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Full structure pseudo-dynamic test method and application based on OpenSees-OpenFresco-MTS

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Abstract. Currently, the electro-hydraulic servo loading control system manufactured by MTS, OpenFresco hybrid test interface software and OpenSees finite element software are widely used in structure laboratories to carry out hybrid test, but there is no relevant public information about full structure pseudo-dynamic test based on the above software and hardware. In order to study the feasibility of using the above software and hardware to carry out full structure pseudo-dynamic test, the full structure pseudo-dynamic virtual experiments of a single degree of freedom (SDOF) structure and a two degrees of freedom (2DOFs) structure are carried out based on the MTS 793 Demo Mode, and the results are respectively compared with the finite element analysis method. The results show that the finite element analysis results and full structure pseudo-dynamic virtual experiment results are highly consistent, which verifies the feasibility of carrying out the full structure pseudo-dynamic test based on the above software and hardware. Then, a three story steel frame full structure pseudo-dynamic test is conducted, and the smooth implementation of full structure pseudo-dynamic test of the three story steel frame further verifies the reliability of this testing method. The implementation method of carrying out the full structure pseudo-dynamic tests are introduced in detail, which can provide some reference for relevant research.

Keywords: full structure pseudo-dynamic test; MTS 793; OpenFresco; OpenSees; three story steel frame

1. Introduction

Seismic testing is a necessary step in research on quakeproof and disaster preventing, aiming to obtain the real response of structures under earthquake action. Currently, there are mainly three commonly used structural seismic test methods: pseudo-static test method, seismic simulation shaking table test method, and pseudo-dynamic test method (Qiu *et al.* 2000). The pseudo-static test is simple to operate and low in cost, enabling the maximum acquisition of the seismic resistance capacity of the test specimen (Qiu *et al.* 2000, Khalaf and Qissab 2020). However, it cannot fully evaluate the mechanical behavior characteristics of the structure under real earthquake action (Qiu *et al.* 2000, Khalaf and Qissab 2020). The shaking table test can obtain the real seismic response of a structure, but it is expensive and limited by the size and load-bearing capacity of the table (Wu *et al.* 2022, Xu *et al.* 2020, Tsai *et al.* 2008, Dong *et al.* 2020). The shaking table test

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method is basically limited to scaled model tests and cannot fully evaluate all the true mechanical behavior characteristics of structural components under earthquake action. The pseudo-dynamic test combines the characteristics of pseudo-static and shaking table tests, enabling to replicating the mechanical response of large-scale or even full-scale structures under real earthquake motion (Mahin and Shing 1985, Shing 1996, Xu *et al.* 2017). With the dual advantages of pseudo-static testing and shaking table testing, the pseudo-dynamic test has been widely used in recent years (Mahin and Shing 1985, Cai *et al.* 2019, Wang and Pan 2018, Cai and Tian 2014, Xu *et al.* 2024).

The electro-hydraulic servo loading control system manufactured by MTS Corporation is known for its excellent stability, comprehensive functional modules, ease of operation, self-programming capabilities, and reserved secondary development interfaces (Cai and Tian 2014). It can meet various testing needs and has been widely used in structural laboratories in recent years (Cai and Tian 2014). It is often necessary to use it in conjunction with the hybrid test interface software OpenFresco and the finite element software OpenSees, when implementing hybrid test (Cai and Tian 2014, Molina *et al.* 1999). OpenFresco, an open-source hybrid test interface software, was developed by the University of California, Berkeley. This software is capable of connecting with various test control systems, offering flexibility and integration in hybrid testing scenarios (Schellenberg *et al.* 2009). Its open-source nature allows for customization and further development by researchers and engineers, promoting innovation in the field of structural test. The combination of OpenFresco with systems like the MTS electro-hydraulic servo loading control system enables precise and efficient testing, advancing the understanding of structural behavior under different conditions (Schellenberg *et al.* 2009, MTS System Corporation 2001). The finite element software OpenSees has been widely used since its excellent nonlinear analysis capabilities and open-source nature, which facilitates secondary development (Mazzoni *et al.* 2007). In order to compensate for the lack of pre- and post-processing modules in OpenSees, the OpenSees Navigator was developed by Schellenberg *et al*., which is a visual software based on the MATLAB platform and can facilitate structural modeling and experimental process control (Schellenberg *et al.* 2009).

Currently, the aforementioned software and hardware for hybrid testing has been widely used in structural laboratories. However, there is no publicly available information regarding the conduct of full-scale pseudo-dynamic test using these software and hardware combinations. Therefore, studying the feasibility of conducting full-scale pseudo-dynamic test using the OpenSees-OpenFresco-MTS series of software and hardware is of great significance for structural seismic testing. In this paper, the full-scale pseudo-dynamic virtual experiments were conducted on a SDOF structure and a 2DOFs structure using the MTS 793 Demo Mode, respectively. The results were then compared with their finite element analysis results, respectively. The results demonstrated that a high degree of consistency between the finite element analysis results and the full-scale pseudo-dynamic virtual experiment results, so the feasibility of conducting full-scale pseudo-dynamic tests using the aforementioned software and hardware is verified. The reliability of this method is further validated by the successful implementation of the full-scale pseudo-dynamic test on the three-story steel frame. The detailed implementation of the full-scale pseudo-dynamic tests are introduced, which can provide a reference for related research.

2. SDOF full-scale pseudo-dynamic test based on beamColumn experimental element

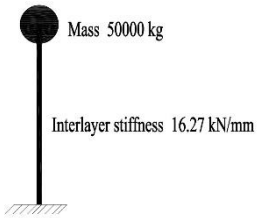

Fig. 1 SDOF structure model

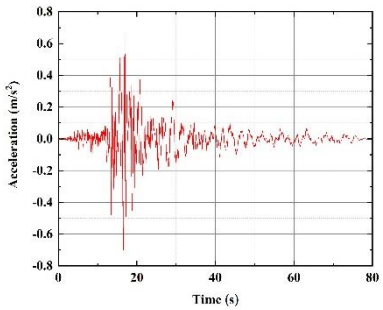

Fig. 2 The Coalinga seismic wave

2.1 Introduction to the SDOF model

The SDOF model has an interlayer stiffness of 16.27 kN/mm and a concentrated mass of 50000 kg at the top of the column, as shown in Fig. 1. The natural frequency of the structure is 1.67 Hz.

2.2 Experimental parameters setting

2.2.1 Parameter settings for time-history analysis of earthquake response in SDOF structures

A unidirectional elastic time-history analysis of earthquake response is conducted for the SDOF structure, employing the Rayleigh damping model. The damping ratio of the structure under minor earthquakes is 0.04. The Coalinga seismic wave with a peak acceleration of 0.7 m/s² is selected as the seismic excitation, and its waveform is shown in Fig. 2.

2.2.2 Parameter settings for the pseudo-dynamic virtual experiment of the full SDOF structure

In conducting the pseudo-dynamic virtual experiment of the full SDOF structure, OpenSees is used as the finite element analysis software, and the damping ratio and seismic input are the same as previously described. The framework for carrying out pseudo-dynamic experiment using OpenSees, OpenFresco and MTS electro-hydraulic servo loading control system is shown in Fig. 3. One experimental control point is defined to control the displacement and force feedback in the horizontal direction. The "OneActuator" experimental setup parameter is selected, with the actuator configuration shown in Fig. 4, and the loading direction is horizontal (Schellenberg *et al.*

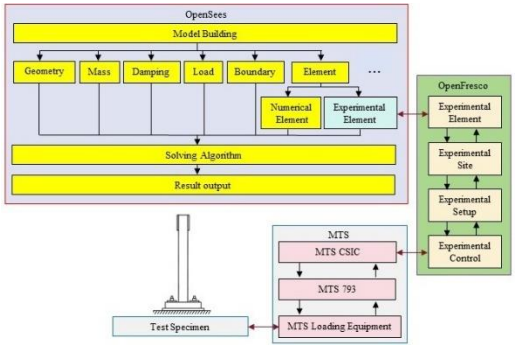

Fig. 3 The framework for carrying out pseudo-dynamic experiment

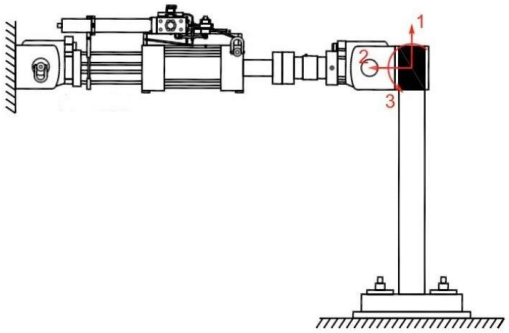

Fig. 4 Schematic diagram of the experimental setup (Schellenberg *et al.* 2009)

2009). The "LocalExperimentalSite" type of experimental site parameter is chosen. The beam-column experimental element is selected to represent the full structure, and its initial stiffness matrix is set (Schellenberg *et al.* 2009), as shown in Eq. (1).

$$\boldsymbol{K}_{\boldsymbol{inital}} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \tag{1}$$

In this equation: $\boldsymbol{K}_{\boldsymbol{inital}}$ is the initial stiffness matrix of the beamColumn experimental element, measured in kN/mm; E is the elastic modulus of the column material, measured in GPa; A is the cross-sectional area, measured in m²; L is the length of the column, measured in m; and I is the moment of inertia of the cross-section, measured in m⁴.

The Demo Mode of MTS 793 software is activated to implement the virtual experiment, as shown in Fig. 5. A virtual actuator loading control channel is created in the MTS 793 software, with virtual output selected as the virtual drive resource. The control modes for displacement and force are set to "Calculated Input" as the computational input resource (MTS System Corporation

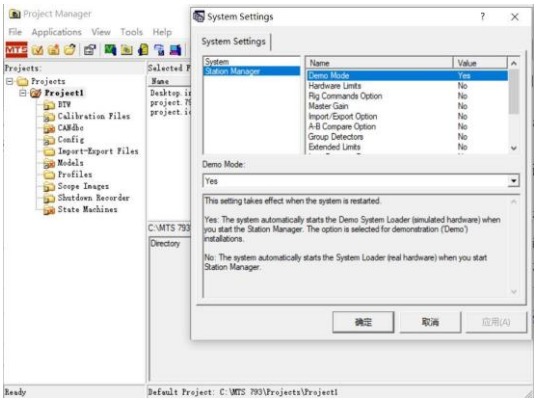

Fig. 5 MTS 793 software Demo Mode startup settings

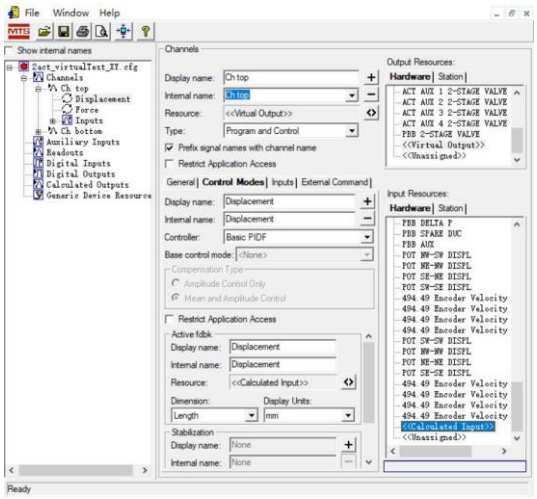

Fig. 6 Station configuration

2001), as shown in Fig. 6. The displacement feedback and force feedback of the virtual actuator are set according to Eqs. (2) and (3), respectively, as follows

$$Ch\ top\ Displacement = Ch\ top\ Displacement\ Command \tag{2}$$

$$Ch\ top\ Force = K \times Ch\ top\ Displacement \tag{3}$$

In those equations: *Ch top Displacement* is the displacement feedback of the actuator, measured in mm; *Ch top Displacement Command* is the displacement command of the actuator, measured in mm; *Ch top Force* is the force feedback of the actuator, measured in kN; and K is the lateral stiffness of the column, which is 16.27 kN/mm.

The connection between the MTS electro-hydraulic servo loading control system and the OpenFresco hybrid testing interface software is achieved through the MTS CSIC software (Schellenberg *et al.* 2009; MTS System Corporation 2001). In the MTS CSIC software, a control

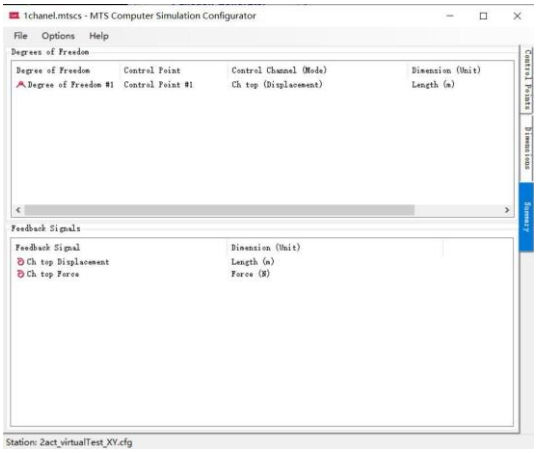

Fig. 7 MTS CSIC configuration

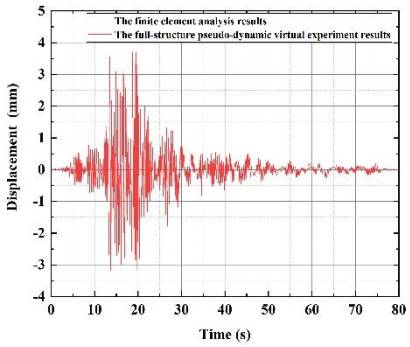

Fig. 8 Comparison of column top displacement

point is created and associated with the virtual actuator. The displacement control mode is selected, and the displacement feedback and force feedback of the actuator are chosen as the feedback signals, as shown in Fig. 7.

2.3 Results comparison and analysis

2.3.1 Results comparison

In this section, the comparison is conducted between the column top displacement obtained from the finite element analysis of the SDOF structure and that from the full-structure pseudo-dynamic virtual experiment. It is evident that the seismic responses of the structure derived from the two methods show a high degree of consistency, as illustrated in Fig. 8.

2.3.2 Error analysis

This section presents an error analysis comparing the column top displacement obtained from the finite element analysis with that from the full-structure pseudo-dynamic virtual experiment as shown in the Eq. (4).

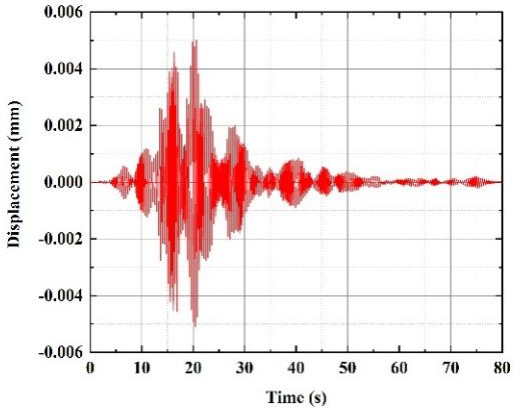

Fig. 9 Error analysis of column top displacement

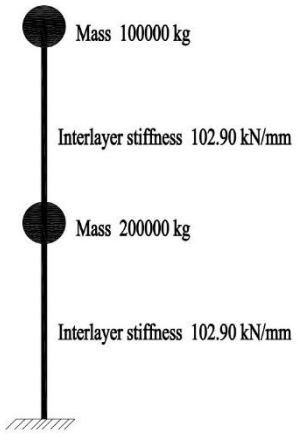

Fig. 10 2DOFs structure model

$$Dis_{Err} = Dis_{Pseudo} - Dis_{FEM} \tag{4}$$

In this equation: Dis_{Err} denotes error in column top displacement, measured in mm; Dis_{Pseudo} represents column top displacement obtained from the full-structure pseudo-dynamic virtual experiment, also measured in mm; and Dis_{FEM} is column top displacement derived from the finite element analysis, measured in mm. The error between the two analysis results is illustrated in Fig. 9.

According to the above results, it can be seen that the maximum difference between the column top displacement obtained from the finite element analysis and that from the full-structure pseudo-dynamic virtual experiment is approximately 0.005 mm, and the two results exhibit a high degree of consistency. The slight difference between them is mainly due to the rounding of data when inputting stiffness in the MTS 793 software, which leads to a minor discrepancy between the stiffness of the specimen in the full-structure virtual experiment and that in the finite element model. This in turn affects the results of the full-structure pseudo-dynamic virtual experiment.

3. Full-structure pseudo-dynamic test of 2DOFs system based on generic experimental element

3.1 Introduction to the 2DOFs model

The 2DOFs model is depicted in Fig. 10, which features a concentrated mass of 200000 kg at the top of the first story and a concentrated mass of 100000 kg at the top of the second story. The interlayer stiffness is uniform throughout, with a value of 102.90 kN/mm. The first-order and second-order natural frequencies of the structure are 2.76 Hz and 6.67 Hz, respectively.

3.2 Experimental parameter settings

3.2.1 Parameter settings for time-history analysis of earthquake response in 2DOFs structures

To conduct a unidirectional elastic time-history analysis of the seismic response of this structure, the seismic wave is the same as previously described in section 2.2.1, and it is amplitude-modulated to increase the seismic response of the structure. The peak acceleration is adjusted to 4 m/s² for this analysis. The Rayleigh damping model is employed, assuming a structural damping ratio of 0.05 under major earthquake conditions.

3.2.2 Parameter settings for the pseudo-dynamic virtual experiment of the full 2DOFs structure

When carrying out the 2DOFs full-structure pseudo-dynamic virtual experiment, two experimental control points are defined. Other parameter settings are similar to previously described in section 2.2.2. However, the beamColumn experimental element in OpenFresco requires one end to be fixed (Schellenberg *et al.* 2009), while the bottom of the second-floor column in this model is not fixed. Therefore, the generic experimental element needs to be adopted for the 2DOFs full-structure pseudo-dynamic virtual experiment. The initial stiffness matrix of this generic experimental element is defined in Eq. (5).

$$\boldsymbol{K}_{\boldsymbol{inital}} = \begin{bmatrix} K_{11}+K_{22} & -K_{22} \\ -K_{22} & K_{22} \end{bmatrix} = \begin{bmatrix} 205.80 & -102.90 \\ -102.90 & 102.90 \end{bmatrix} \text{ kN/mm} \tag{5}$$

In the equation: $\boldsymbol{K}_{\boldsymbol{inital}}$ represents initial stiffness matrix of the generic experimental element, measured in kN/mm; K_{11} is lateral stiffness of the first-floor column, measured in kN/mm; and K_{22} is lateral stiffness of the second-floor column, also measured in kN/mm.

It is necessary to create two virtual actuator channels in the MTS 793 software, Ch top and Ch bottom, using the same method as previously described in section 2.2.2. The displacement feedback and force feedback of the virtual actuators are set as follows in Eqs. (6)-(9).

$$Ch\ top\ Displacement = Ch\ top\ Displacement\ Command \tag{6}$$

$$Ch\ top\ Force = K_{22} \times Ch\ top\ Displacement - K_{22} \times Ch\ bottom\ Displacement \tag{7}$$

$$Ch\ bottom\ Displacement = Ch\ bottom\ Displacement\ Command \tag{8}$$

$$Ch\ bottom\ Force = (K_{11}+K_{22}) \times Ch\ bottom\ Displacement$$

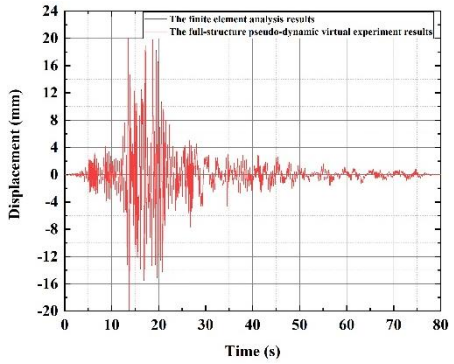

Fig. 11 Comparison of column top displacement at the first floor

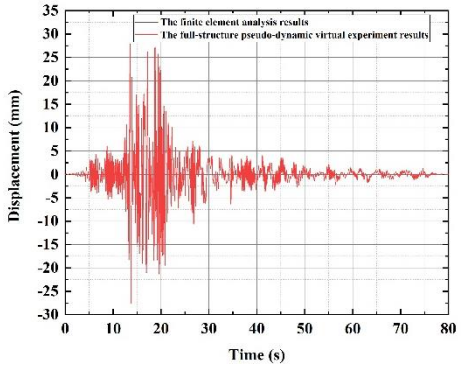

Fig. 12 Comparison of column top displacement at the second floor

$$- K_{22} \times Ch\ top\ Displacement \tag{9}$$

In those equations: *Ch bottom Displacement* and *Ch top Displacement* represent displacement feedback of Ch top and Ch bottom actuator, respectively, measured in mm; *Ch bottom Displacement Command* and *Ch top Displacement Command* are displacement commands of Ch top and Ch bottom actuator, respectively, also measured in mm; and *Ch bottom Force* and *Ch top Force* are force feedback of Ch top and Ch bottom actuator, respectively, measured in kN.

3.3 Result comparison and analysis

3.3.1 Result comparison

In this section, the comparison is conducted between the column top displacements obtained from the finite element analysis of the 2DOFs structure and those from the full-structure pseudo-dynamic virtual experiment. It is found that the structural seismic responses obtained by the two methods are highly consistent, as shown in Figs. 11 and 12.

3.3.2 Error analysis

In this section, the error analysis is conducted on the column top displacements obtained from

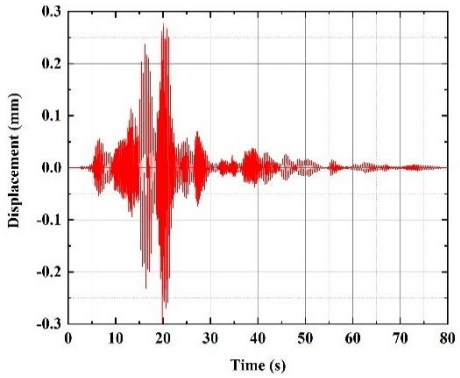

Fig. 13 Error analysis of column top displacement at the first floor

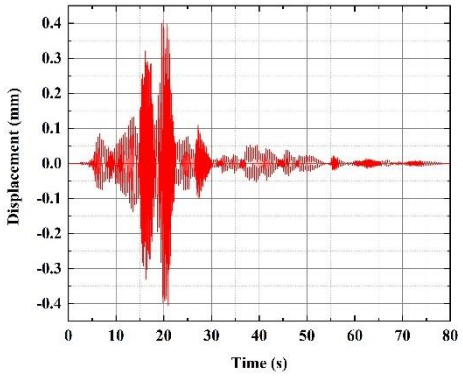

Fig. 14 Error analysis of column top displacement at the second floor

the finite element analysis and the full-structure pseudo-dynamic virtual experiment results. The results are presented in Figs. 13 and 14.

Based on the above results, it can be seen that the maximum difference between the column top displacements obtained from the finite element analysis and the full-structure pseudo-dynamic virtual experiment is approximately 0.40 mm. The results of the two methods are highly consistent. The difference is mainly due to the rounding of data when inputting stiffness in MTS 793, which leads to slight differences in the stiffness of the specimens used in the full-structure virtual experiment and the finite element model, thus affecting the results of the full-structure pseudo-dynamic virtual experiment.

4. Pseudo-dynamic test of three story steel frame based on the generic experimental element

4.1 Introduction to the three story steel frame specimens

The test specimen of the three-story steel frame has a story height of 2000.00mm for all stories.

Fig. 15 Full structure pseudo-dynamic test of a three story steel frame

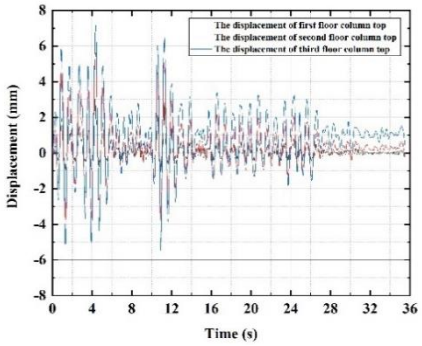

Fig. 16 Full structure pseudo-dynamic displacement response time history of a three story steel frame

The concentrated masses of the first and second stories are both 35000 kg, while the concentrated mass of the third story is 34948kg, as shown in Fig. 15.

4.2 Experimental parameter settings

To conduct a unidirectional pseudo-dynamic test on this structure, the EL-Centro earthquake wave is selected and amplitude-modulated to achieve a peak acceleration of 0.3 m/s^2. The Rayleigh damping model is employed, with a structural damping ratio is 0.02. Utilizing the generic experimental element, and the initial stiffness matrix of this element is defined.

4.3 Test result

Through this method, the displacement response of the three story steel frame under earthquake action can be obtained as shown in Fig. 16.

5. Conclusions

Conducting hybrid tests using the OpenSees-OpenFresco-MTS software and hardware suite is a widely adopted approach in most structural engineering laboratories. In order to verify the

feasibility of conducting full-structure pseudo-dynamic tests using the aforementioned software and hardware, full-structure pseudo-dynamic virtual experiments on a SDOF structure and a 2DOFs structure based on the MTS Demo Mode are conducted in this paper. The results are then compared with those obtained from finite element analysis. Subsequently, a full-structure pseudo-dynamic test is carried out on a three-story steel frame. The specific conclusions are as follows:

(1) The column top displacements obtained from the finite element analysis exhibit a high degree of consistency with those from the full-structure pseudo-dynamic virtual experiments, with minimal errors.

(2) For the SDOF structure, the beamColumn experimental element can be employed to complete the full-structure pseudo-dynamic test. Meanwhile, the multi degree of freedom structure can utilize the generic experimental element for the same purpose.

(3) The implementation approach adopted in this paper fully validates the feasibility of conducting full-structure pseudo-dynamic tests based on the OpenSees-OpenFresco-MTS software and hardware suite. This can provide a useful reference for related research.

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