of each component of the foundation under the action of earthquake, strain gauges are embedded in the positions of steel bars and concrete on the model structure, with a total of 28 strain measuring points. At the same time, displacement sensors are arranged at each key point, with a total of 8 displacement measuring points, as shown in Figure 2.

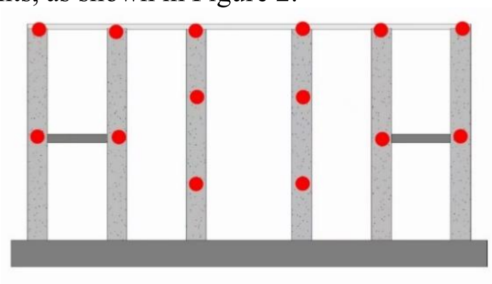


Figure 2. Model Sketch

2.4 Experimental Equipment

Table 2. Equipment Name

	Model	Range	Resolution
Actuator / force sensor	-	±250mm	0.0015kN
Digital collection board	IMP35951B	±2V	-
Displacement transducer	YHD-50	±25mm	0.1mm
	WY-50	±25mm	200$\mu\varepsilon$/mm
Microscope for crack measurement	SW-LW-101	1mm	-

The main equipment of this experimental study includes electro-hydraulic servo loading system, IMP data acquisition system, crack observation instrument and displacement meter, as shown in Figures 3-6. See Table 2 below for all equipment conditions.

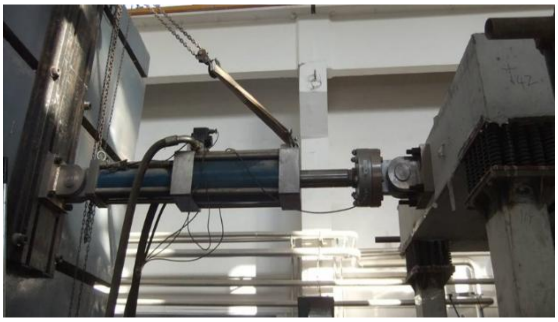


Figure 3. Electro-hydraulic Servo Loading System

Figure 4. IMPstrain Acquisition System

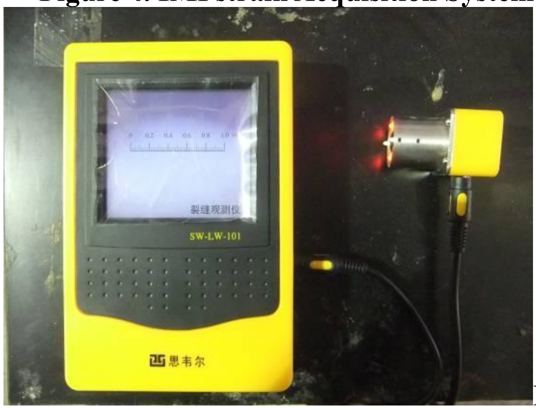


Figure 5. Microscope for Crack Measurement

Figure 6. WY-50 Displacement Gauge

3. Test Content

3.1 Experimental Steps

The test steps are as follows:

(1) Input seismic acceleration time history;
(2) The mass and damping ratio of the input model;
(3) Determine the initial stiffness and natural vibration period of the model;
(4) The displacement of the model is applied by the test electro-hydraulic servo brake;
(5) Measure the restoring force of the structure, according to the measured restoring force, through the computer control system, get the next displacement; [7]
(6) The cyclic test is carried out according to the above steps until the pseudo-dynamic test process is completed. Thus, the restoring force and displacement response of the structure at each moment during the whole test process are obtained.

3.2 Selection of Seismic Wave

The design response spectrum provided by the seismic code is used as the target response spectrum. In this experiment, the artificial synthetic 6-degree rare seismic wave is selected, and the maximum time-history acceleration is 0.12 g. The acceleration time history is shown in Figure 7.

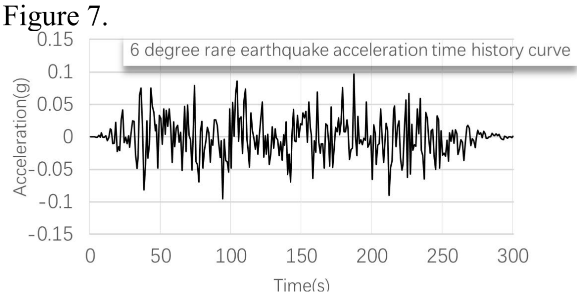
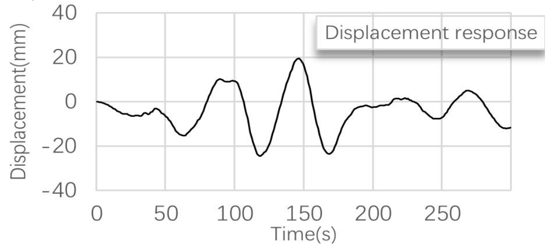


Figure 7. Artificially Synthesized Seismic Acceleration Time History Curve

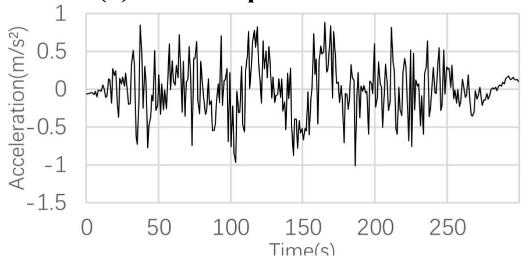
3.3 Seismic Response Curve

According to the natural frequency of the model and the input seismic wave, the acceleration, velocity and displacement response of the model can be solved to obtain the seismic response curve. The acceleration response curve reflects the instantaneous response of the plant model under earthquake, which can judge the dynamic performance of the structure under extreme conditions. The displacement response curve can reflect the deformation of the structure and be used to analyze the possible plastic deformation and damage location.

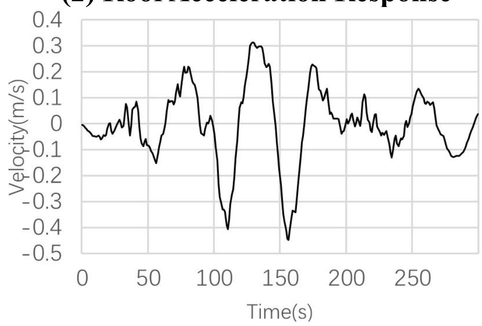
Figure 8 is the response curve of roof under 6 degree rare earthquake, including roof displacement, roof acceleration, roof velocity and roof restoring force. The maximum acceleration response of the roof is : 1.01m / s2 is 1.145 times the maximum acceleration (0.09g) of the input ground motion, and the seismic amplification coefficient is 1.14. Under the action of earthquake, the maximum displacement of the foundation structure is 24.51 mm, as shown in Table 3.



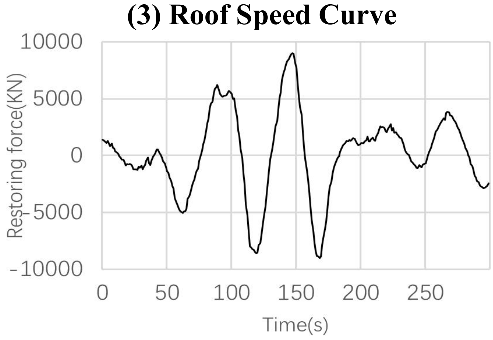
(1) Roof Displacement Curve



(2) Roof Acceleration Response



(3) Roof Speed Curve



(4) Roof Restoring Force Response

Figure 8. Roof Response Curve of 6 Degree Rare Earthquake

Table 3 Maximum Roof Response

working condition	Acceleration (m/s^2)	displacement(mm)	restoring force(kN)	velocity(m/s)
earthquake	0.84	24.51	8975	0.44

3.4 Stress Analysis

Combined with structural strain, structural displacement measurement and a variety of force analysis, we can analyze the seismic performance of the structure.

The stress analysis mainly includes:

1. Inertial force analysis: the seismic action makes the structure produce inertial force, and the magnitude of inertial force is related to the mass and acceleration of the structure.[8] Through the acceleration response of different layers, the inertial force distribution of each layer can be calculated.

2. Shear force analysis: For the multi-storey factory model, the seismic action will produce the shear force between the floors. By accumulating the inertial force of each layer, the shear force distribution from the top layer to the foundation layer can be obtained. The shear force of the foundation layer is the largest, which has an important influence on the foundation design.

3. Bending moment analysis: Under the action of earthquake, vertical and horizontal components such as columns and beams will produce bending moments. [9] The bending moment can be solved by using the inter-story displacement and the stiffness of the component. For columns and walls, the bending moment is larger at the bottom, and the maximum bending moment can be calculated and whether it exceeds the yield strength of the material can be verified.

4. Axial force analysis: The horizontal action of earthquake causes the structure to move laterally, resulting in additional axial force (tension or pressure) of vertical members (such as columns). This axial force depends on the horizontal force and the inclination angle of the component. The structural analysis method is used to calculate the axial force of each column under earthquake action, and to check whether the critical value of bearing capacity is reached.

3.5 Reinforcement Strain

In this experiment, the strain of the column is measured and analyzed. On the basis of the whole model, the strain measuring points are mainly arranged at the root of the column, the second layer and the third layer, that is, the two sides of the column root, the two sides of the second layer node and the two sides of the third layer. The following Table 4 takes a set of strain curves as an example. It is known from the table that the maximum strain of the steel bar caused by the 6-degree rare earthquake is 711 μE, which is less than the yield strain of the steel bar of 2000 μE. The steel bar does not yield, and the structure has the ability to resist the 6-degree rare earthquake.

Table 4. Maximum Strain of Some Steel Bars

position	Column root	The second layer node	column top
Maximum steel strain(με)	323	106	711

3.6 Displacement Response of Measuring Point

In order to compare the displacement changes from low to high at the same position of the structure under the action of 6 degree rare earthquake, the displacement time history curves of the three layers at the corresponding position are compared in the same figure. It can be seen from the Figure 9 that the maximum displacement occurs at the roof, and the displacement at the beam-column joints is smaller. Under dynamic loading, the deformation mode of the structure is usually that the top deformation is larger and the bottom is smaller. Because the beam-column joints are located in the middle, the displacement is often less than the top displacement. Especially in shear deformation and bending deformation, the displacement response of the top layer will be more obvious.

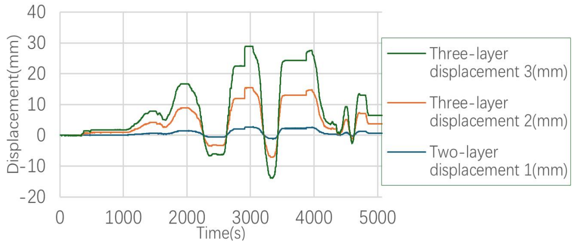


Figure 9. Comparison of Displacement at Different Positions

3.7 Hysteresis Curve

The hysteresis curve of the structure refers to the relationship curve between the force and displacement of the structure under the action of repeated load. It is the comprehensive embodiment of the seismic performance of the structure, and it is also the main basis for the analysis of the seismic elastic-plastic dynamic response of the structure. [10]

Figure 10 is the ' restoring force-displacement ' curve of the structure under rare earthquakes. From the figure, the hysteresis curve is basically linear. As the earthquake progresses, the area surrounded by the curve increases slightly, the slope of the loading curve decreases, and the structural stiffness degrades slightly over time. When the test process is completed, the displacement of the structure returns to zero, and there is no residual deformation.

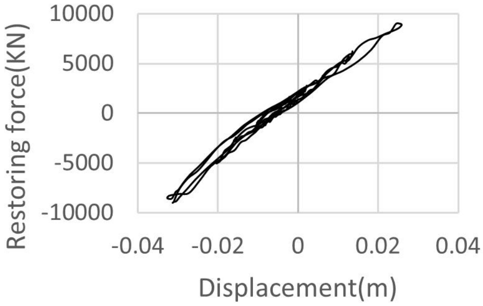


Figure 10. Hysteresis Loop

3.8 Structural Crack Analysis

In this rare earthquake experiment, several common crack points were selected, including the specific crack positions in beams, columns, plates and other components, and the location of structural cracks was prepared for detailed recording. In this experiment, the crack information was observed from the 100 th step, once every 10 steps, and recorded after the end of the experiment: after the whole experimental process, no obvious cracks were found in the structure, and the model structure was in good condition, indicating that the structure had strong resistance to 6 degree rare earthquake.

4. Conclusion

This pseudo-dynamic test uses a 1: 10 frame foundation model for seismic performance test research, and obtains the seismic response of the prototype foundation platform, the displacement response of the structure, the strain of the steel bar, and the development of cracks. The seismic performance of the frame foundation under the rare condition of 6 degrees is evaluated as follows

(1) As a conventional rigid foundation, the maximum acceleration response of the platform is1.01m / s2and the seismic amplification factor is1.15under rare earthquake.

(2) Under the action of rare earthquake, the maximum displacement of the foundation slab is 24.51 mm. With the increase of load, there are no obvious cracks in the column root and column top of the foundation. It is judged that the stiffness of the structure is slightly degraded, showing a certain elastoplasticity, but the foundation can still maintain good working performance at this time, and there is no obvious failure trend, which meets the requirements of China's seismic code.

(3) The maximum strain of the column root is 323.98, the maximum strain of the second layer is 106.73, and the maximum strain of the third layer is 711.42. At this time, the strain of the steel bar is less than the yield strain of the steel bar 2000. It can be seen that under the action of rare earthquakes, the steel bars did not yield, and the structure still had certain bearing capacity.

(4) The experimental results show that the pseudo-dynamic test can better reflect the nonlinear response characteristics of the structure, especially in the study of the seismic performance of large-scale industrial buildings, the pseudo-dynamic test has high practical application value.

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