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DEVELOPMENT OF HYBRID SIMULATION METHOD AND ITS APPLICATION ON BRIDGES AND OTHER INFRASTRUCTURES

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Abstract

Hybrid simulation method, an innovative dynamic testing method originating from pseudo-dynamic test method and substructure analysis technique while reinforced by modern numerical integration algorithm and advanced hardware control capacity, is believed to be a promising seismic testing solution for bridges and other infrastructures. When applying hybrid simulation, usually the interested part of the structure or the part supposed to have significant nonlinear response is taken as experimental sub-structure; while the rest of the structure becomes numerical sub-structure. Both substructures are then integrated into a unified dynamic formula, which can be solved as a whole.

The development of a hybrid testing system was introduced in this paper. Opensees is selected as numerical calculator owing to its wide applicability and fast calculation speed, OpenFresco is used as a middle-ware for equipment set-up and data interaction, and MTS FT100 controller and its actuator is used for physical loading. The applications of hybrid simulation on two structure models were reported afterwards. In Application No.1, a single-span girder bridge was studied. The rubber bearing was selected as experimental sub-structure and all other parts of the bridge model became numerical sub-structure. In Application No.2, a subway station was studied. The intermediate column was physically loaded while the whole station and its surrounding soil were numerically modeled in Opensees. The results of the two application cases were further analyzed, in order to discuss the feasibility and accuracy of the innovative testing method and study the potential improvement for hybrid simulation.

Keywords: hybrid simulation; bridge; subway station

1. Introduction

Earthquake is one of the largest natural hazards which cause numerous life lost and infrastructure damage throughout the history of mankind. As a key component of the transportation system, the damage or collapse of bridge structure under earthquake attack will not only cause the casualty but cut off the road network which may lead to severe secondary loss. Therefore, the seismic performance of bridge structure is of great significance in terms of maintaining the completion and trafficability of city lifeline when earthquake attacks. Similarly, as an essential component of underground transportation system, subway station is designed to provide nonstop-function after both frequent and rare seismic events. Though it is generally believed that the seismic performance of underground structures is superior to superstructure since underground structures are surrounded and restricted by soil and rock, several severe damages of underground structure have been reported after recent huge earthquake attacks, especially the Daikai subway station during the Hyogoken-Nanbu earthquake in 1995[1, 2].

Usually the study of dynamic performance of bridges and other infrastructures subjected to seismic loading can be performed in 2 methods: numerical simulation and lab testing. Benefiting from knowledge construction and progress of computer technology during the past several decades, the application of numerical simulation, such as finite element analysis, on structural performance under dynamic loading has made significant progress in terms of accuracy and efficiency. 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, the accuracy of numerical simulation highly 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 when structure's behavior closes to or enters nonlinear phase) 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, such as NEES[3] facilities developed by NSF of USA and the Multi-functional Shaking Tables Lab of Tongji University in China, 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[4].

Hybrid simulation method, an innovative dynamic testing method originating from pseudo-dynamic testing method[5] and substructure analysis technique while reinforced by modern numerical integration algorithm and advanced hardware control capacity, is believed to be a promising seismic testing solution with better effect but lower cost compared with conventional seismic testing methods. When applying hybrid simulation, the target structure is divided into 2 parts: the physical sub-structure for testing and the numerical sub-structure for simulation (see Fig.1). Usually the interested part of the structure or the part supposed to have significant nonlinear response is taken as physical sub-structure; while the rest of the structure becomes numerical sub-structure. Both substructures are then integrated into a unified dynamic formula, which can be solved as a whole. As a newly developed testing method, many scholars have been putting efforts in its development and improvement, including the construction of the control scheme, the development of dedicated integration methods and compensation methods for time delay and error[6-10].

A hybrid simulation testing system was recently developed at the Multi-Functional Shaking Tables Lab of Tongji University and introduced in this paper. The applications of hybrid simulation on two infrastructure models were reported afterwards. In Application No.1, a single-span girder bridge was studied. The rubber bearing was selected as experimental sub-structure and all other parts of the bridge model became numerical sub-structure. In Application No.2, a subway station was studied. The intermediate column was physically loaded while the whole station and its surrounding soil were numerically modeled. Part of the testing results was presented in this paper and the discussion on the feasibility of this newly-developed testing method was also provided.

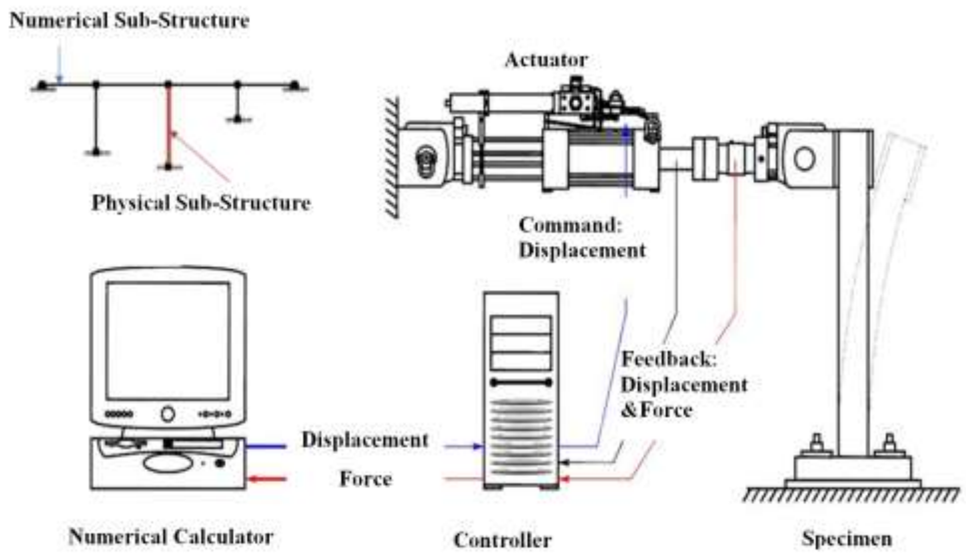


Fig. 1 – Concept of hybrid simulation

2. Framework of hybrid simulation testing system

A testing system based on OpenSees-OpenFresco-MTS controller was constructed for hybrid simulation. In this system, OpenSees is used for numerical calculation, OpenFresco is used for data interaction, and MTS actuator driven by its controller is used for physical loading. The framework can be seen in Fig.2.

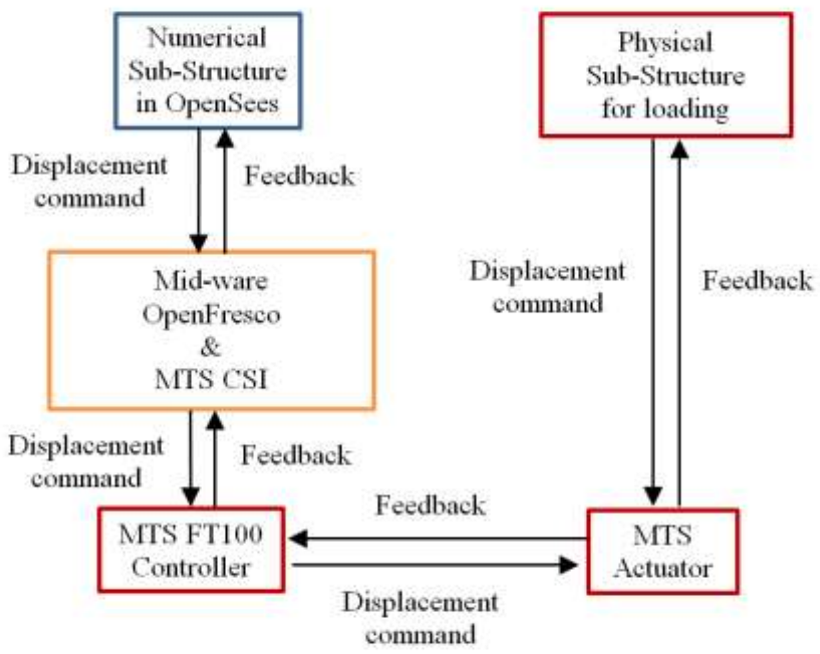


Fig. 2 – Framework of hybrid simulation testing system

OpenSees (Open System for Earthquake Engineering Simulation), as a well-known structural dynamic analysis software for numerical simulation of response of structural and geotechnical systems under seismic loading, is selected as the computational driver for hybrid simulation. OpenFresco (the Open-source Framework for Experimental Setup and Control) [11] is a middleware software package for performing hybrid simulations involving numerical models, test specimens, experimental setups and loading conditions. It can be the communicate bridge between a variety of finite element analysis software and a variety of testing equipment, and it can be also used for data interaction and control for physical substructure and numerical substructure. With MTS CSI, the interface software developed by MTS, OpenFresco can set the link between OpenSees with MTS controller, which works as data exchange channel from numerical sub-structure to physical sub-structure.

The hardware for a fundamental hybrid simulation testing system includes: 1 PC, 1 MTS FT100 controller, 1 MTS actuator and connection cables, as shown in Fig.3. OpenSees, OpenFresco, MTS CSI and MTS station manager (operation software for FT100 controller) are all installed and running in the same PC. The 1st step of target displacement calculated by OpenSees is transmitted through OpenFresco/MTS CSI to FT100 controller by RJ45 Ethernet cable. The command is then AD/DA transformed in FT100 and becomes electrical signal set to MTS actuator by BNC cables. After the loading action, the feedback of 1st step, namely measured displacement and restoring force, is then returned to OpenSees along the inverse routine. With the feedback joining in the dynamic formula, OpenSees will calculate the target displacement for the 2nd step; hence form the close-loop for hybrid simulation.

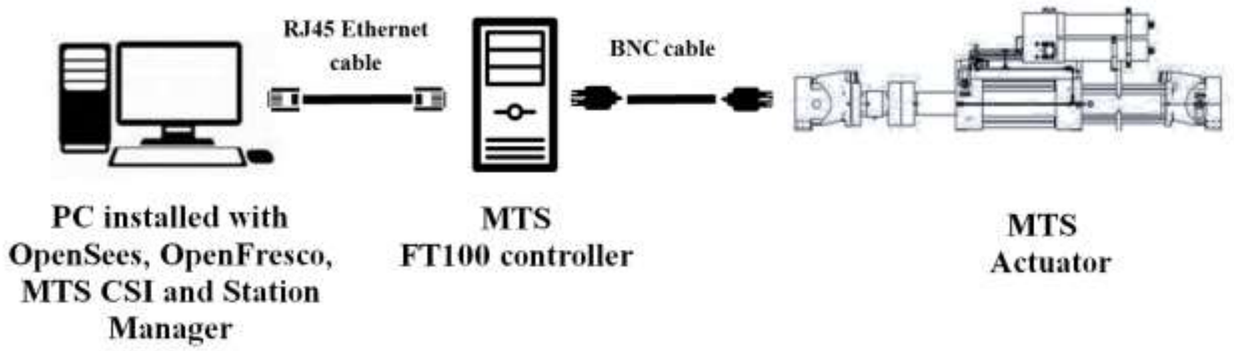


Fig. 3 – Hardware for a hybrid simulation testing system

3. Application on a girder bridge model

A single-span girder bridge was conducted as the prototype model, as shown in Fig.4. The girder was 7.95m long, which was supported by 4 rubber bearings on the top of double-column piers on each end. The total weight of the prototype model was about 35.2tons. When applying hybrid simulation, the rubber bearing was taken as physical sub-structure, and the rest parts of the bridge model became numerical sub-structure. The seismic loading on bearing was applied by one MTS 244.41 50ton actuator driven by MTS controller, as shown in Fig.5.

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 raw acceleration time-history and frequency information can be found in Fig.6. The earthquake loading is only applied on lateral direction of the specimen, no longitudinal or vertical D.O.F. is considered in this test.

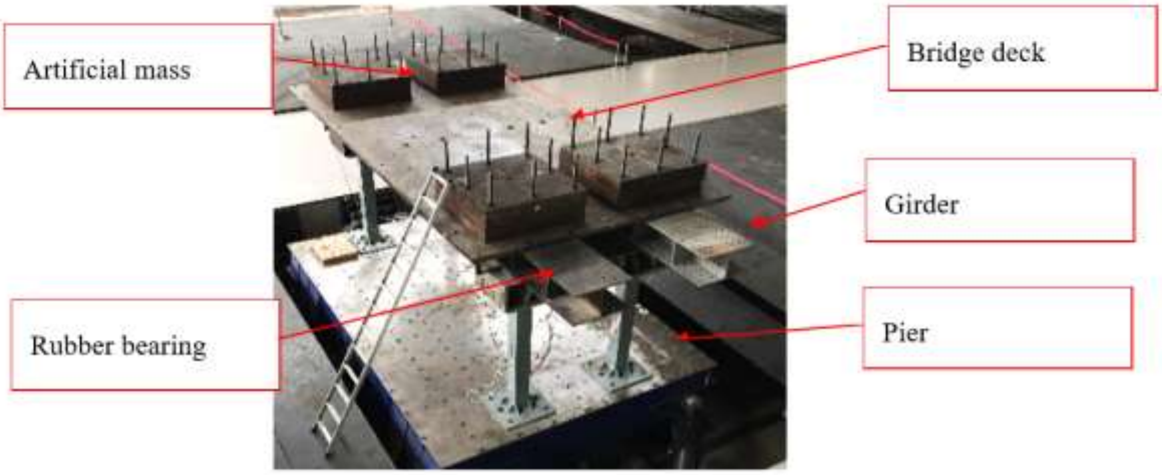
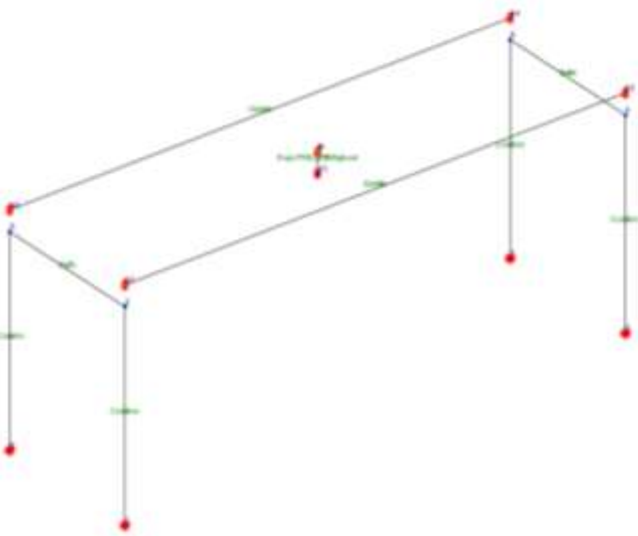


Fig. 4 – Prototype for application case No.1: girder bridge



(a) Numerical sub-structure in OpenSees

(b) Physical sub-structure in lab

Fig. 5 – Testing setup

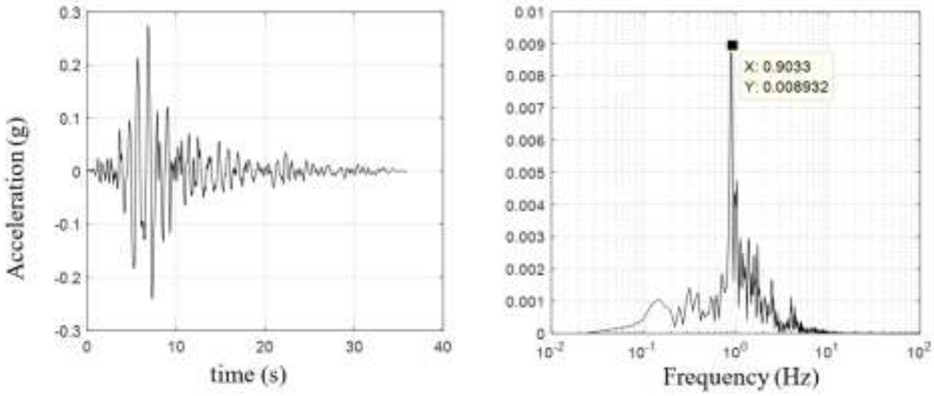


Fig. 6 –Input ground motion

As a preliminary application of hybrid simulation on large scale structure model, the main purpose for the test is to check the feasibility of the proposed testing method. Key data related to the command and the feedback of the system was recorded (as shown in Fig.7), including: computed displacement by OpenSees (as target), applied displacement by controller (as command) and measured displacement/force from the actuator (as feedback).

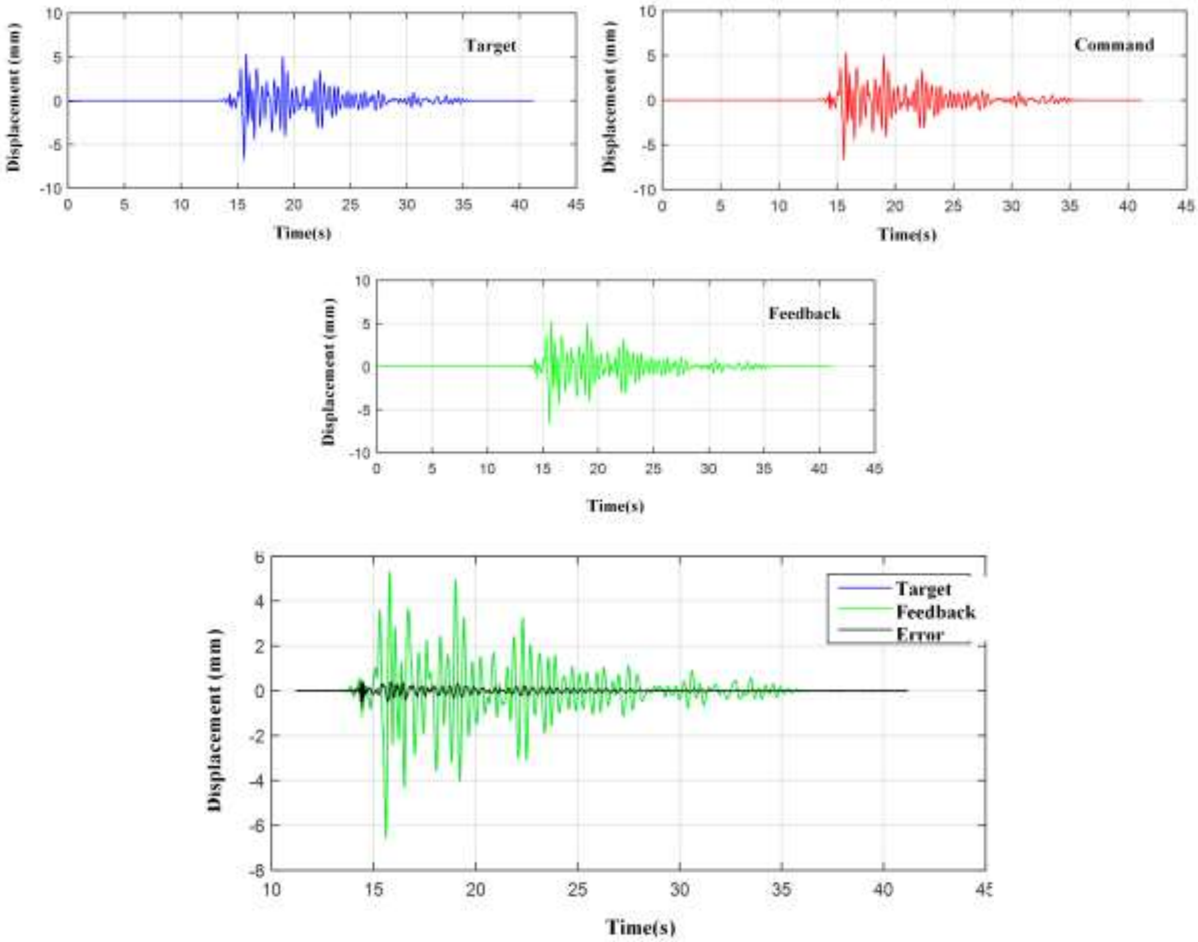
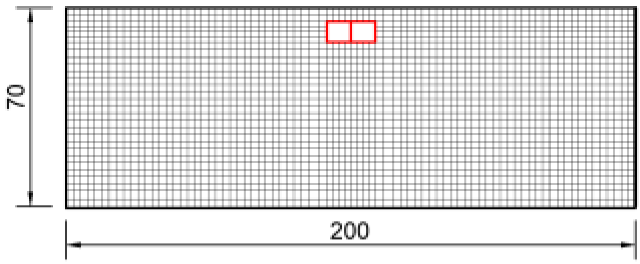


Fig. 7 –Shear displacement on bearing: Target, Command, Feedback and Error

From Fig.7, one may find that in this hybrid simulation application case, the calculated commands from numerical sub-structure were physically applied on the physical sub-structure with very small error, as the "Target", the "Command" and the "Feedback" displacements matched reasonably well. The maximum error between the "Target" and the "Feedback" is less than 0.8mm, and the correlation coefficient between the two time-histories is 0.9961, which showing a high consistency.

4. Application on a subway station model

A typical rectangular subway station was studied in this application. An intermediate column (truncated at middle as inflection point) in the subway station was adopted as physical sub-structure, while the remainder of the subway station and the soil surrounding it was simulated in OpenSees as numerical sub-structure. The dimensions of the soil domain modeled in this case were 200 m long and 70 m deep. The rectangular subway station section was 17 m × 7.2 m, and the station was embedded 4.8m deep below ground surface. Detailed dimension can be found in Fig.8.



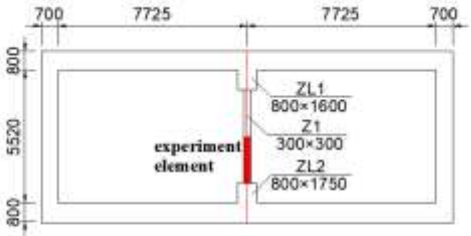


Fig. 8 –Cross section of soil domain (unit in m) and cross section of station (unit in mm)

Fig. 9 – Testing setup

A novel steel specimen was used for the physical loading. A special design was adopted for the bottom part of the steel specimen. Four screws were installed to connect steel column specimen and bottom base. The bending stiffness of steel column specimen could be changed by replacing the screws at the column foot.

There are 2 benefits of this specific design: firstly, the bending stiffness could be specified according to the real intermediate column in the subway station. Secondly, since the bending stiffness of the column itself was much larger than that of the screws, the failure mode would be the bucking failure of screws without destroying the upper column. As a preliminary study on hybrid simulation for large scale structure model, this special design helps to allow frequent testing failure due to non-convergence or data transmission error during the initial stage of such research work, as the experimental specimen could be easily repeated by just replacing screws.

The Shanghai artificial wave is used as input ground motion for the test. The raw acceleration time-history and frequency information can be found in Fig.10. The earthquake loading is only applied on longitudinal direction of the specimen, no transversal or vertical D.O.F. is considered in this test.

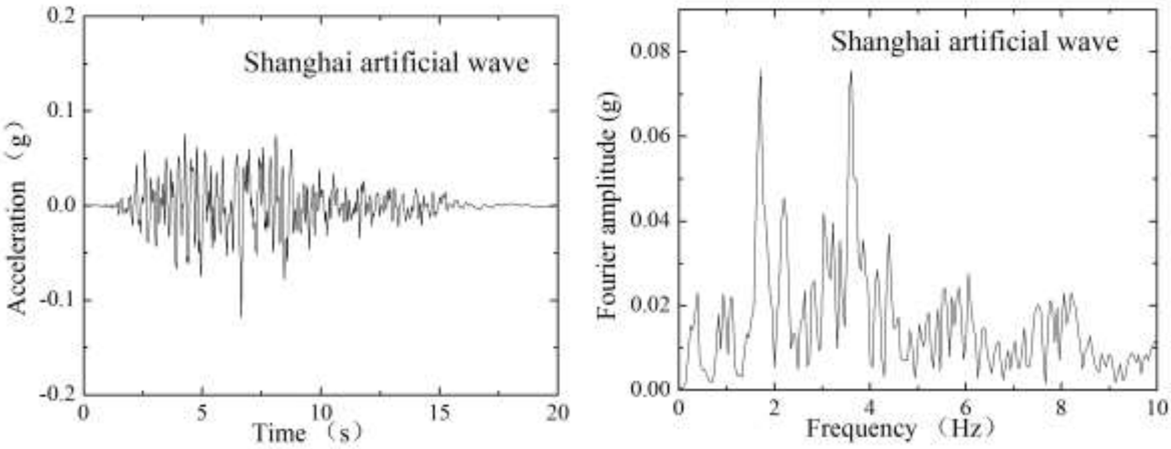


Fig. 10 –Input ground motion

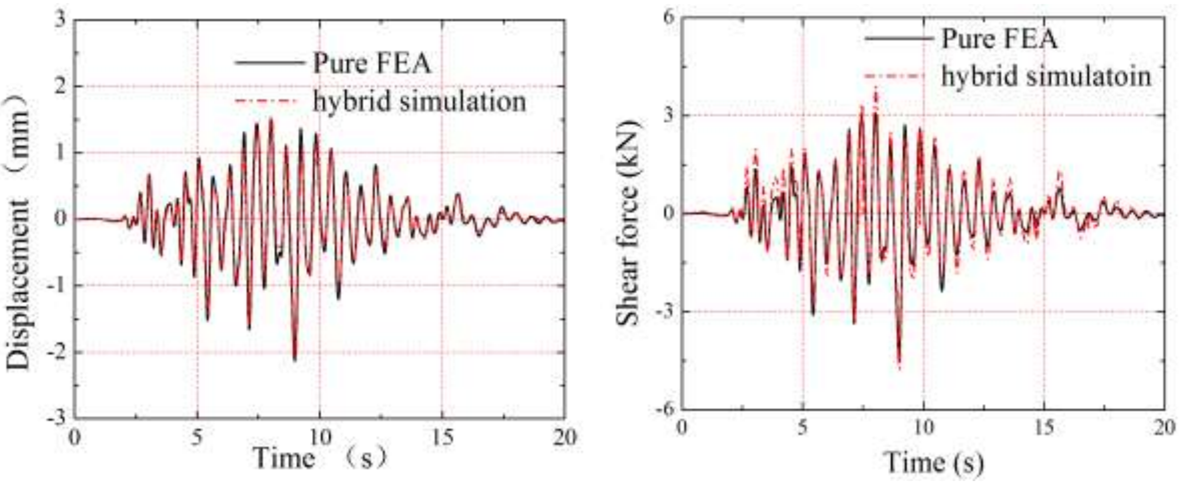


Fig. 11 –Horizontal displacement and shearing force: Pure FEA vs. hybrid simulation

The horizontal displacement and shearing force at the middle of intermediate column (i.e. the top of physical sub-structure) subjected to Shanghai artificial wave (PGA=0.12g) can be found in Fig.11. In order to study the feasibility and the accuracy of hybrid simulation method, the horizontal displacement and the shear force collected from a pure finite element analysis were also plotted in the same figure. One may find that the finite element analysis results matched well with the hybrid simulation results under earthquake excitation. Thus, the feasibility and accuracy of the proposed hybrid simulation testing method could be verified. The comparison suggested a good agreement, which indicated the developed hybrid simulation testing system based on OpenSees, OpenFresco and MTS controller performed well in the application on subway station analysis.

5. Conclusion

The application of hybrid simulation on a) a girder bridge model and b) a subway station model were recently performed in the Multi-Functional Shaking Tables Lab of Tongji University. The following conclusions can be drawn:

1) The completion of seismic loading process in the aforementioned two application cases indicated that the concept of hybrid simulation was valid and achievable, and the proposed OpenSees-OpenFresco-MTS controller based hybrid simulation testing system was capable of applying hybrid simulation.

2) Only preliminary testing results were reported in this paper. To shed more light on the reliability of this innovative testing method and widen its application, further study including the discussion of source of errors and the potential solution for a faster-to-real time loading rate will be carried out.

6. References

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