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DISTRIBUTED ONLINE HYBRID TEST OF A FOUR-STORY STEEL MOMENT FRAME USING FLEXIBLE TEST SCHEME

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ABSTRACT

An extensible framework is developed to conduct distributed online hybrid tests using a generalized interface that encapsulates the dynamic response of each substructure. Only boundary displacements and forces are exchanged through the interface with the ability to model each substructure either in the laboratory or using various finite element software. Equilibrium and compatibility between substructures are imposed by a coordinator program associated with a flexible test scheme, which employs open-loop or closed-loop controls at each degrees of freedom at the boundaries. The open-loop control is often exerted on the less important degrees of freedom which affect the structural performance indirectly, thus it is possible to release the compatibility or equilibrium requirement to simplify the experimental test setup. Other degrees of freedom having significant influence on the structural behavior are treated by the closed-loop control to simultaneously satisfy both compatibility and equilibrium. The effectiveness of the flexible test scheme was demonstrated by a geographically distributed test that examined the collapse of a four-story, two-bay, steel moment frame. The numerical and experimental results confirm the viability of the flexible test scheme as an alternative tool for distributed online hybrid testing that is able to reproduce the collapse behavior of structures.

Introduction

After the 1994 Northridge and the 1995 Hyogoken-Nanbu earthquakes, the seismic design codes were revised to consider larger deformation demands to structures (Bertero 1994, FEMA 350, 2000, Midorikawa, 2003). Although each code stipulates the most critical performance level explicitly, the margin between these collapse-prevention states and the real collapse limits (denoted as collapse margin) needs further examination, particularly through experiments. Online hybrid tests provide a good alternative in which the complex portions of a structure are treated experimentally, while the rest of the structure is treated numerically. This approach combines the benefits of both numerical analysis and physical testing. Although several geographically distributed hybrid simulations have been carried out between different locations around the world (Watanabe et al. 2001, Tsai et al. 2003, Mosqueda et al. 2008), a

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limited number of applications explored the potential of hybrid simulation to the collapse level of structures (Shellenberg et al. 2008).

In this study, the seismic response of a two-bay, four-story steel moment frame is simulated up to collapse using a distributed hybrid test framework. The entire structure is divided into three substructures: the superstructure above the first story is to be simulated numerically, while the rest is further partitioned into two substructures and distributed to different locations for physical tests. They are organized within the overall distributed hybrid test framework through the internet, in which a coordinator program enforces equilibrium and compatibility between the substructures employing open-loop and/or closed-loop control to the boundary degrees of freedom. The efficacy of hybrid simulations framework to trace structural behavior through collapse is assessed by comparing an internationally distributed hybrid simulation with an earthquake simulator test.

Distributed hybrid test framework using iterative procedure

The theoretical basis and detailed implementation of the distributed online hybrid test system can be found in previous studies (Pan 2006). Only the major features are introduced here. In this system, the simulated structure is divided into multiple substructures. All substructures are equally treated and can be geographically distributed to various laboratories, with the dynamics considered in each substructure rather than in the overall structure model. A central part of this system, called the "Coordinator", is devised to achieve the compatibility and equilibrium at the boundaries between substructures. The boundary displacements and the corresponding forces are exchanged between each substructure, and the "Coordinator" via an I/O interface. In this manner, each substructure is implemented as a highly encapsulated "Partner", and can be treated as either an experimental part or an analytical part. In each step, the "Coordinator" implements the substructures in three stages: predicting, loading, and correcting, respectively. The predicting and correcting stages adopt an iterative quasi-Newton procedure to search and guarantee the boundary compatibility, where a linear assumption is employed for the tested substructures. Only in the loading stage, the tested substructures are loaded physically using the predicted displacements as target values, thus avoiding physical iterations for tested substructures.

Target structure and flexible test scheme

The Hyogo Earthquake Engineering Research Center of Japan (E-Defense) conducted a full scale earthquake simulator test of a four story steel moment frame shown in Fig. 1 (Suita 2008). The structure was designed following the typical Japanese seismic design procedure (BCJ, 1997). The structure was excited in three dimensions using the Takatori acceleration record at 5, 20, 40, 60 and 100% amplitude. At the 100% amplitude, the structure collapsed primarily in the longitudinal direction by forming a first-story mechanism consisting of the local failure of columns at the top and bottom of the story and the plasticity redistribution. One objective of this study was to verify if hybrid simulation can be used to reproduce the collapse behavior in the longitudinal direction of the structure. However, to physically implement a hybrid test considering laboratory limitations, only unidirectional loading was applied and the boundaries of the experimental substructures were simplified.

In the E-Defense shaking table test, it was found that the behavior of the first story columns was the most complex, and the plastification was redistributed because of the failure of the first story columns, whereas the beams and other columns had relatively limited damage. In this hybrid test, the tested substructures focused on the first story columns and the remainder of the upper stories was simulated numerically by OpenSEES (Mazzoni, 2006). In order to reproduce the behavior of the overall structure precisely, compatibility and equilibrium shall be satisfied at all nine degrees of freedom of the boundary (seven assuming 3 axially rigid beams), as shown in Fig. 2 (a). However, it is not feasible to physically realize all of the compatible boundaries, particularly for the axial and rotational deformations. It becomes more practical to release some boundary conditions such as the axial deformations of columns (compatibility) while maintaining equilibrium to apply the correct axial load. As shown in Fig. 2 (b), the vertical displacements of the boundary nodes of the numerical substructure are restrained and the corresponding reaction forces are collected and sent to the tested substructure for physical loading using force controlled actuators. The axial deformations of the columns of the tested substructure were not fed back to the numerical substructure. This simplification avoids iterations in the axial direction, at the expense of not explicitly satisfying compatibility with the column axial deformations.

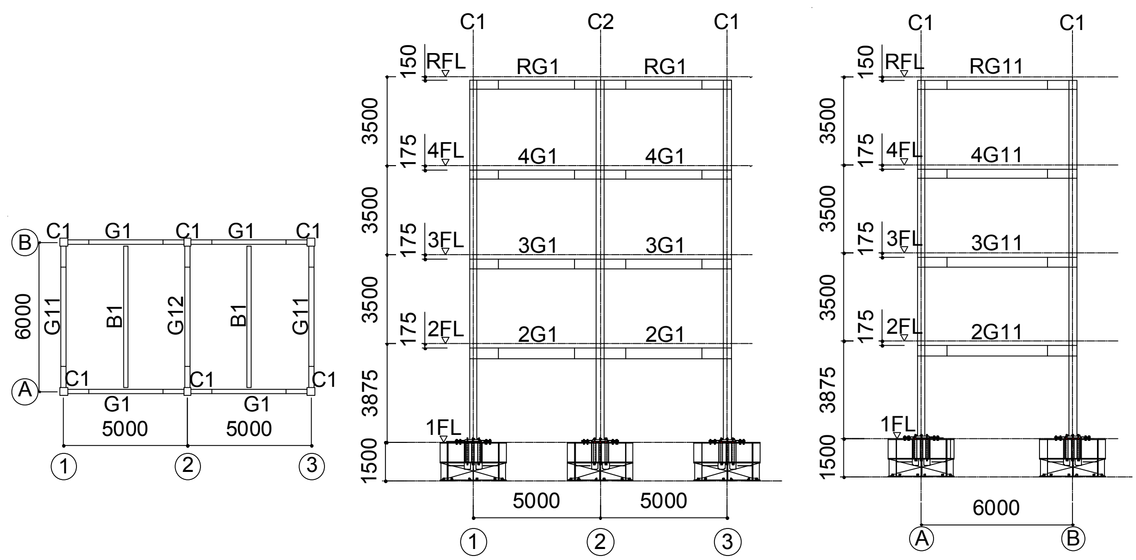

Figure 1. Prototype of four-story steel moment frame.

The laboratory loading mechanism is further simplified by extending the boundary of the physical substructure to the mid-height of the second story columns. In this approach, hinges are assumed at the mid-height of the second story columns. The effects of this assumption are further investigated in a companion paper (Mosqueda et al. 2010). The supplemental members are included to approximate the rotational boundary condition at the top end of the columns. The supplemental members such as beams and second story half columns in the specimen have the same sections as those in the numerical substructure. Therefore, if the displacements obtained from the numerical substructure are applied to the corresponding mid-nodes in the tested substructure, the rotation at the top ends of the first story columns can be approximated. Further, panel zones and beam behavior are also captured experimentally to capture other potential collapse mechanisms.

In this hybrid test framework, the boundary conditions are implemented in a flexible manner. The horizontal degree of freedom at the first story level is implemented as closed-loop control because the reaction forces obtained from the substructures are fed back to the coordinator to maintain the compatibility and equilibrium requirements. For the vertical degrees of freedom an open-loop control is adopted, where only the target forces are passed from the numerical substructure to the tested substructure while no feedback is requested. The rotational degrees of freedom are actually not directly controllable, while the horizontal displacements imposed on the top ends of the supplemental columns only approximate the rotation. The control flow chart is shown in Fig. 3.

Considering the loading capacity of the structural laboratories at University at Buffalo (UB) and Kyoto University (KU), the tested substructure is further divided at the mid-span of one bay, where a link with certain flexibility is used to emulate the shear force in the beam while assuming the moment at the mid-span to be zero.

Before the hybrid test, the errors introduced by the flexible test scheme, were also examined to verify the validity and accuracy of the partitioned structure and software implementation. To achieve this, the overall structure responses were compared with those obtained from the numerical simulation using the distributed hybrid test framework in which all tested substructures are numerically modeled using OpenSEES. The results corresponding to 40% scale JR Takatori ground motion are used for the comparison. The displacement responses at the first story and the roof are compared in Fig. 4 where the maximum difference is 18% in amplitude and 0.1 sec increase in the response period.

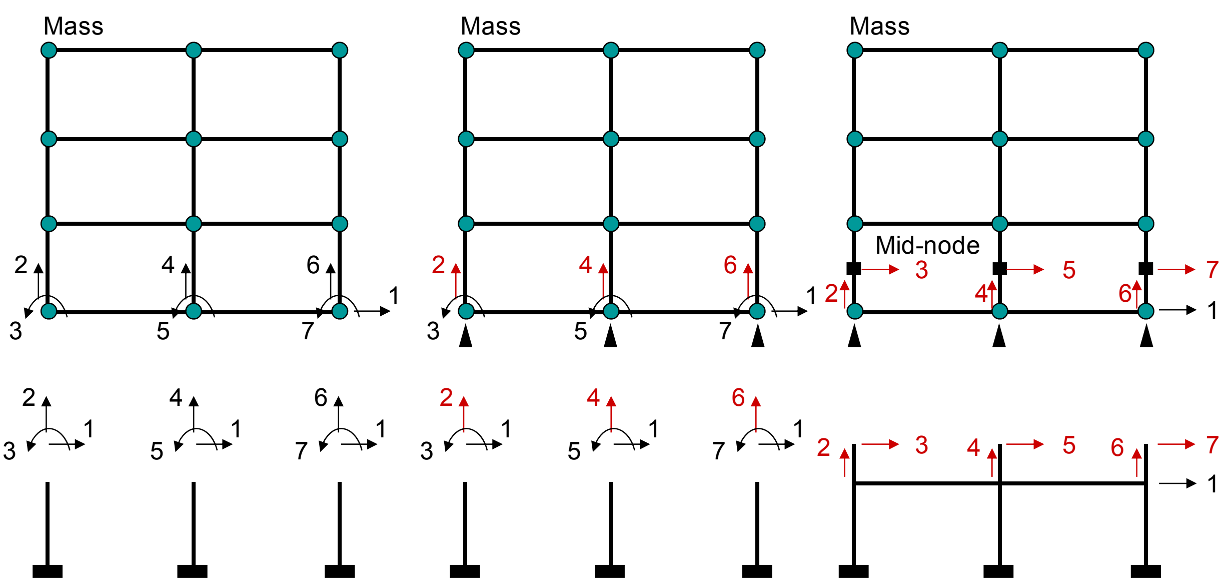

Figure 2. Approximation of boundary conditions: (a) Closed loop; (b) Open loop for vertical displacement; (c) Free rotation.

Specimen design and test setup

The substructure specimens were designed considering a scale factor of two due to the constraints of the testing facilities. As previously mentioned, the first story was divided into two specimens. The first specimen, tested at UB consisted of one and half bay by one and half story. The second specimen, tested at KU, consisted in half a bay by one and half story. As exactly scaled sections were unavailable, the specimens were designed to match the strength and stiffness of the E-Defense frame. The section of the beams was increased to include the effect of the floor slabs. Fig. 5 shows the dimensions and sections used for the experimental substructures.

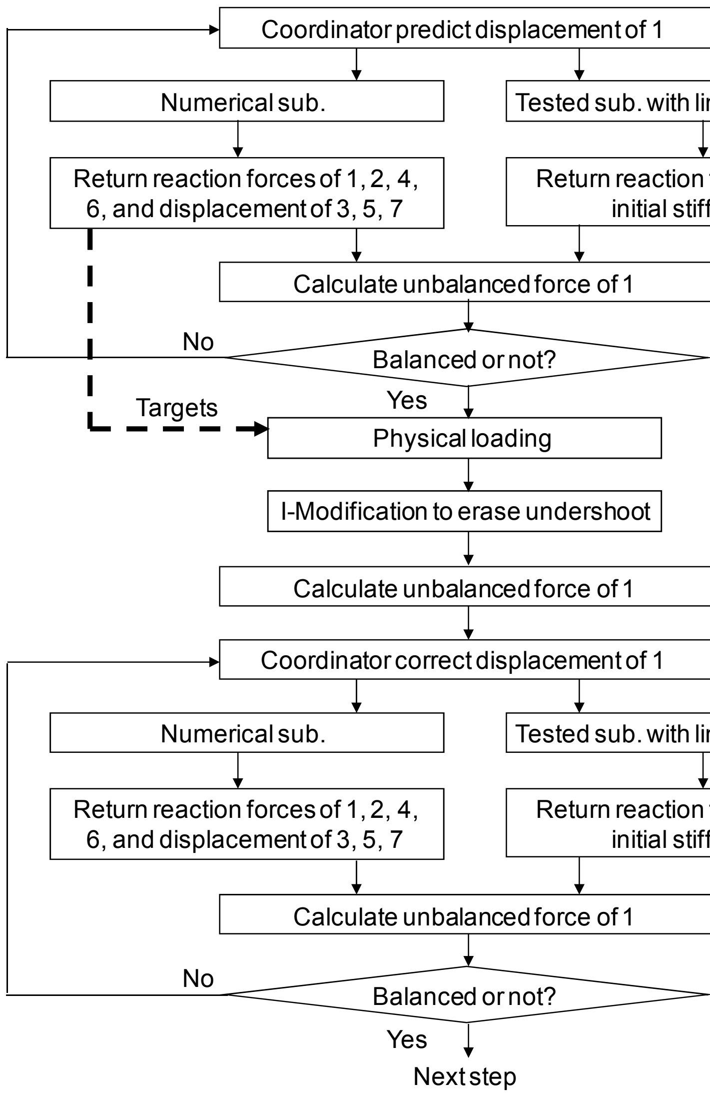

Figure 3. Flow chart of flexible test scheme.

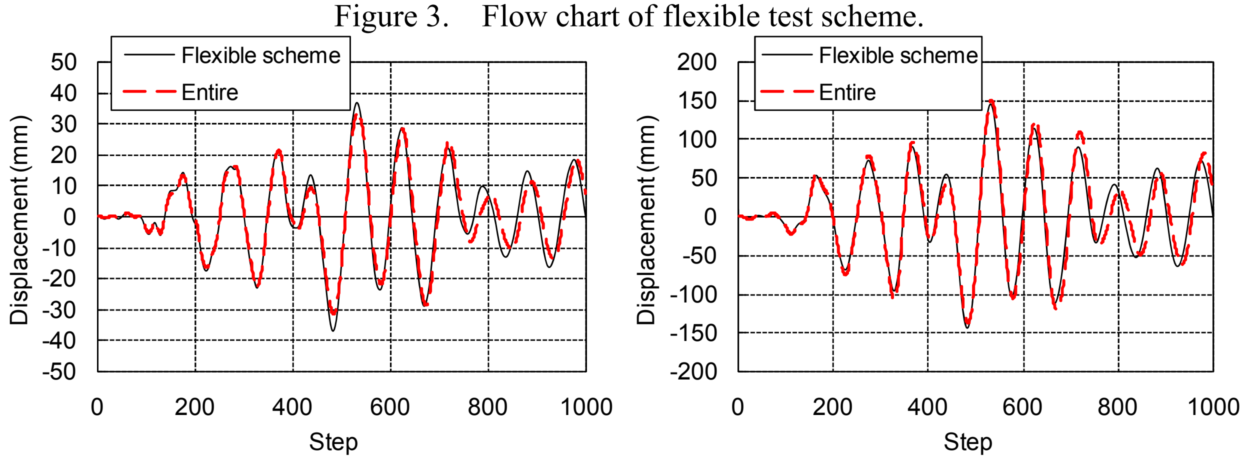

Figure 4. Error introduced by substructuring in the flexible test scheme: (a) First story

response; (b) Roof story response.

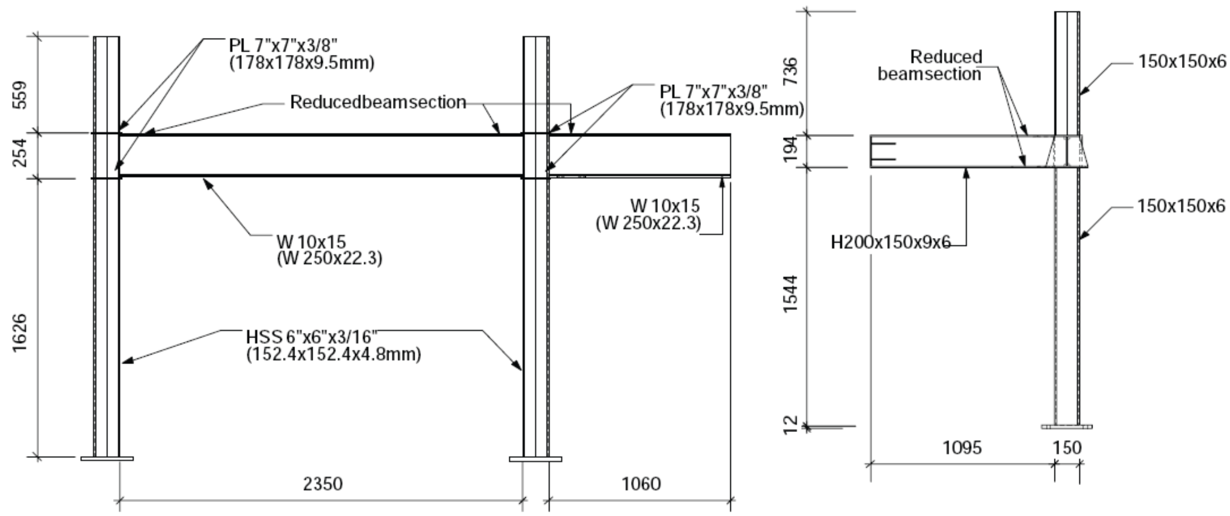

Figure 5. Specimens: (a) Specimen at Buffalo; (b) Specimen at Kyoto University.

Test results

The comparison of the response of the hybrid simulation and the E-Defense test is plotted in Fig. 6 (a). The hybrid simulation provides a good approximation to the dynamic response, validating the experiment. Fig. 6 (b) quantifies the test control accuracy in terms of the difference between the target and measured displacements in the first story jack for the 60% Takatori test. The tolerance of the displacement control was set at ±0.1 mm. According to the figure, the average error resides within this range, demonstrating an accurate control of the test, despite some particular cases where the error spikes to 0.6 mm at KU and 1.0 mm at UB.

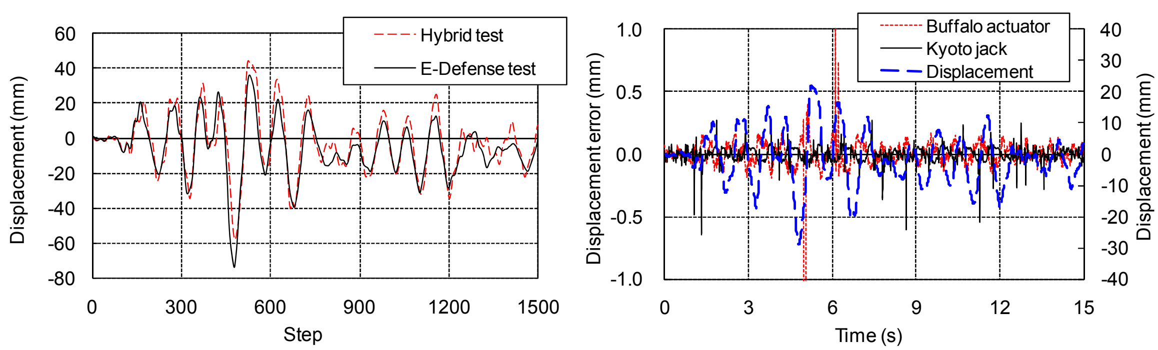

Figure 6. System performance: (a) Response comparison; (b) Facility control accuracy.

Capability to trace collapse

The first story shear force and story drift angle relationships in the longitudinal direction at the 60% and 100% JR Takatori records for the distributed test and E-defense test are shown in Fig. 7 (a) and (b), respectively. For the 60% JR Takatori distributed test only the first 5 seconds of the test are shown including the peak displacement. During this test, an actuator interlock was triggered at UB, which temporarily shut down the actuators. The test setup was recovered and the test continued, but with some temporary offset in the measured force data. From the hysteretic behavior, it is evident that similar strengths were achieved for both tests, but smaller peak displacements were observed for the distributed test. During the 100% JR Takatori distributed test, the peak story drift angle is 0.017 radians at the first story at a story shear of 788 kN. Figure 7 (b) shows a substantially higher strength for the distributed tests compared to the shake table test. After the 60% test, the shake table specimen appeared to have suffered much more damage as indicated by the loss in strength in the 100% test. These differences observed in behavior may be due to several reasons, the most important reason being the simplification of the hybrid test such as loading in only one direction. Additionally, the hybrid test did not include the non-structural components and concrete slabs as in the E-Defense tests that accumulated damage under smaller ground motions. Further, the boundary condition simplification adopted for the distributed test such as restraining the vertical deformations in the numerical substructure and neglecting their influence in large deformations, may have contributed to these differences. Unavoidably, there were also differences in the material properties in the hybrid simulation specimens, where standard coupon tests indicate that yield strength for the steel used in the column in the KU specimen is 30% larger than the value obtained for the E-Defense specimen.

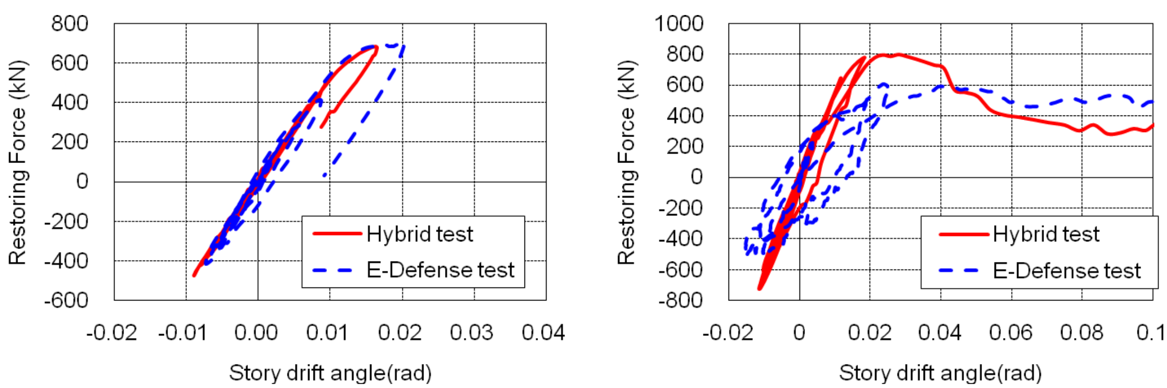

Figure 7. Hysteretic curves of the first story: (a) 60% JR Takatori; (b) 100% JR Takatori.

Efficiency of hybrid test framework

The hybrid test framework used in this study is in essence an iterative trial and error method. In spite of the significant nonlinearity and strength degradation, convergence was always achieved after 3-4 iterations, as shown in Fig.8 in which the predicting procedure used 1-2 iterations, while the correcting took about 1-2 for mild nonlinearity, and 3-4 for large responses.

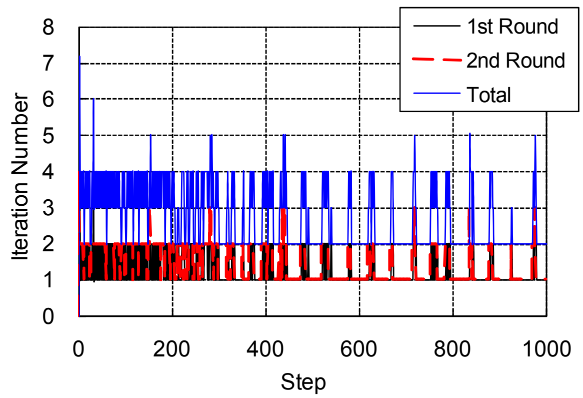

Figure 8. Efficiency of hybrid test framework.

Conclusions

A distributed online hybrid test was conducted in this study to trace the collapse behavior of a steel moment frame. Two key issues were investigated: (1) the implementation of the boundaries between substructures; and (2) the capability of the distributed hybrid test framework to capture the realistic collapse behavior of a structure. With these two objectives, both numerical and experimental study were conducted to examine the boundary implementation and to explore the collapse behavior by comparison to a four-story steel moment frame which was tested on the world's largest shaking table, E-Defense, Japan. Several observations were summarized as follows:

a) The boundary implementation is a key issue in the distributed hybrid test. In order to achieve the highest precision, both equilibrium and compatibility shall be satisfied at all of the boundary degrees of freedom. The reality, however, is that we always have difficulties in controlling stiff degrees of freedom, and the loading facilities and test space are sometimes limited to control all degrees of freedom. Therefore, the simplified implementation is often adopted. The flexible boundary implementation proposed in this study was verified effective and accurate enough through both numerical and experimental examinations;

b) The distributed hybrid test frame used in this study encapsulated each substructure with a standard interface. Significant advantage of this is to minimize the troubles introduced by handling with numerical substructures using different finite element programs and more important, laboratories with different hardware equipment. In this distributed test, two different types of facilities: servo-controlled hydraulic actuators and simply-controlled jack system, were employed. Each laboratory developed its control software separately, but collaborated smoothly without any malfunction;

c) Even though the hybrid simulation included several simplifications such as unidirectional loading and boundary assumptions, a similar response and collapse mechanism was observed in the distributed hybrid simulation. Examination of the local distribution of stresses in the experimental substructure reveals that the substructuring assumptions were adequate in capturing the distribution of forces in the frame. While the hybrid simulation approach cannot match the realism of full-scale earthquake simulator testing, it can provide a cost-effective method for evaluating the seismic performance of buildings at large scales with the capabilities available in many laboratories.

Acknowledgments

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