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A STUDY OF PERFORMING REAL-TIME HYBRID TESTING ON BRIDGE STRUCTURES BY USING NUMERICAL SIMULATION

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ABSTRACT

Real-time hybrid testing, a recently developed dynamic testing method combining shake table test, pseudo-dynamic test, substructure testing technique and numerical analysis, is believed to be a promising solution to testing complicated structures subjected to earthquake loading. A study of performing real-time hybrid test on bridge structure is introduced in this paper. Firstly, the concept of real-time hybrid test is demonstrated. Secondly, the control method and flowchart for real-time hybrid testing is discussed. Later on, a numerical simulation platform for real-time hybrid testing is developed. Finally, the numerical simulation of a simplified bridge model subjected to real-time hybrid test is performed and the feasibility of proposed testing method is verified.

Keywords: Real-time hybrid test, shake table test, pseudo-dynamic test.

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. The research work on seismic performance of bridge structures usually can be conducted in 2 ways: theoretical analysis and lab testing. Benefiting from knowledge construction and progress of IT technology during the last semi-century, the application of theoretical analysis, or more exactly numerical analysis, has made significant advancement in this research area. More refined numerical modeling and less time-consuming helps to obtain satisfying results, which leads to a wide acceptance of theoretical analysis method in both academic and industry society. However, the accuracy and reliability of numerical result to some extent still relies on the accuracy of several key hypotheses, e.g., the constitutive formula of materials, the restoring force model of structural components as well as the collapse mechanism of

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structures. These hypotheses are usually brought forward by scholars and need proof from experimental study. Therefore, lab testing remains an indispensable tool and plays an important role in seismic analysis research area.

Experimental method is regarded as a strong research technique which can be applied to study the real behaviour of structure under earthquake loadings and to verify theoretical analysis method. Quasi-static, shaking table and pseudo-dynamic are the three most commonly used testing methods for experimental research on dynamic performance of bridge structure 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, some key performance factors of the testing structure can be acquired, including the restoring force model, damping ratio, skeleton curve and etc. Shake 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 equipments (Kim et al. 2007; Saiidi et al. 2007; Iijima et al. 2009). In a shake table test, collected or generated earthquake records or certain waveforms are applied to the test specimen mounted on shake 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.

With the development of research work on seismic analysis of structures, the shortcomings of aforementioned common testing methods are of awareness. For quasi-static test, the load applying to specimen is cyclic load instead of earthquake load. For shake table test, table size and payload are regarded as a bottleneck for its application to large-to-full scale specimen. For pseudo-dynamic test, the target structure must be simplified to discrete model with limited degrees of freedom, which is hard to achieve for structure with large size and complex configuration.

Real-time hybrid testing, a recently developed dynamic testing method combining shake table test, pseudo-dynamic test, substructure testing technique and numerical analysis, is believed to be a promising solution to testing complicated structures subjected to earthquake loading. A study of performing real-time hybrid test on bridge structure is introduced in this paper. Firstly, the concept of real-time hybrid test is demonstrated. Secondly, the control method and flowchart for real-time hybrid testing is discussed. Later on, a numerical simulation platform for real-time hybrid testing is developed. Finally, the numerical simulation of a simplified bridge model subjected to real-time hybrid test is performed and the feasibility of proposed testing method is verified.

2. THE CONCEPT OF REAL-TIME HYBRID TEST

Real-time hybrid testing is a novel dynamic testing method involving the combination of shake table and pseudo-dynamic testing methods while extending the application scope of the two conventional methods and overcoming their limits (Reinhorn et al. 2004; Wang 2010).

In real-time hybrid test (as shown in Figure 1), by using substructure technique, the target bridge 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 (the middle pier in this example) or the part supposed to have significant nonlinear response under earthquake loading is taken as experimental sub-structure and put on the shaking table; while the rest of the structure becomes numerical sub-structure. The both substructures are integrated into a whole dynamic formula, which usually is calculated by certain Finite Element package. The interface action between the experimental sub-structure and the numerical sub-structure is applied by actuators, and the response of experimental substructure is measured and input into special “experimental element” (Schellenberg et al. 2009) developed in FE package. During a real-time hybrid test, the shaking table performs the input ground motion and vibrates the experimental sub-structure, the FE package executes the real-time numerical analysis for whole structure, and the actuator applies certain interaction on experimental sub-structure according to the FE calculation.

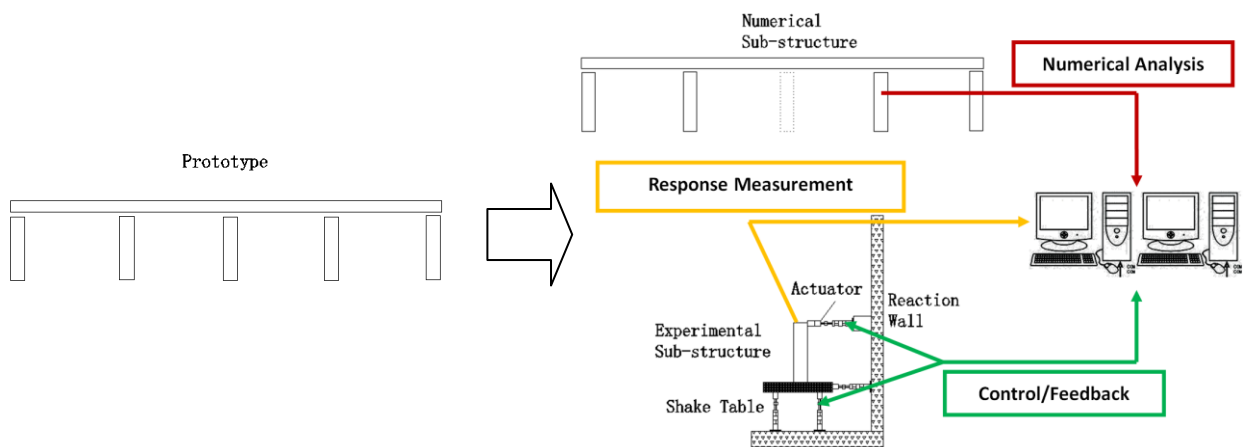


Figure 1: Schematic diagram of real-time hybrid testing for bridge structure.

3. CONTROL METHOD OF REAL-TIME HYBRID TEST

According to different control principle for applying interface action, the real-time hybrid test can be implemented in 2 ways, i.e., force control or displacement control. In force control method, the calculated interface force between numerical sub-structure and experimental sub-structure is imposed by actuator, and the measured specimen's motion information, i.e., displacement, velocity and acceleration is fed back to computer for numerical simulation. In displacement control method, the calculated displacement is set as target of actuator and the reaction force and other response is measured and fed back to computer.

Take a one degree-of-freedom experimental substructure for example, the flowcharts for both control methods can be seen in Figure 2. In the flowchart, R represents interface force, a_g represents input ground acceleration, and d , v , a represent interface displacement, velocity and acceleration, respectively.

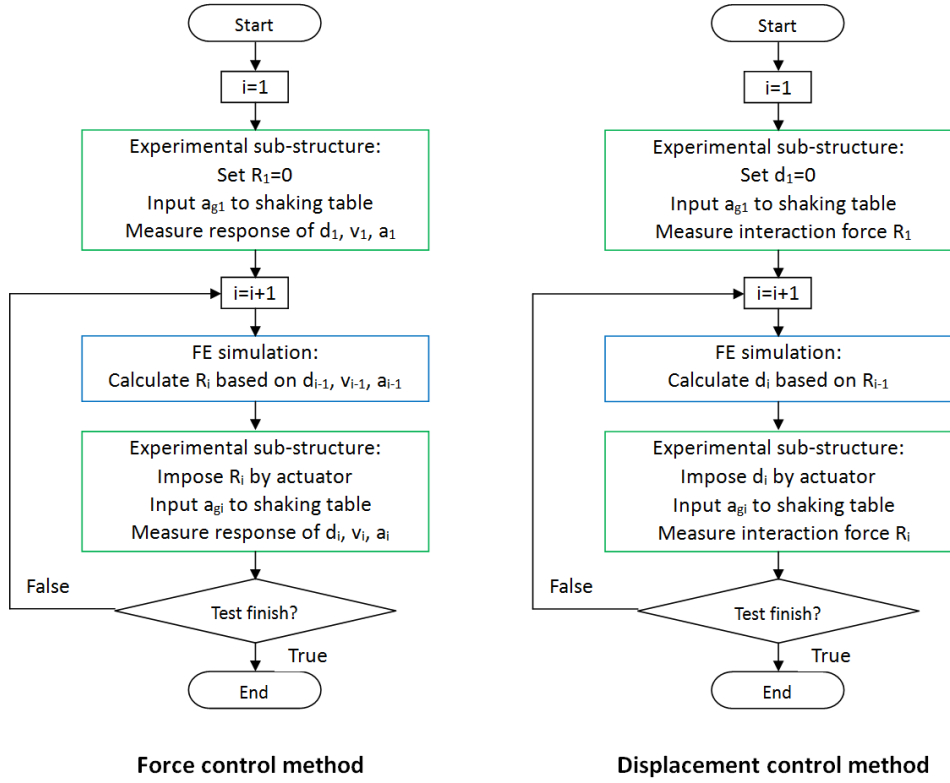


Figure 2: Flowchart for force/displacement control based real-time hybrid test

Similar to pseudo-dynamic and real-time pseudo-dynamic test, numerical integration techniques are adopted in real-time hybrid test for FE simulation and calculating desired target loading (force or displacement) for actuator. Lots of well-known numerical integration techniques had been studied in this application, such as CDM (Central Difference Method), Newmark's method, Operator Splitting method and etc. The stability and efficiency of these numerical integration methods has a great influence on the operation and completion of real-time hybrid test (Wu et al. 2009).

4. DEVELOPMENT OF NUMERICAL SIMULATION PLATFORM

A general numerical simulation platform for real-time hybrid test is developed by using Visual Basic for Applications (VBA) and commercial finite element software SAP2000. The data/command communication between SAP2000 with VBA program is achieved by Application Programming Interface (API). API (SAP2000 2009) is a powerful tool that allows users to automate many of the processes required to build, analyze and design models and to obtain customized analysis and design results. It also allows users to link SAP2000 with third-party software (like VBA), providing a path for two-way exchange of model information with other programs.

In this numerical simulation platform, SAP2000 software is applied for modeling experimental sub-structure as well as loading action in real-time hybrid test. The action of shaking table and actuator on experimental sub-structure is achieved by setting unrelated displacement time-history input at pier base and pier top in the software. The displacement input at pier base is converted from selected acceleration time-history record of ground motion. The displacement input at pier top is target displacement of actuator, which is real-time calculated based on previous results of each loading step.

The main program for this numerical simulation platform is coded in VBA, which has two major functions: a) working as numerical sub-structure calculator for getting interface displacement based on feedback of experimental sub-structure (actually the feedback is the result of finite element analysis collecting from finite element software) and b) controlling the running process of finite element software and exchanging data/results between experimental and numerical sub-structures. Take displacement control method as example, the flowchart for main program coded in VBA can be seen as follows:

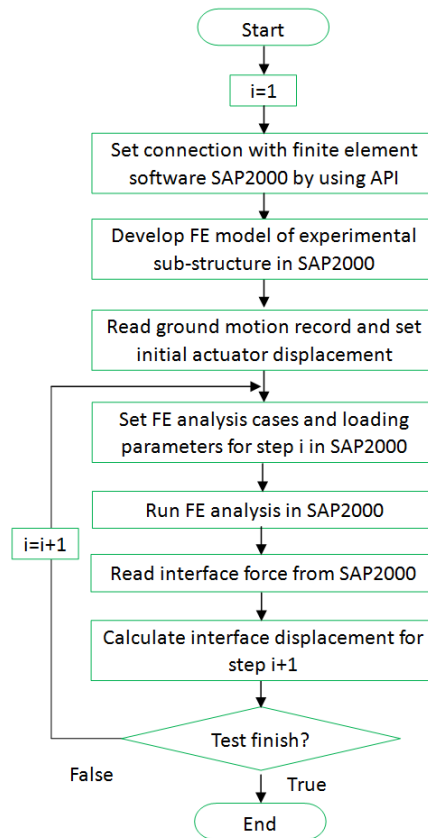


Figure 3: Flowchart for main program of numerical simulation platform

5. CASE STUDY: REAL-TIME HYBRID TESTING ON BRIDGE STRUCTURE

For a typical girder bridge, the structural model for seismic analysis can be simplified as a single column with concentrated mass at top representing inertia contribution from superstructure. When

applying real-time hybrid test, the concentrated mass at top can be taken as numerical substructure and the column can be taken as experimental substructure, as shown in Figure 4.

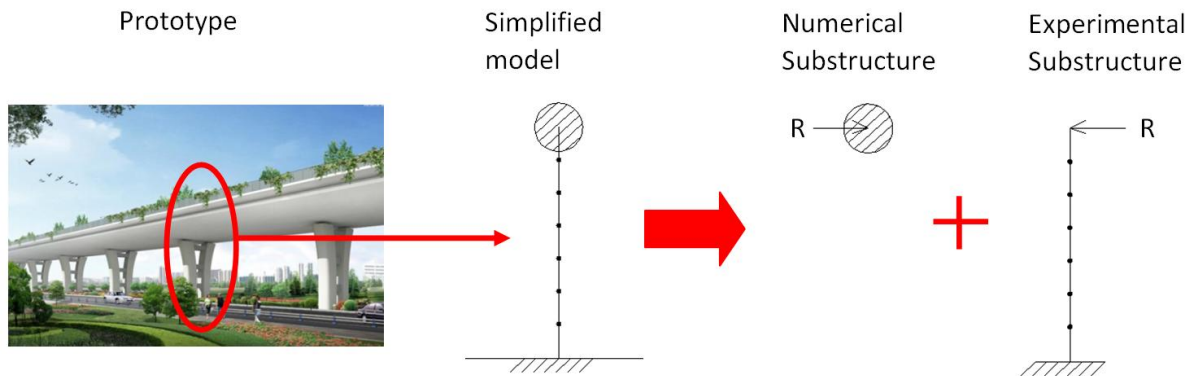


Figure 4: Simplified model for real-time hybrid test

In order to verify the feasibility of performing real-time hybrid test on bridge structure, case study is performed by using numerical simulation platform. The simplified girder bridge model as shown in Figure 3 is used for the case study. The reinforced concrete pier is 20m high, with a square cross section of 11.2m*11.2m. The concentrated mass at pier top is set to 1000ton. The central difference method is used for numerical integration. The selected input ground motion (acceleration time-history) is shown in Figure 5 and the numerical simulated real-time hybrid test (RTHT) results are listed in Figure 6.

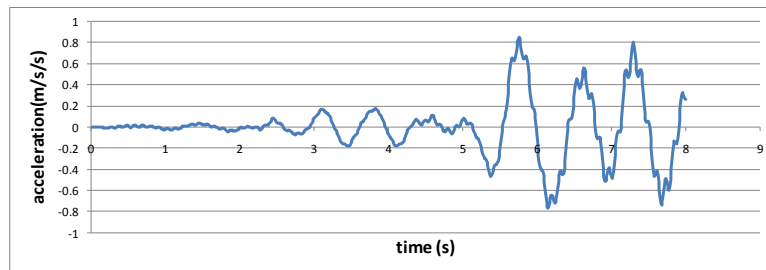


Figure 5: Input acceleration record

In Figure 6, the “prototype” results represent response of prototype model (single column pier with concentrated mass at pier top) subjected to acceleration input at pier base. The “RTHT” results represent response of experimental sub-structure (single column pier) subjected to displacement time-history input at pier base as well as calculated displacement time-history loading at pier top. From Figure 6, one may find that the results of displacement control based real-time hybrid test tally with the one of prototype test quite well, which proves the feasibility of proposed real-time hybrid test method. The waveform of “shear force at pier top”, “shear force at pier base” and “bending moment at pier base” from RTHT almost overlap those from prototype test. Only a tiny difference can be observed in “displacement at pier top”.

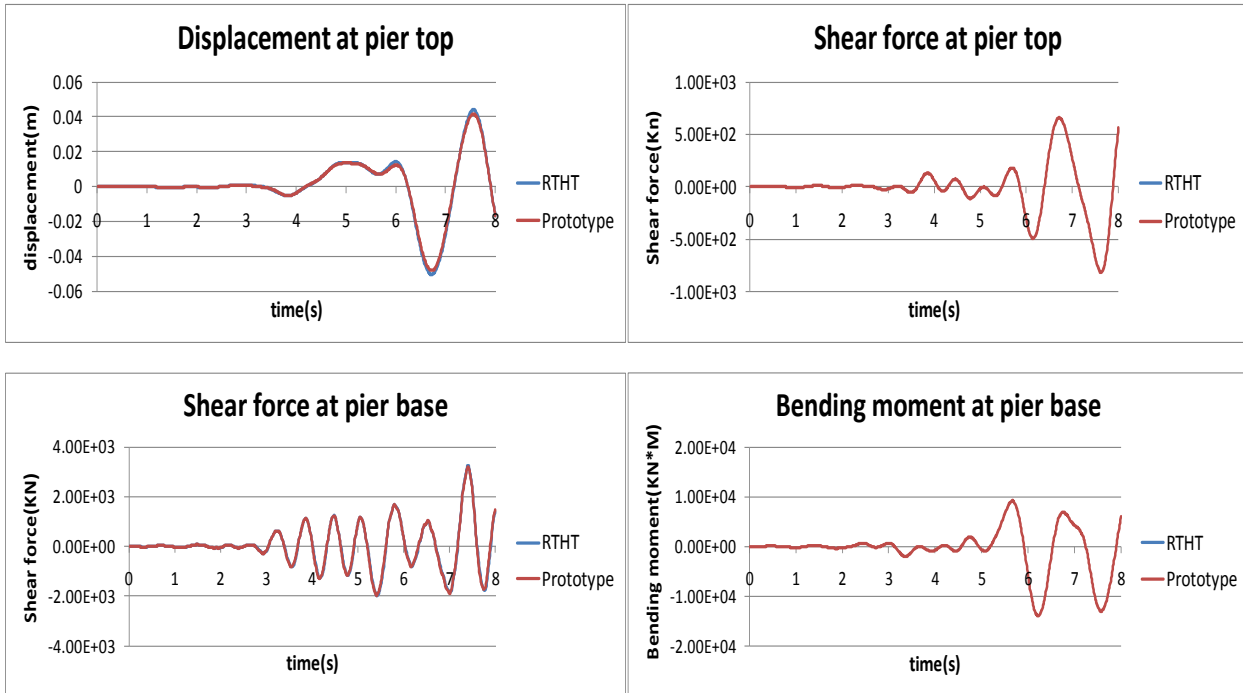


Figure 6: Results comparison between RTHT and Prototype test

6. CONCLUSIONS

The concept of real-time hybrid test and a preliminary research on this newly developed test method by using numerical simulation is presented in this paper. A brief summary can be made as follows:

- 1) Real-time hybrid test is a novel dynamic testing method involving the combination of shaking table test, pseudo-dynamic test, sub-structure test technique and numerical analysis, which extends the application scope of conventional testing methods and overcoming their limits.
- 2) A numerical simulation platform for real-time hybrid test is developed by using Visual Basic for Applications (VBA) and commercial finite element software SAP2000. The data/command communication between SAP2000 with VBA program is achieved by Application Programming Interface (API).
- 3) The feasibility of proposed real-time hybrid test method is verified by case study of a simplified girder bridge model.

7. ACKNOWLEDGMENTS

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