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Real-time hybrid testing on a girder bridge model by using shaking- table and actuator

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ABSTRACT
Real-time hybrid test method, an innovative dynamic testing method combining pseudo-dynamic test method, shaking-table testing method, substructure analysis technique and numerical integration algorithm, is believed to be a promising solution to testing structures subjected to earthquake loading. The application of real-time hybrid testing on a girder bridge model was recently performed in Tongji University by using shaking-table and actuator. The prototype model is a single-span girder bridge. In order to study different kinds of hybrid simulation and its feasibility, three different applications based on the same prototype model was carried out: 1) the first test is hybrid test with single actuator; 2) the second test is hybrid test with single shaking-table and 3) the third test is a hybrid application by using both shaking-table and actuator. The testing procedure and result of the above three hybrid applications was reported in this paper. The feasibility of the real-time hybrid testing method was also discussed.

KEYWORDS: *real-time hybrid test, shaking-table test, pseudo-dynamic test*

1. INTRODUCTION

The analysis of seismic performance of structures and infrastructures can be conducted in 2 ways: numerical simulation or lab testing. Benefiting from knowledge construction and progress of computer and information technology during the last several decades, the application of numerical simulation on structural performance under dynamic loading has made significant progress in this research area. Refined finite element modeling of target structure and precise simulation of assigned loading helps to obtain satisfying analysis results within acceptable calculation time, which leads to a wide acceptance of numerical simulation method in both academic and industry society. However, lab testing remains an indispensable tool and still plays an important role in seismic analysis research area nowadays. On one hand, to some extent the accuracy of numerical simulation still relies on the accuracy of some key hypotheses, e.g., the constitutive formula of materials (especially concrete), the restoring force model of structural components (especially close to/under nonlinear stage) as well as the collapse mechanism of structures. These hypotheses are usually brought forward by different scholars with different formula and empirical factors, which need comprehensive proof from large quantities of experimental study. On the other hand, with more and more advanced and large-scale testing facilities being developed in this research area, the researchers can create a testing environment that is much closer to the real-world condition than several decades ago, which results in a better prediction of real structure response and makes the results of lab testing more creditable and reliable in the academic world.

Quasi-static, shaking-table and pseudo-dynamic are the three most commonly used lab testing methods for research on dynamic performance of structures subjected to earthquake loading. The quasi-static test is the first developed testing method in seismic analysis area and has been widely adopted by researchers and engineers for many years (Leon and Deierlein 1996). By applying low-frequency cyclic loading on specimen, key performance factors of the testing structure can be acquired. Shaking-table is one of the most important test facilities in earthquake engineering research and has been widely used in the study of linear and nonlinear dynamic response of building structures, bridges and industry equipment (Kim et al. 2007; Saiidi et al. 2007; Iijima et al. 2009). In a shaking-table test, collected or generated earthquake records or certain waveforms are applied to the test specimen mounted on shaking-table, and the structure behavior can be directly observed. The pseudo-dynamic test is an extension of quasi-static test, which can simulate the specimen response subjected to real earthquake loading by considering the effect of inertial force in numerical calculation (Takanashi and Nakashima 1987). The testing process of a pseudo-dynamic test includes numerical calculation, loading control and response acquisition. The common pseudo-dynamic test is carried out by applying non-real-time numerical calculation and slow actuator loading, which is not applicable to study velocity-related targets such as dampers and time-related structural behavior.

Real-time hybrid test method, a newly developed dynamic testing method founded on common pseudo-dynamic test method, shaking-table test method, substructure analysis technique and numerical integration algorithm, is believed to be a promising solution to testing structures subjected to earthquake loading. In real-time hybrid test, by using substructure technique, the target structure is divided into 2 parts: the experimental sub-structure for testing and the numerical sub-structure for simulation. Usually the interested part of the structure or the part supposed to have significant nonlinear response under earthquake loading is taken as experimental sub-structure; while the rest of the structure becomes numerical sub-structure. The both substructures are integrated into a whole dynamic formula, which can be solved by integration algorithm. The real-time hybrid test can be executed by using 1) only actuator (as advanced level of pseudo-dynamic test), 2) only shaking-table (so-called Smart Shaking-Table test) and 3) both shaking-table and actuator.

The application of real-time hybrid testing on a girder bridge model, which was recently performed in Tongji University by using shaking-table and actuator, was reported in this paper. The prototype model is a single-span girder bridge. In order to study different kinds of hybrid simulation and its feasibility, three different applications based on the same prototype model was carried out. The first test is hybrid test with single actuator. The second test is hybrid test with single shaking-table. And the third test is a hybrid application by using both shaking-table and actuator. The design of the specimen, the test plan and part of the testing results were described in this paper. The discussion on the feasibility and accuracy of real-time hybrid testing method was also provided.

2. REAL-TIME HYBRID TESTING FRAMEWORK

2.1. Testing Facilities in Tongji University

The newly-developed multiple shaking tables testing system of Tongji University is located in the Jiading Campus, Shanghai. As one of the largest and most capable multiple shaking tables testing facilities in the world, the testing system manufactured by MTS Systems Corporation is composed of four shaking tables and two trenches (70m and 30m in length respectively). The table size is the same for all tables as 4m by 6m, while the maximum capacity is 70tons for Table B and C, and 30tons for Table A and D. The tables can provide 3 degree-of-freedom in-plane motion, i.e., longitudinal, lateral and yaw. The specifications are listed in Table 2.1. All the four shaking tables can be easily moved/relocated in two trenches to meet different specimen design, which leads to three specific working modes (see Fig. 2.1). 1) All four tables are moveable within the first 70 meter trench and work as a large linear shaking table array. 2) Two of these tables can be placed in the second 30meters trench and are moveable throughout its length. Four tables can work as a rectangular shaking table array. 3) Two main tables (Table B&C) can be combined into a large shaking table used as a single shaking table. With the completion of the system in the end of 2012, a world-class multi-purpose earthquake simulation platform for the vibration and seismic testing research of bridge engineering, building and spatial structure engineering, underground structure engineering and lifeline engineering was developed in Tongji University.

During the early planning stage of the multiple shaking tables testing system, the application of real-time hybrid testing was already considered. A 24.5m long and 10m high reaction wall was casted at the end of both short and long trench, which can provide mounting point and reaction support for actuators when a hybrid simulation with both shaking table and actuator will be carried out. Each shaking table is equipped with SCRAMNet card in its controller and forms the internal ring for data communication, which can be easily updated to include new nodes (for actuators) in the ring for hybrid simulation.

Table 2.1 Performance Specifications of multiple shaking tables testing system

Item	Table A and D	Table B and C
Table size	6m×4m	
Specimen mass at maximum acceleration	30ton	70ton
Degree of freedom in control	3 D.O.F.（longitudinal, lateral, yaw）	
Stroke	±500mm (X axis 、Y axis)	
Velocity	±1000mm/s (X axis 、Y axis)	
Acceleration	±1.5g (X axis 、Y axis)	
Frequency of operation	0.1～50Hz	
Overturning moment	200ton·m	400ton·m

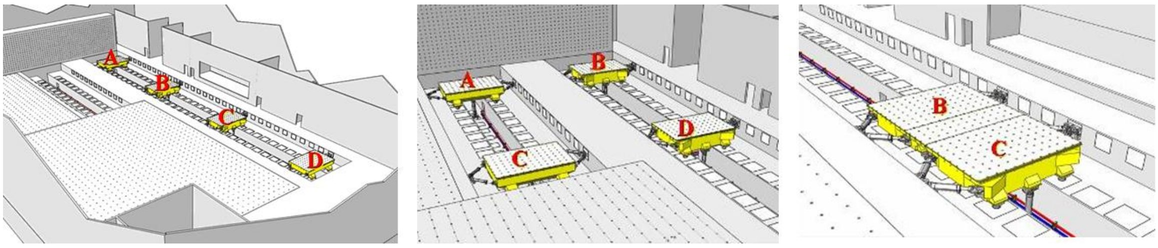

Figure 2.1 Specific working modes of multiple shaking tables testing system

2.2. Control Framework for hybrid testing

An OpenSees-OpenFresco-Simulink-MTS controller based hybrid testing framework was developed for the application in Tongji University, as shown in Fig. 2.2.

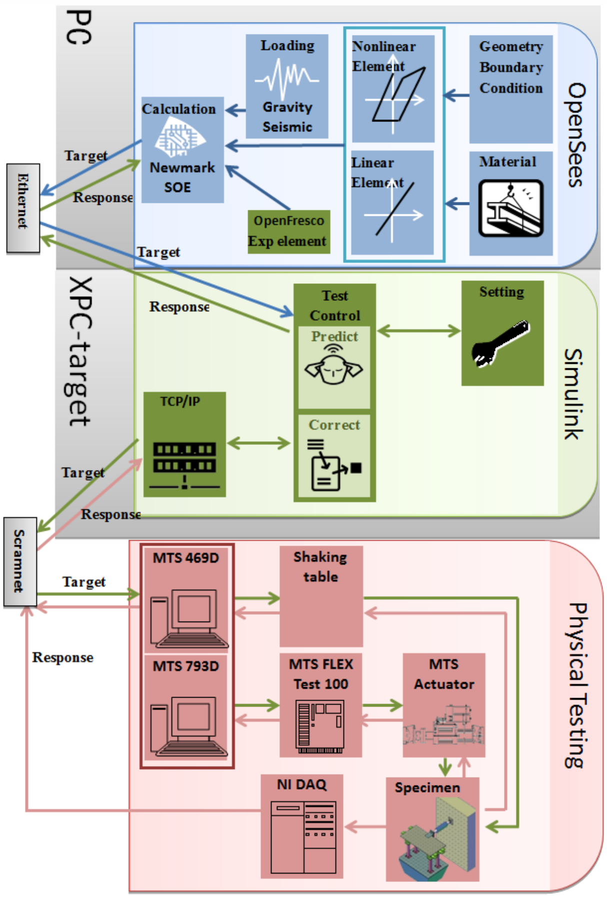

Figure 2.2 Control framework for hybrid testing

OpenSees (Open System for Earthquake Engineering Simulation), developed by the Pacific Earthquake Engineering Research Center (known as PEER), is a software framework for numerical simulation of response of structural and geotechnical systems under seismic loading (Mazzoni et al. 2006). In view of its open-source, comprehensive coverage and fast calculation speed, the software has been widely adopted by the academic and industry society during the last 10 years. In the proposed hybrid simulation framework, OpenSees is selected as the computational driver.

OpenFresco (the Open-source Framework for Experimental Setup and Control) is a middleware software package for performing hybrid simulations involving numerical models, test specimens, experimental setups and loading conditions (Schellenberg et al. 2007). On the numerical simulation side, it can support computational softwares such as OpenSees, Matlab, Simulink, LS-DYNA, Abaqus, and etc. On the physical testing side, it can connect to controllers provided by dSpace, MTS, National Instrument and etc.

Simulink is a block diagram environment for simulation and design. Integrated with MATLAB, Simulink provides a graphical editor and solver for modeling and simulating of dynamic systems. The predictor-corrector module (Schellenberg et al. 2009) is developed in Simulink, which talks to OpenFresco through the interface and provide the prediction-correction and harmonization of working frequency among different system in the hybrid simulation.

MTS actuator is controlled by MTS 793 controller and shaking-table is controlled by MTS 496D controller. The data acquisition system provided by National Instrument is also included in the framework for collecting the response of the specimen. The controllers of shaking-table, actuator and DAQ are all equipped with SCRAMNet card for high-speed data transit.

3. SPECIMEN AND TEST DESIGN

The prototype model for real-time hybrid testing is a single-span girder bridge, as shown in Fig. 3.1. The main girder is 7.95m long, supported by 4 rubber bearings on the top of double-column piers on each end. The total weight for the prototype model is about 35.2tons.

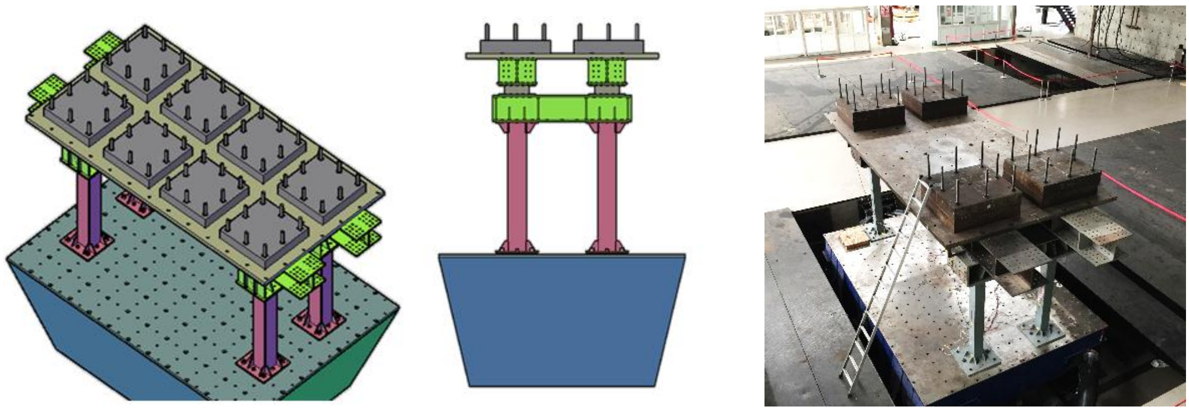

Figure 3.1 Full bridge model

In order to study different kinds of hybrid simulation and its feasibility, three different applications based on the same prototype model was carried out:

1) The Test I is hybrid test with single actuator. The rubber bearing is designed as experimental sub-structure and all other parts of the bridge model become the numerical sub-structure. The seismic loading on bearing is applied by actuator driven by real-time simulation command. See Fig.3.2.

2) The Test II is hybrid test with single shaking-table. The main girder with 4 rubber bearings is fixed on shaking-table as testing part and all double-column piers become numerical part. The displacement time-history at the top of bridge pier is played out by shaking-table with command signal from real-time simulation. See Fig.3.3.

3) The Test III is a hybrid application by using both shaking-table and actuator, which is the most challenge case in this application. The whole bridge model is fixed on shaking-table and one actuator is attached to the model at the center of girder. About 16tons of artificial mass is removed from the girder and the inertial effect of these

mass is applied by the actuator. Both shaking-table and actuator are driven by real-time signal to complete the earthquake simulation. See Fig.3.4.

One big shaking-table, with maximum capacity of 70ton, was used for Test II and III. One MTS 244.41 50ton actuator was used for Test I and one MTS 244.51 100ton actuator was used for Test III.

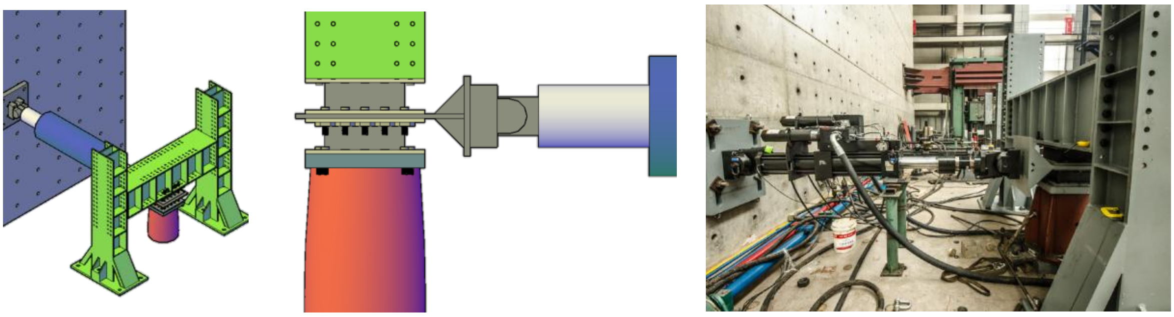

Figure 3.2 Specimen and test design for Test I

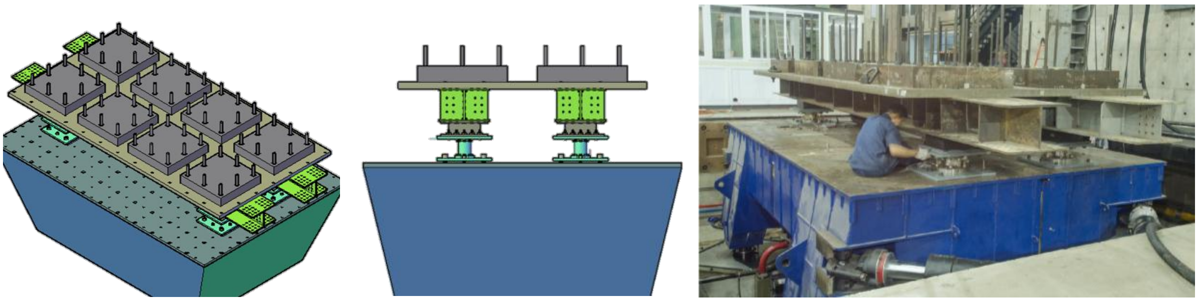

Figure 3.3 Specimen and test design for Test II

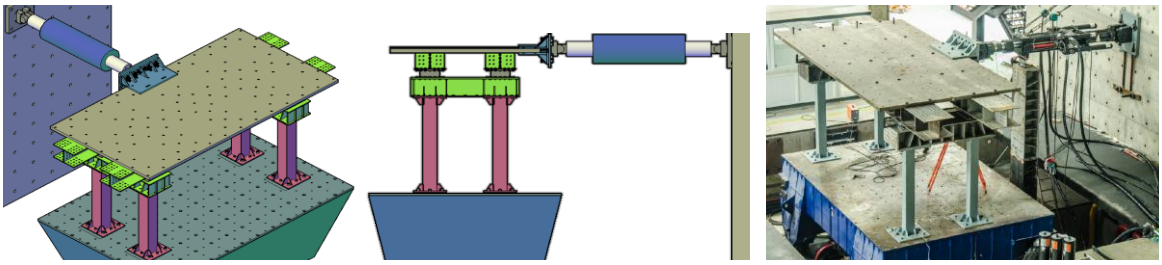

Figure 3.4 Specimen and test design for Test III

4. TESTING RESULTS AND DISCUSSION

The record from Loma Prieta Gilroy #4 Array, with 50% and 10% chance of exceedance in 50 years (peak acceleration of 85gal and 225 gal, respectively), are used as input ground motion for the test. The earthquake loading is only applied on lateral direction of the specimen, no longitudinal or vertical D.O.F. is considered in this test.

Since the main purpose for the test is to check the feasibility and accuracy of proposed hybrid simulation framework, some key data related to the command/response and condition of the system were recorded, including: computed target displacement by OpenSees, command displacement after predict-correct by Simulink/OpenFresco, measured displacement/force at the connection point of the specimen and the loading equipment.

In Test I, the relative displacement between pier top and bridge girder, i.e., the shear displacement of bearing was applied to experimental substructure by a 50ton actuator. In Test II, the calculated displacement at pier top was applied to experimental substructure as input motion of shaking-table. In Test III, the ground motion was applied by shaking-table while the inertia force from removed mass at top of bridge deck was simulated by a 100ton actuator. Selected testing results are shown in Fig.4.1-4.3.

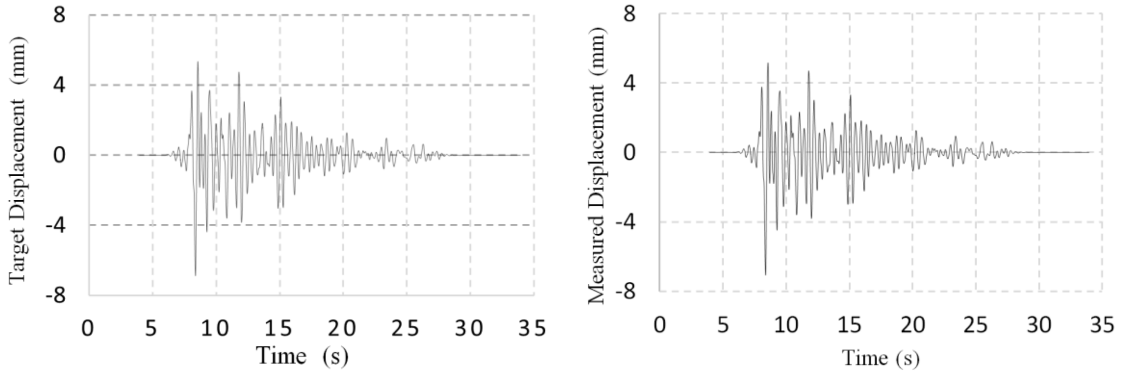

Figure 4.1 Target displacement and measured displacement for Test I

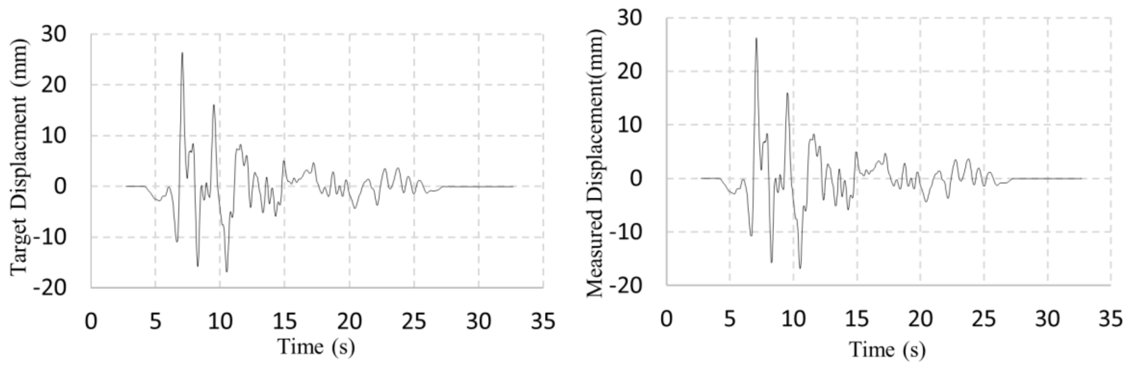

Figure 4.2 Target displacement and measured displacement for Test II

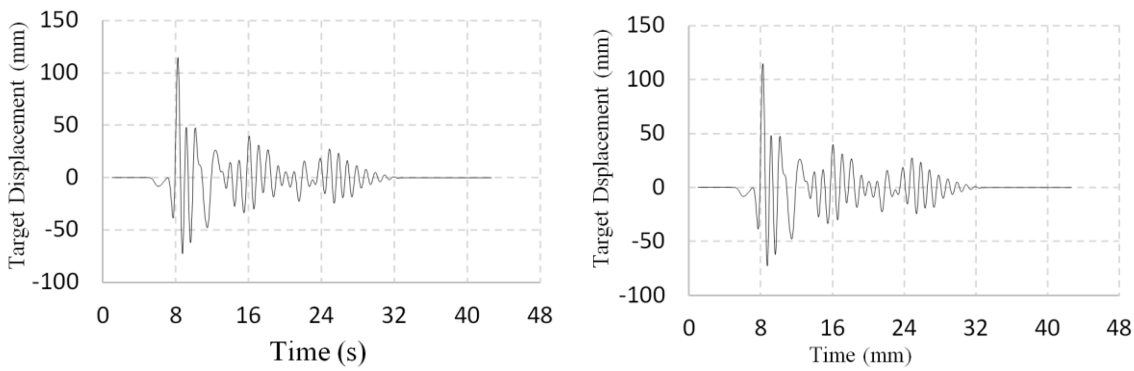

Figure 4.3 Target displacement and measured displacement for Test III

From Fig. 4.1 to Fig. 4.3, one may find that in most cases, the calculated commands from numerical substructure were physically applied on the testing substructure with very small error, as the “Target” and the “measured” signal matched reasonably well. The completion of seismic loading process in the aforementioned three applications showed that the concept of real-time hybrid testing was valid and achievable, and the proposed OpenSees-OpenFresco-Simulink-MTS controller based hybrid testing framework was capable of applying hybrid simulation.

A preliminary analysis of results from Test III (the hybrid testing with both shaking-table and actuator) were also performed, in order to discuss the reliability and the source of error for real-time hybrid testing. The target displacement and its error for actuator are shown in Fig. 4.4 and Fig. 4.5, in time domain and frequency domain, respectively. In time domain, as shown in Fig. 4.4, the displacement error is about 1% of the target displacement. In frequency domain, one can find though the target doesn't have peak after 1.025hz (the 1st natural frequency for the specimen), there are several peaks after 1.025hz for the error, including 1.625hz, 2.975hz, 4.975hz and 8.125hz. The first 2 peaks are the 2nd and 3rd natural frequency of the specimen, the third peak is close to the predominant frequency of input ground motion and the fourth peak is believed to be related with the oil-column resonance of the system. The target energy (only from actuator) and the error are shown in Fig. 4.6. Though the error of energy is negative, which implies more compensation should be made, the negative error is relatively small compared with the total energy in terms of quantity, therefore no divergence or instability issue will be raised in the system.

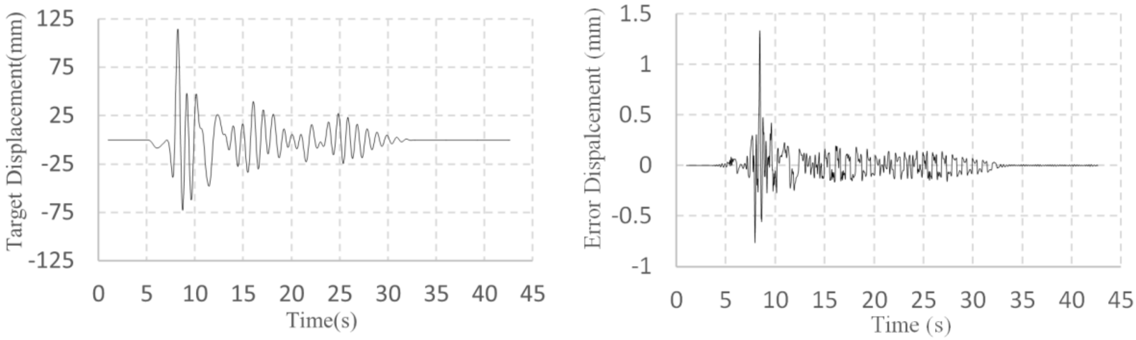

Figure 4.4 Target displacement and the error in time domain for Test III

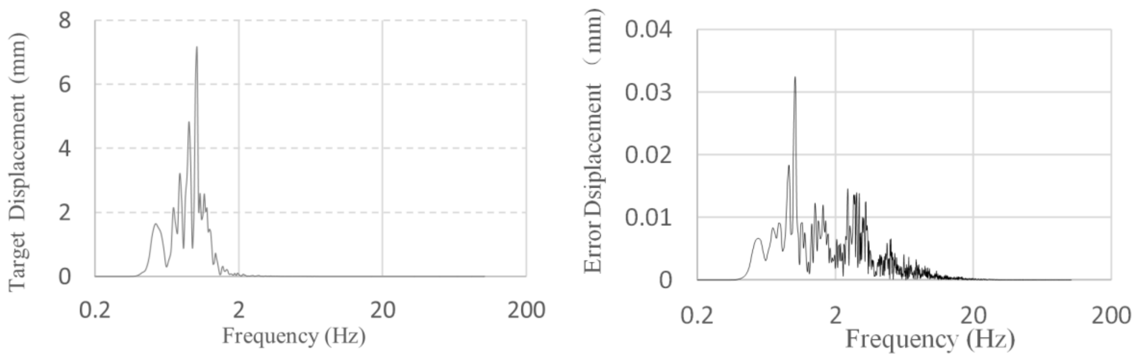

Figure 4.5 Target displacement and the error in frequency domain for Test III

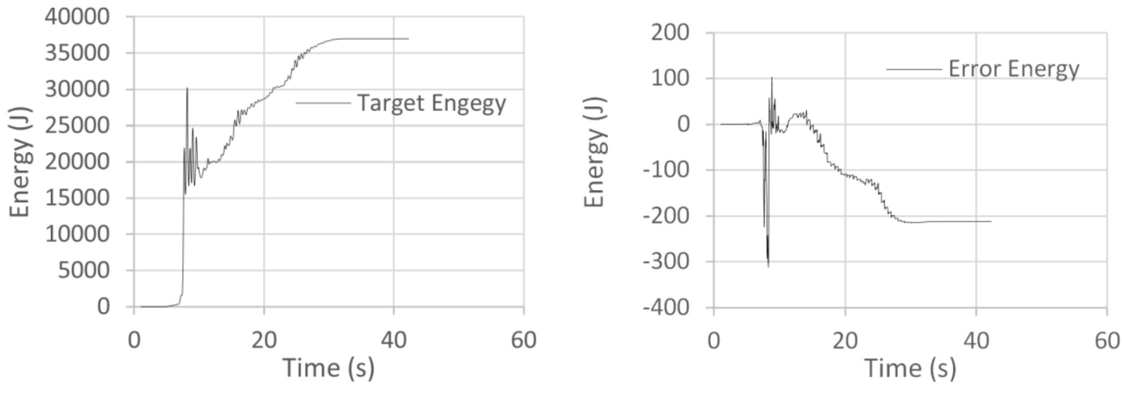

Figure 4.6 Target energy and the error for Test III

5. CONCLUSION

The application of real-time hybrid testing on a girder bridge model was recently performed in Tongji University. The following conclusions can be drawn:

1) Based on the same prototype model, three different applications of hybrid simulation were carried out: a) only actuator, b) only shaking-table and c) both shaking-table and actuator.
2) The completion of seismic loading process in the aforementioned three applications indicated that the concept of real-time hybrid testing was valid and achievable, and the proposed OpenSees-OpenFresco-Simulink-MTS controller based hybrid testing framework was capable of applying hybrid simulation.
3) A preliminary analysis on selected testing results was performed. To shed more light on the reliability and source of errors in hybrid simulation, further study will be carried out.

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