Study on Pseudo-Dynamic Test Method of Reinforced Concrete Frame Foundation

Zhangjie Yu, Xianyun Wang*, Lianfu Zhou, Kexin Zhao
North China University of Technology, Beijing, China
**Corresponding Author.*

Abstract: With the acceleration of urbanization, reinforced concrete frame structures are widely used in construction projects because of their excellent mechanical properties and economy. In order to study its response characteristics under seismic loading, the proposed dynamic test, as an effective test method, is widely used in engineering research. This paper focuses on the proposed dynamic test method for reinforced concrete frame foundations, including the test principle, main equipment, test steps and data processing, etc., to provide reference for the subsequent research.

Keywords: Seismic; Proposed Dynamics; Industrial Buildings; Reinforced Concrete

1. Introduction

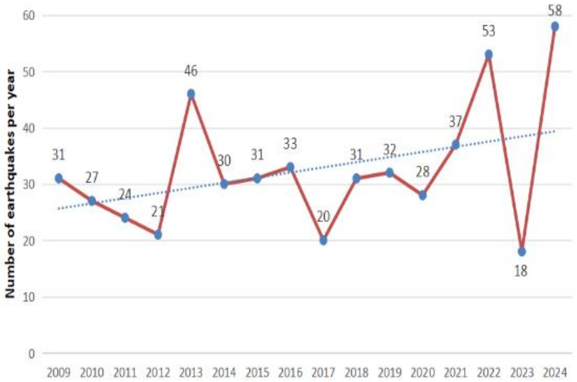

Figure 1. The Number Table of Earthquakes Above Magnitude 5 in China from 2009 to August 2024

China is a multi-earthquake country, from 2009 to August 2024, the number of earthquakes of magnitude 5 or higher is on the rise [1] (e.g., Figure 1 The number table of earthquakes above magnitude 5 in China from 2009 to August 2024), and the overall economic loss is up to more than 500 million yuan [2], and lead to a large number of casualties. The number of earthquakes is on the rise, China's building structure is also changing, from masonry structure to reinforced concrete structure, structural changes to cope with earthquakes should also rely on the structure of the current continuous optimization, accompanied by China's urbanization process continues to advance, to be before 2050, the urbanization rate from 36% to more than 70%, means that the density of China's buildings will become more compact, earthquakes will be more and more serious threat to people's lives. Earthquake will produce more and more serious threat to people's lives, which requires buildings with good seismic performance, to achieve the building seismic defense objectives required by the "small earthquake is not bad, the earthquake can be repaired, the big earthquake does not fall". Therefore, it is imperative to study the seismic performance of reinforced concrete frame foundation.

2. Test Method Selection

With the deepening of seismic research, the demand for structural seismic requirements and defenses is constantly increasing. The common seismic test methods for building structures mainly include the proposed static test, seismic simulation shaker test and the proposed dynamic test, which are of great significance in evaluating and improving the seismic performance of building structures, and they provide key technical support from different perspectives and levels for in-depth investigation of structural seismic characteristics, optimization of seismic design, and guaranteeing the safety of the building in earthquakes. and data basis.

2.1 Proposed Static Test

The proposed static test is one of the most widely used test methods in the study of seismic performance of structures. By applying certain cyclic loads or displacements to the specimens, the nonlinear load-deformation characteristics of the structure can be obtained, so as to establish a restoring force model, analyze the damage mechanism of the structure, and improve the seismic design measures of the structure. The commonly used loading equipments for the proposed static test include electro-hydraulic servo loading system, which can be used for test control and data acquisition by computer [3]. At present, there are three kinds of commonly used test rules for proposed static loading: displacement-controlled loading, force-controlled loading, and force-displacement hybrid controlled loading. (1) Displacement-controlled loading is to load the displacement of the process as a control amount in accordance with a certain displacement increase for cyclic loading, sometimes from small to large amplitude, sometimes the amplitude is constant, and sometimes the amplitude is a mixture of large and small; (2) force-control loading is to load the amplitude of the force as a control amount of each cycle, but it is difficult to use the force control of the specimen after the yielding, so this type of loading method is less individually (3) force-displacement hybrid control loading method is firstly loaded by force control, and when the specimen reaches yielding, it is changed to displacement control. Among them, the proposed static loading test can maximize the use of the specimen to provide a variety of basic information, such as: bearing capacity, stiffness, deformation capacity, energy dissipation capacity and damage characteristics, etc [4-6]. For the test of multi-story structure, multi-point synchronized loading is required, usually an upper electro-hydraulic servo loader is selected as the master loader, and the rest of the loaders are coordinated to load according to the displacement control mode of the master loader. The proposed static test can be widely used in the research of seismic performance of all kinds of engineering structures or components, and it is an important test method.

2.2 Seismic Shaker Tests

Seismic simulation shaker test is one of the main test means to study the seismic performance of structures in the laboratory at present. By loading the desired waveform to simulate a certain vibration environment, not only can we understand the macroscopic performance of structures against earthquakes and the damage mechanism of engineering structures under seismic action, but also the weak parts of structures under seismic action [7].

Seismic simulation shakers provide excellent reproduction of seismic processes and testing of artificial seismic waves, and are the most direct method of investigating structural seismic response and damage mechanisms in the laboratory. In fact, as long as the weight, size, and response characteristics of the specimen are within the maximum functional range of the shaker, shaker tests can be performed; the waveforms reproduced on the table are not limited to seismic records, but can be other types of vibration problems [8]. However, the error of scaled-down simulation tests on large structures is very large, which limits the development of shaker tests; while foot-scale shaker simulation tests require a large earthquake simulation shaker, and the investment in equipment is quite huge restricting the scale of its construction, thus restricting many large-scale structural seismic simulation tests [9]. Shaking table tests are very widely used, with a variety of specimen forms.

Earthquake simulation shakers are mainly composed of electro-hydraulic servo systems, exciter systems, hydraulic source systems and table tops. In the shaker test, usually go through the following steps: first of all, the stored white noise signal or other typical control input signal loaded to the shaker to complete a certain vibration, through the shaker response to the transfer function of the system and the inverse function to identify, by the seismic simulation of the acceleration response of the shaker expectations of the system to find out the initial drive signal, through the hydraulic servo system loaded to the actuator to drive the seismic The initial drive signal is derived from the desired acceleration response of the seismic shaker and loaded onto the actuator through a hydraulic servo system to drive the seismic shaker. Then the response signal is collected by the acceleration sensor, and the controller is used to control and save the data. The desired trajectory signal is continuously tracked through iterative control, and the control signal of the system is corrected according to the error between the actual output signal and the desired signal until the output error is within the required range.

2.3 Proposed Power Test

The anthropomorphic test method, on the other hand, combines the advantages of the first two, and is also known as on-line test or hybrid test because it is performed on-line with the help of a computer. The concept of the proposed dynamic test experiment was first introduced in 1969 by

Japanese scholars such as Hakuno. The proposed dynamic test is an organic integration of the solution of structural dynamics equations and the proposed static test, in which the structural inertia force and damping force are considered through numerical calculations, and the structural restoring force needs to be obtained by actual test loading, which can be said to combine the advantages of the proposed static test and the shaking table test [10].

2.3.1 Principle of the proposed dynamic test-central difference method

The proposed dynamic test, also known as computer-actuator on-line test (On-Line Computer Test), is a structural seismic test method that organically combines the computational control of a computer with structural testing. It absorbs the advantages of the proposed static test and shaking table test, and can reproduce the elastic-plastic seismic response of a larger scale model by recording a given seismic acceleration and conducting structural tests with a computer-controlled actuator. Since the loading during the test is carried out gradually, the damage process of the structure can be observed in detail, and the restoring force-displacement curve of the structure can be measured at the same time, which has been successfully applied in practical engineering.

The proposed dynamic test is based on the principle of numerical calculation of structural dynamic equations. The vibration equation of a multi-degree-of-freedom structure under seismic action is:

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

where M , C and K are the mass, damping and stiffness matrices, respectively, a, v and d are the relative acceleration, velocity and displacement vectors, respectively, and f is the known seismic action vector. The selection of numerical methods in the proposed dynamic tests is mainly based on their stability and accuracy. Explicit methods include the central difference method and so on, and implicit methods include the Newmark-β and Wilson-θ methods, α method and so on. Methods that require previous step conditions for solving differential equations are called explicit methods. The central difference method is a conditionally stabilized explicit method, and it is a widely used numerical method in anthropomorphic dynamics tests. In order to be able to solve (1) numerically, the above vibration equation is written in discrete form, and the time step is set to be Δt , then equation (1) is at i time:

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

The central difference method is generally used in the proposed dynamic test to solve the above equation. i The velocity and acceleration at the moment are:

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

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

d_{i+1} The displacements at $i+1$ and $i-1$ are the displacements at the time of the model control point d_{i-1} , respectively. Substituting Eqs. (3) and (4) into the discrete equation (2) and making $Kd_i = r_i$, it can be obtained after finishing:

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

The above equation shows that the displacement at the time of $i+1$ d_{i+1} is related to the displacement at the time of i , the restoring force at the time of i , the seismic effect at the time of i , and the displacement at the time of $i-1$. Equation (5) determines the displacement at the time of $i+1$, the computer applies the command to the actuator, and the actuator makes the model produce the displacement d_{i+1} , and the restoring force r_{i+1} is measured by the force sensor on the actuator. Repeating the above steps, the time course of structural response can be measured under the seismic action.

2.3.2 Proposed power test advantages

(1) Loading method close to real seismic effects

The proposed dynamic test is capable of simulating the dynamic response of a structure under seismic action. It controls the loading equipment by computer and gradually applies the force equivalent to the seismic action according to the acceleration record of the ground shaking. This loading method can well simulate the inertia force and restoring force that the structure is subjected to during an earthquake, and it can more realistically reflect the behavior of the structure under dynamic loading such as an earthquake than some static test methods. For example, for a multi-story frame building, the proposed dynamic test can apply the load according to the time course of the actual seismic wave (e.g., the 1995 Hanshin seismic wave in Japan), so that the internal forces and deformations of the structural members will change dynamically with the loading process of the seismic wave, just like what the building experiences in a real earthquake.

(2) The nonlinear properties of the structure can be considered

Many building structures will enter a nonlinear phase under seismic action, such as yielding of reinforcement in concrete structures and local buckling of steel structures. The proposed dynamic test can effectively consider these nonlinear factors. During the test, with the increase of loading force, the mechanical characteristics of the structure, such as stiffness and damping, will change, and the proposed dynamic test system can monitor in real time and adjust the loading strategy according to these changes. Take a reinforced concrete bridge pier as an example, when the steel reinforcement at the bottom of the pier reaches the yield strength, the stiffness of the structure will decrease, and the proposed dynamic test equipment can continue to apply the load according to the requirements of seismic waves based on this change in the stiffness of the structure, so as to accurately record the structure's deformation, internal force, and other responses in the nonlinear phase, and to provide reliable data for the assessment of the structure's ultimate load-bearing capacity under strong earthquakes.

(3) Greater scale and flexibility of experimentation

Proposed dynamic testing has unique advantages for the experimental study of large building structures. Compared with seismic simulation shaker tests, the proposed dynamic test does not require the entire structure to be placed on the shaker, and therefore is not limited by the shaker size and bearing capacity. It is possible to test large structural members or substructures of actual size, such as the main girder segments of large bridges and frame substructures of high-rise buildings. The proposed dynamic test can easily change various test parameters during the test. Researchers can adjust the input characteristics of seismic waves (e.g., peak acceleration, spectral characteristics, etc.), and also change the boundary conditions of the structure, the material properties of the components, and other factors, according to the purpose and needs of the study. This flexibility enables the proposed dynamic test to study the seismic performance of structures in a variety of complex situations.

2.3.3 Substructure test methods

The substructure test method is to divide the structure into two parts: the experimental substructure and the numerical substructure. The test substructure is usually the critical and difficult to accurately numerical simulation part of the structure, such as special connection nodes, new material components, etc., which are physically tested in the laboratory; while the numerical substructure is the relatively regular and easy to model and calculate part of the structure, which is simulated by computer numerical analysis to simulate its mechanical behavior. In the test process, the two work together through the transfer and interaction of boundary conditions to complete the simulation of the response of the whole structure under seismic action. For example, for a high-rise mixed-structure building, the steel beam connection node of the section steel concrete column at the bottom is taken as the test substructure, and the frame structure at the top is taken as the numerical substructure. In the proposed dynamic test, the force acting on the test substructure is calculated according to the seismic wave input and applied by a loading device, and at the same time, the response of the test substructure such as the displacement is fed back to the numerical substructure computational model to realize the dynamic Coupling.

3. Proposed Power Test Equipment

(1) Electro-hydraulic servo loading test system, this test system is mainly divided into five parts: reaction wall, electro-hydraulic servo actuator, hydraulic servo oil source, oil distributor and piping system, full digital electro-hydraulic servo control system. The actuator of the electro-hydraulic servo loading system is shown in Figure 2 Electrohydraulic Servo Loading System, and the main control of the electro-hydraulic servo control system is shown in Figure 3 Electro-hydraulic servo control system. The two ends of the actuator have ball-articulated flanges to connect with the counterforce wall and the model respectively.

Figure 2. Electrohydraulic Servo Loading System

Figure 3. Electro-Hydraulic Servo Control System

(2) IMP Strain Acquisition System, this system consists of a computer, strain acquisition software, IMP wiring board and data acquisition board. See Figure 4 Strain Acquisition System - Computer,Figure 5 Strain Gauge System - Data Acquisition Boards.

Figure 4. Strain Acquisition System - Computer

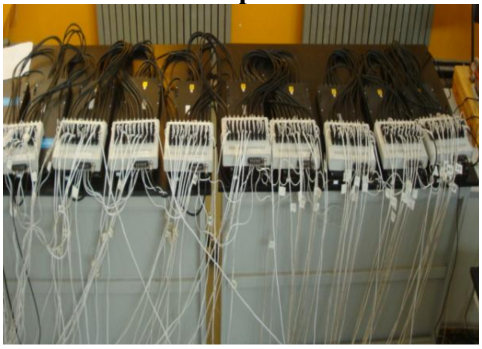

Figure 5. Strain Gauge System - Data Acquisition Boards

(3) Reading microscope and crack viewer for reading the width of cracks, see Figure 6 Crack Observer

Figure 6. Crack Observer

(4) Displacement transducer, used to measure the displacement deformation of each part of the test structure, see Figure 7 YHD-50 Displacement Gauge

Figure 7. YHD-50 Displacement Gauge

4. Proposed Power Test Steps

The steps of the test are as follows:
(1) Input seismic acceleration time course;
(2) Input model mass, damping ratio;
(3) Determine the initial stiffness of the model;
(4) Apply displacement to the model;
(5) Measure the restoring force of the structure;
(6) According to the measured restoring force, the next displacement is obtained by the computer control system.

Repeat the above (4), (5) and (6) until all the proposed dynamic tests are completed. The crack development shall be observed several times during the seismic test.

5. Processing of Test Results

After the completion of the test, the collected raw data are initially checked, and if it is found that there are obvious abnormalities in some of the data points, such as a great jump value of the displacement sensor at a certain moment, and a continuous zero value of the acceleration sensor, etc., the data points will be deleted. By setting a reasonable threshold value, according to the normal value range of each physical quantity, the points that deviate from the normal range beyond the set threshold value are judged as abnormal data points and are deleted. For example, for displacement data, if the difference between the displacement value of a point and the displacement value of a neighboring point exceeds the displacement threshold, the point is considered to be an abnormal point.

5.1 Time Course Analysis

5.1.1 Displacement time course analysis

After obtaining the test data, it is necessary to draw the horizontal displacement time-course curves of each floor and the relative displacement time-course curves at the key nodes. From these curves, the corresponding trends can be clearly obtained, for example, in the early stage of seismic loading, the structural displacement grows more slowly, and with the increase of ground shaking intensity, the displacement shows a rapid growth trend.

5.1.2 Acceleration time-course analysis

The time course curves of horizontal acceleration of each layer are plotted. Observation of the curves shows the overall direction of the acceleration at each level of the structure under the impact of seismic waves, e.g., the acceleration at each level of the structure rises rapidly under the impact of seismic waves, and then gradually decays during the fluctuations. The moment of the peak acceleration appears has some correlation with the peak moment of the seismic wave.

5.1.3 Strain time-course analysis

Plot the strain time course curves at critical sections of major members such as columns and beams. Corresponding phenomena are seen in the curves, e.g., during seismic loading, the strains of the members change continuously with time, and some members show a sudden increase in strain at specific moments.

5.2 Eigenvalue Extraction

5.2.1 Peak extraction

The peak values of each physical quantity are extracted from the resulting displacement, acceleration and strain time-course curves. In addition to the peak maximum horizontal displacement at each floor level, the peak maximum horizontal acceleration at each floor level, and the peak maximum strain at key sections of each major member mentioned above, the peak maximum relative displacement at key nodes, etc. should also be extracted.

These peaks serve as important indicators for evaluating the dynamic response of a structure under seismic action and can visually reflect the intensity of deformation, vibration, and stresses on the structure.

5.2.2 Periodic extraction

The acceleration time-course curves are analyzed using the autocorrelation function method to extract the vibration period of the structure. The autocorrelation function of the acceleration time-course curves of each layer is calculated, and the vibration period of the structure at that layer is determined by finding the time interval corresponding to the first peak of the autocorrelation function.

5.3 Comparison with Theoretical Models

5.3.1 Theoretical modeling

According to the principle of structural mechanics, a finite element theoretical model corresponding to the frame structure is established using a networked test platform. In the model, the number of actuators, the number of degrees of freedom of the specimen, the channel number of the external displacement transducer, the channel number of the internal displacement transducer, the channel number of the force transducer, the channel number of the control channel, the number of the degrees of freedom where the actuator is located, the initial target value, the amplitude increment, the loading step, the number of cycle revolutions for each value, the tolerance value of error, the maximum speed of the actuator, etc., are inputted accurately, and the appropriate intrinsic relationships are adopted to describe the stressing behavior of the material. The theoretical model is simulated using finite element analysis software, and in the simulation process, the same ground vibration acceleration time course curve as the test is input as the loading condition in order to obtain the response data of the theoretical model under simulated seismic action.

5.3.2 Comparative analysis

Compare the peak values of physical quantities (e.g. displacement, acceleration, etc.) and the characteristic values of vibration period in the test results with those calculated by the theoretical model. Analyze the reasons for the differences, on the one hand, it may be due to the measurement errors in the test process, the loading system errors, etc.; on the other hand, it may be due to the theoretical model in the establishment of the process of simplifying the treatment of some complex factors (such as the nonlinear behavior of the nodes, the damage evolution of the material, etc.).

Through the comparative analysis, the accuracy of the theoretical model can be verified, and the possible problems in the test process can also be found to provide a basis for further improving the test and perfecting the theoretical model.

6. Conclusion

The proposed dynamic test, as an effective research method, has played an important role in the seismic study of reinforced concrete frame foundations. The dynamic characteristic parameters obtained through the test can not only reflect the behavior of the structure under seismic loading, but also provide an empirical basis for the subsequent seismic design. In this paper, we discuss in detail the principle of the proposed dynamic test, the main equipment, the test steps and data processing, emphasizing the rationality of the test design and the importance of data analysis.

With the continuous development of technology, the proposed dynamic test method is also gradually improved and optimized. Future research should focus on combining modern sensor technology, data acquisition system and numerical simulation means to improve the accuracy and efficiency of the test. In addition, for the seismic performance research of new materials and structural forms, the proposed dynamic test will also play a greater role.

In conclusion, the study of seismic performance of reinforced concrete frame structures is an important part of ensuring building safety, and the proposed dynamic test, as an advanced testing method, will continue to provide strong support for the development of this field. Through continuous and in-depth research and practice, we are expected to make greater progress in seismic design and engineering applications to ensure the safety of people's lives and properties.

Acknowledgments

This work was supported in part by a grant from Research business expenses of Beijing Municipal Education Commission in 2020. And this work was supported in part by a grant from College Student Innovation and Entrepreneurship Training Program in 2024

References

[1] From: National Earthquake Science Data Center (earthquake.cn)
[2] From: Statistics-Emergency Management Department of the People's Republic of China (mem.gov.cn)
[3] Cui Haijun, Fan Hua. Review of Structural Seismic Static Test Methods. Techno-Economic Market, 2008, (09): 27-28.
[4] Zhu Bolong editor. Seismic test of buildings Beijing: Earthquake Press, 1989
[5] Yao Zhengang, Liu Zuhua. Structural Experiments Shanghai: Tongji University Press 1996.
[6] Qiu Fawei, Qian Jiaru, Chen Zhipeng. Structural seismic test method Beijing: Science Press 2000.
[7] Zhang Bo. Research on seismic simulation shaking table and its control method. Lanzhou University of Technology, 2013.
[8] Wang Qianying. Real-time substructure testing method and its application. Harbin University of Technology, 2007.
[9] Qiu Fawei, Pan Peng. Structural quasi-static loading test method and control. Journal of Civil Engineering. 2002, 35(1): 1-10.
[10]Yang Shide, Yu Dehu, Wang Xiangying. Research and application of pseudo-dynamic test in the field of structural earthquake resistance. Low temperature building technology, 2021, 43(08): 49-53.