AN ULTIMATE CHOICE BETWEEN SHAKING TABLE TEST AND HYBRID SIMULATION FOR ADVANCING SEISMIC ANALYSIS AND DESIGN

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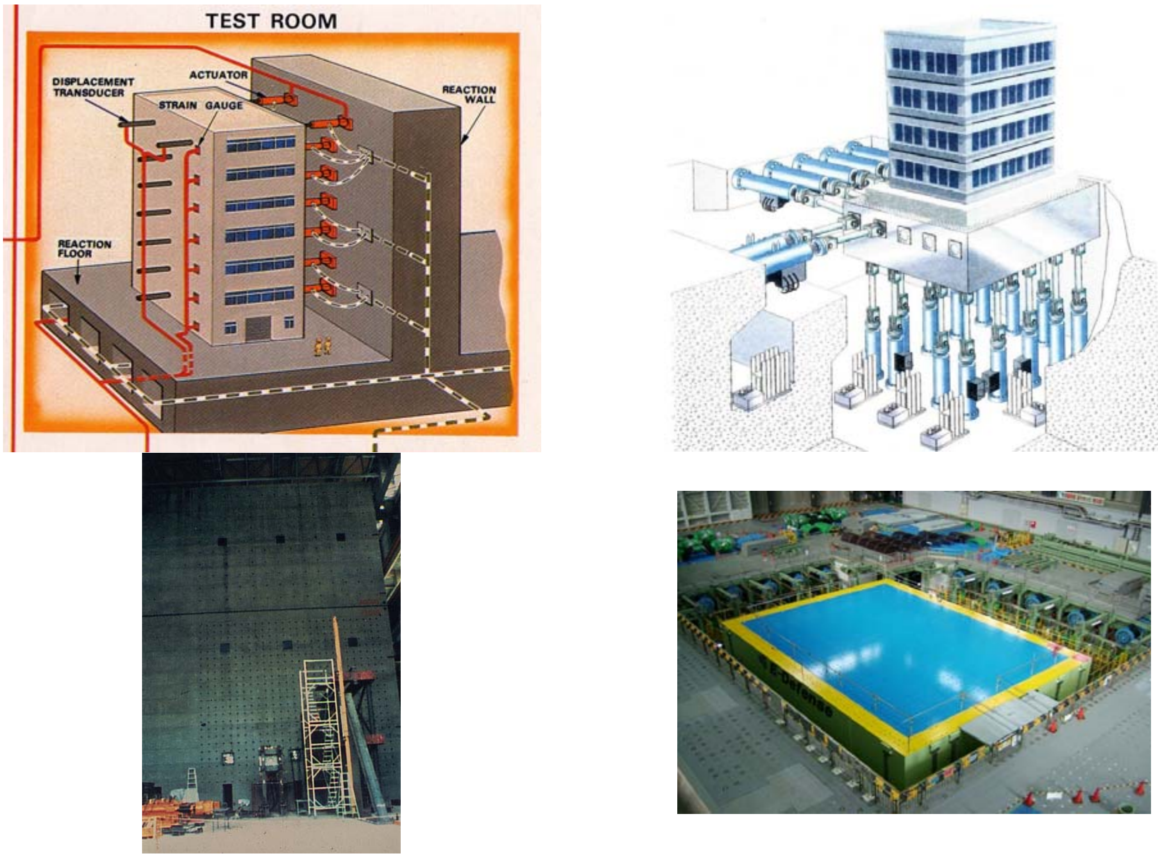
Abstract: *This article presents the authors' view about the pros and cons of the two popular experimental methods in earthquake engineering, i.e., the shaking table test and the hybrid simulation, when they are adopted for testing large-scale structures. First, the fundamental roles of structural testing as a "proving" and "teaching" tool to characterize the structural performance and capacity are touched upon. Second, the commonly used quasi-static loading test (with a prescribed loading history) and the classic (quasi-statically loaded) hybrid simulation are compared. Both are effective experimental tools regarding the roles of structural testing, with the quasi-static test more advantageous for "capacity verification" (such as characterizing strength and ductility of structural members and systems), while the classic hybrid simulation more oriented toward "performance evaluation" (such as reproducing earthquake responses and evaluating structural performance).*

Third, the shaking table test and the classic hybrid simulation are compared. Both are effective in performance evaluation. The classic hybrid simulation is advantageous because of its capacity to closely observe the structural behavior and damage progress during the test. The classic hybrid simulation is more beneficial in preserving the prototype scale thanks to its smaller hydraulic power demand with no dynamic loading. The shaking table test can examine the rate-of-loading effect directly, while the classic hybrid simulation cannot. Care must be taken for the difficulty in preserving the prototype rate-of-loading effect once a scaled model is adopted in the shaking table test. Nonetheless, the shaking table test has a notable impact on "public appeal." It is so because of its ability to visualize the dynamic phenomena directly.

Fourth, comparison is extended among the shaking table test and the classic and real-time hybrid simulation. The real-time hybrid simulation is a suitable replacement for the classic hybrid simulation when the structure includes load-resisting elements whose restoring forces depends strongly on the loading speed. Despite its history of 30 years, real-time hybrid simulation applications are limited. No large-scale, real-time hybrid simulation was ever achieved with several dynamic actuators controlled under near-perfect synchronization. We must wait for the judgment of the genuine value of this method until the method is adopted more widely in our discipline.

1. Introduction

This article focuses on (1) experimental research as a method of study, (2) large-scale testing as a type of experimentation, (3) conventional quasi-static test (implemented by prescribed loading protocols), shaking table test, and hybrid simulation as tools of examination, and (4) choice of the tools in light of the advancement of earthquake engineering. The presentation and discussion are primarily based on the first author's experiences on (i) large-scale tests using quasi-static devices (Figure 1a) conducted at the Building Research Institute (BRI) of Japan in the 1980s (Okamoto, et al., 1983; Nakashima 2020), (ii) large-scale shaking table tests using the world largest shaking table (Figure 1b) and conducted at E-Defense of the National Research Institute for Earth Science and Disaster Resilience (NIED) of Japan (Nakashima et al., 2018), and (iii) quasi-static test, hybrid simulation, and shaking table test, conducted with his students at the medium-size structural laboratory owned by the Disaster Prevention Research Institute (DPRI) of Kyoto University of Japan. The first author worked for BRI and participated as one of the most junior members in a series of full-scale tests carried out in the 1980s. The tests were applied to RC and steel buildings as part of a joint project between the United States of America and Japan (Wright Ed., 1985; Okamoto, et al., 1986; Hanson and Watabe Ed., 1989). The first author served as the founding director of E-Defense and led a series of large-scale tests applied to RC, steel, timber buildings, RC bridge structures, and building foundations using a soil box for the first several years after the inauguration of E-Defense in 2004. The first author taught at Kyoto University as a professor for a quarter century from the late 1990s until 2017 and implemented with his students a variety of structural testing using the test facilities mentioned above. The two junior authors of this article were engaged heavily in several large-scale tests conducted at E-Defense and many tests conducted at DPRI, Kyoto University.



(a) (b)

Figure 1 Large-scale testing facilities in Japan. (a) BRI's strong floor and wall (25m in length, 20 m in width, and 25 m in height) system (Okamoto et al., 1983); (b) E-Defense shaking table (20 m by 15 m in plan) (Nakashima et al., 2020).

In this article, the authors present their experiences on large-scale and medium-scale testing and their views, cultivated by those experiences, about the roles of large-scale testing, relative advantages and drawbacks of the quasi-static test, shaking table test, and hybrid simulation. The authors also discuss which one of the shaking table test or hybrid simulation one prefers or should adopt for experimental research aiming at the advancement of earthquake engineering.

To make the argument most explicitly and to facilitate the comparison among the various experimental methods, in what follows, the authors classify the methods into: (a) conventional quasi-static loading test with predetermined histories (referred to as quasi-static test), (b) shaking table test, (c) original hybrid simulation loaded quasi-statically (referred to as classic hybrid simulation), and (d) real-time (fast speed) hybrid simulation.

2. Roles of Experiment (Structural Testing) against Analysis

The objectives and functions of the structural experiment (or the structural test, and called the experiment or test hereinafter) are multiple, the benefits are manifold, and views and opinions on the relative importance are likely to differ from one researcher to another and vary by the research objective. To the authors' belief, the experiment has two primary roles. One significant role is to "prove" the accuracy of our predictions regarding structural behavior. The predictions have a variety of sources, such as hypotheses developed based on previous findings and experiences, and analyses derived from theories of elasticity, plasticity, and dynamics, among others. The second significant role of the experiment is to "teach" us about actual structural behavior and to provide us with new knowledge. New knowledge can be acquired when the test results reveal discrepancies from what had been expected before the test. Such knowledge becomes an engine to open new research subjects, whose results, in turn, lead us to further advancement of structural analysis and design. The three primary methods, i.e., quasi-static test, shaking table test, and hybrid simulation, are in the repertoire of experimental techniques. Therefore, their roles can be discussed most effectively in reference to the fundamental roles of the experiment. More details about the authors' view on the roles of experimenta are found in Nakashima (2001).

3. Quasi-static test versus classic hybrid simulation

The quasi-static test (using a predetermined displacement history) is used most commonly in experimental research on structural engineering, and there is no exception in earthquake engineering as part of global structural engineering. In earthquake engineering, we shall consider the effect of cyclic loading (characterized by the change of loading directions) and the effect of varying deformation per loading cycle. Commonly, the quasi-static loading test adopts one of the standard cyclic loading protocols (for instance, Clark, et al., 1997; AISC, 2016), characterized by the sequential magnitudes of loading displacement and the number of cycles for each amplitude. As far as the required test facilities and procedures are concerned, the quasi-static test and classic hybrid simulation (based on quasi-static loading) are essentially the same. The only difference between the two tests is the loading history imposed in the test. In the quasi-static test, the entire loading history is prescribed prior to the test, with its history determined by the researcher's choice. In contrast, in hybrid simulation, the history is created parallel to the loading rather than prescribed a priori by solving the associated equations of motion. In reference to the roles of the experiment, both quasi-static test and classic hybrid simulation are deemed equally helpful in providing benchmark information on the accuracy of our predictions.

4. Capacity verification versus performance evaluation

However, emphasis on the targets to be proven and taught appears not identical between the quasi-static test and classic hybrid simulation. If one wants to acquire primary data on the capacity of the structure or structural elements, such as the maximum resistance and ductility, the quasi-static test is no doubt the most direct and effective experimental method. Numerous formulas and equations adopted in practical design are calibrated against the experimental data obtained from the quasi-static test. It is rather hard to calibrate such formulas and equations from the test with a random-looking loading history. On the other hand, if one is asked to check how the earthquake response of a structure would look like and how the damage would progress with time, i.e., if one is asked to reproduce the response and performance of the structure under earthquake loading, the classic hybrid simulation is a sensible choice. As such, both the quasi-static test and classic hybrid simulation are effective in proving and teaching. However, the quasi-static test is more advantageous for "capacity verification," while the classic hybrid simulation is oriented more toward "performance evaluation." Since the quasi-static test and classic hybrid simulation require a similar testing environment, one can use both experimental techniques using the same testing facilities. The authors believe that it is a notable benefit of the classic hybrid simulation.

5. Shaking table test versus classic hybrid simulation

In the context of "capacity verification" versus "performance evaluation," both the shaking table test and classic hybrid simulation can demonstrate their strength more positively to "performance evaluation." Then comes the issue of comparison between the shaking table test and classic hybrid simulation, with a question of which method is more capable of implementing "performance evaluation." The classic hybrid simulation has one significant advantage over the shaking-table test; that is, the classic hybrid simulation does not require dynamic loading, although it is to simulate the earthquake response of the tested structure. The slow loading and possibility of pausing upon request make it possible to carefully observe the evolution of the damage to the test structure. Considering the role of the experiment as the proving and teaching tool, the ability to carefully observe the initiation and progress of damage and the failure of the structure is one of the greatest assets of the classic hybrid simulation relative to the shaking-table test. It is also notable that the slow (quasi-static) loading commonly allows testing at a larger scale because quasi-static actuators can be much greater in load applying capacity than dynamic actuators for the same hydraulic capacity/cost.

6. Size effect when comparing between shaking table test and classic hybrid simulation

At this point, the discussion should address the question: does a reduced-scale model accurately simulate the prototype behavior? The so-called “size effect” has been examined by many researchers for many years, and an old-day summary of this effect is presented, for example, in Krawinkler (1988), Nakashima (1988), and SAC (2000). According to Krawinkler, it is by no means an easy task to scale down the prototype properties properly. For example, in steel structures, thermal energy inputted by welding is much larger per unit volume in a reduced-scale model than in its prototype, which tends to significantly alter the stress distribution and the material properties of the reduced-scale model. Krawinkler concluded that reduced-scale models of RC and steel structures and their components, even if fabricated with minute care and modern technologies, can simulate at most the global behavior of the prototype (like the force-deflection relationship before severe deterioration in resistance). Still, local behavior such as local buckling, crack propagation, bond deterioration, and field-workmanship is beyond what can be simulated accurately in a reduced-scale model. It leads to the following conclusion: if one wants to obtain information on the structural local behavior, the test specimen should be fabricated as close in size as possible to the prototype. There is no question about the importance of local behavior in assessing the seismic performance of structures if structural damage occurring in previous earthquakes is recalled; in many cases structural damage was triggered by local defects such as connection failure or bond deterioration (for instance, Nakashima et al., 1998). In reference again to the roles of the experiment, it is a very natural conclusion that the prototype details should be duplicated as much as possible in the test specimen. It is evident that the prototype details in the test specimen can be preserved much more handily in the classic hybrid simulation (with a realistic-scaled specimen) than in the shaking-table test (with a reduced-scaled specimen) unless a huge shaking table is adopted.

7. Rate-of-loading effect when comparing between shaking table test and classic hybrid simulation

The “rate-of-loading effect” is mentioned when arguing the limitation of the classic hybrid simulation because loading is made only quasi-statically in the classic hybrid simulation, while actual structures sustain dynamic forces during earthquakes. It is particularly relevant when the hysteretic characteristics of the structure depend significantly on velocity. Still, this argument is often made even when the test is applied to structures made of conventional materials such as RC, steel, and timber. It is notable, however, that the shaking-table test cannot simulate the entire prototype properties either, as long as the test structure is a scaled model. According to the similitude law, if a structure tested is a scaled model, with its size scaled down to $1/\lambda$ ($\lambda > 1.0$), a ballast whose weight equals $1/\lambda$ times the prototype weight (if the test structure’s own weight is ignored) may have to be added to the test structure to reproduce the strain-rate induced in the prototype. By adding such a ballast, however, the axial stress imposed on the test structure becomes λ times the prototype axial stress. On the other hand, the axial force is one of the primary factors that lead the structure to failure. As this example demonstrates, maintaining the prototype properties once a reduced-scale model is adopted is complicated and not handy

8. Choice between shaking table test and classic hybrid simulation

Which one of the shaking-table test or classic hybrid simulation can give more prosperous and reliable information? This fundamental question is closely related to which one of the rate-of-loading or size effect has a larger influence on the hysteretic behavior of the structure to be tested. When the structure is made of conventional structural materials like RC, steel, and timber, the change in resistance for the level of velocities induced during earthquakes is relatively small, ranging at most from 10 to 20% (for instance, Suita, et al., 1998; Lamarche and Tremblay, 2011). Overemphasis on the rate-of-loading effect may lead researchers to shaking-table tests using small-scale specimens, which may introduce scaling effects that compromise the test data quality.

The first author was fortuitous that he could witness one of the largest classic hybrid simulations used to an RC building structure and one of the largest shaking table tests applied to another RC building structure. The RC structure tested at the BRI's strong floor and wall was a seven-story building with a story height of 3.0 m, had two by three bays and a total plan dimension of 17 m by 16 m, and consisted of RC frames with a shear wall located at the center of the structural plan and extended from the bottom to the top stories. The RC structure tested on the world's largest shaking table, E-Defense, was a six-story building with a story height of 2.5 m, had two by three bays and a total plan dimension of 10 m by 15 m, and consisted of RC frames with a shear wall located at the center of the structural plan and extended from the bottom to the top stories. As such, the two tested RC buildings could be considered "full-scale," with the volume ratio of the two buildings, the one for the classic hybrid simulation versus the other for the shaking table test, about 2 to 1. Both tests successfully reproduced severe damage and near-collapse behavior (Wright, Ed., 1985; Matsumori et al., 2007). In the E-Defense shaking table, five dynamic actuators are installed to activate the motion in one horizontal direction, with each actuator having a capacity of 4,500 kN in the maximum force and ± 1 m in the maximum displacement, and 2.0 m/s in the maximum velocity. In the BRI's hybrid simulation, eight quasi-static actuators were installed to reproduce the earthquake response of the seven-story building, with each actuator having the capacity of 1,000 kN in the maximum force and ± 1.0 m (for the top two actuators) or ± 0.5 m (for the remaining five actuators) in the maximum displacement, and 2 mm/s in the maximum velocity. The difference in the required actuator capacities, particularly in the velocity (2m/s versus 2mm/s), is notable. Although precise cost compassion is hard to achieve, the order of investment necessary to develop the test facility differs by a factor of more than 10.

Nonetheless, the shaking table test has a distinct advantage over the classic hybrid simulation, i.e., the public appeal. The authors learned it through their interactions with the general public and public media in their endeavor to promote large-scale tests. Despite the more significant cost involved in the shaking table test, its strength for public appeal is vital because it shows the phenomena most directly and visibly. It should not be overlooked when examining the dissemination of research outcome to the general public.

9. Classic hybrid simulation versus real-time hybrid simulation

Next, we evaluate the values of the real-time hybrid simulation relative to the classic hybrid simulation. One of the most significant disadvantages of the classic hybrid simulation is its inability to reproduce the restoring force of the elements whose hysteretic behavior is notably velocity-dependent. It is evident that the classic hybrid simulation cannot simulate such behavior, and the real-time hybrid simulation is an appealing alternative.

However, the magnitude of experience differs significantly between the classic and real-time hybrid simulation. The classic hybrid simulation has a history of 50 years since the early 1970s (Takanashi and Nakashima, 1987), and multiple large-scale tests were conducted (for instance, Wright, Ed., 1985; Hanson and Watabe, Ed., 1989). The real-time hybrid simulation has a history of 30 years since the early 1990s (Nakashima et al., 1992), but actual applications to solve engineering problems still remain very limited. To the authors' best knowledge, no large-scale test in the real time was ever conducted under the synchronized control of multiple dynamic actuators.

It is also notable that the argument regarding the size effect, noted earlier when comparing the shaking table test and classic hybrid simulation, remains effective in comparing the classic and real-time hybrid simulation. Because of heavy demand for dynamic actuation, the specimen is usually forced to be smaller in the real-time hybrid simulation. To overcome this disadvantage, one who favors the real-time hybrid simulation often notes the effective use of the substructuring technique (Nakashima et al., 1990; Shing et al., 1991). It is a promising approach, but many issues impede the broad application of real-time hybrid simulation, some related to real-time control and some pertaining to engineering judgment about selecting experimental portions, among others. To summarize, it appears immature to argue the comparison between the classic and real-time hybrid simulations.

10. Shaking table test versus real-time hybrid simulation

For the same reason mentioned above, it is too early to compare the shaking table test and real-time hybrid simulation. However, we may foresee the following argument by extrapolating our experiences on the shaking table test and classic hybrid simulation. The first is about the actuator control. In the shaking table operation, we concentrate on accurately reproducing the specified motion on the table. In the real-time hybrid simulation, we must produce the prescribed motions for respective actuators that spread over the tested structure and ensure near-perfect synchronization among all actuators. The control issue, characterized by time delay and many others, may be more challenging in the real-time hybrid simulation.

There is another aspect from the test operation perspective: the handiness to simulate so-called collapse behavior. In the context of performance-based seismic design (for instance, PEER, 2017; LATBSDC, 2018), quantification and characterization of near-collapse and collapse behavior of structural systems and components have received more attention lately, and the experiment is believed to be the most effective tool to provide relevant fundamental data, prove our collapse predictions, and teach new research subjects to characterize collapse. At the same time, all experimentalists know the difficulty in conducting such tests, as it is so hard to protect our experimental facilities from any damage, while we want to produce severe damage such as collapse using the same facilities. As far as the safety related to the experimentation is concerned, the hybrid simulation, either classic or real-time, is more tractable in collapse reproduction as the collapsing target continues to be connected to the loading actuators, which in turn can serve to prevent the collapsing structure from excessive deformations.

11. Conclusions

This paper presents the authors' view about the pros and cons of the three popular experimental techniques adopted in earthquake engineering research: the quasi-static test, shaking table test, and hybrid simulation. The principal contentions of the authors are summarized as follows.

(1) The fundamental objectives of structural experiments are for "prove" the accuracy of our predictions and "teach" new subjects of research for further advancement of earthquake engineering. The pros and cons of respective experimental methods are best argued in light of this fundamental objective of experimentation.

(2) The conventional quasi-static test and classic hybrid simulation are compared. Notably, both are valuable tools for proving and teaching abilities. The quasi-static test is more toward "capacity verification," while the classic hybrid simulation is more toward "performance evaluation."

(3) The shaking table test and classic hybrid simulation are similar in their emphasis on "performance evaluation." The size effect and rate-of-loading effect are essential factors in choosing the method. The classic hybrid simulation has a clear advantage if the size effect is more dominant. In the perspective of "appeal to the public," the shaking table test has a more significant impact primarily because of its power to visualize the dynamic phenomena most directly.

(4) The real-time hybrid simulation is a suitable replacement of the classic hybrid simulation when the structure includes major load-resisting elements whose restoring force behavior depends strongly on the loading speed. However, their applications are limited as of today, with no large-scale, real-time hybrid simulation ever achieved with more than several dynamic actuators controlled under near-perfect synchronization. We must wait for the judgment of the genuine value of this method until the method is adopted more widely for research that explores actual engineering problems.

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