



## PROGRESS AND APPLICATIONS OF A PEER-TO-PEER (P2P) INTERNET ONLINE HYBRID TEST SYSTEM

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### ABSTRACT

The peer-to-peer (P2P) Internet online hybrid test system provides a means of dividing a structure into multiple substructures which can be analyzed in parallel through numerical simulation or physical testing. Each substructure is considered equally and independently requiring only the formulation of the equations of motion for each substructure as opposed to the entire structural system. Only force and displacement values at the boundaries are required to be passed through a standard Input/Output interface between each substructure and a Coordinator program. The Coordinator program ensures both compatibility and equilibrium at the boundaries through the use of a two-step iterative quasi-Newton procedure. The viability of the P2P Internet online hybrid test system is verified through a series of tests. Through a base isolation study, a verification of the P2P system is undertaken and a comparison with conventional hybrid test methods is made. The ability to handle multiple finite element programs, accurately simulate highly nonlinear behavior in both the analytical and experimental substructures, and allow for the use of multiple experiments in multiple locations is shown through a study of a steel encased reinforced concrete structure and a four-story steel moment frame.

### Introduction

The need to be able to test full-scale structures under seismic loadings coupled with a lack of laboratories which have the capability of performing such tests led to the development of hybrid testing. Hybrid testing techniques have allowed for the most complex behavior of a structure to be obtained experimentally while the rest of the structure is simulated analytically. Advances in the use of substructuring have increased the capability of online hybrid testing to look at large-scale structures under seismic loadings by being able to treat the structure as separate parts (Takanashi 1975; Nakashima 2001). However, these substructural online hybrid test systems require that the equation of motion be formulated and solved for the entire structure making it difficult to effectively test large or complex structures. Early systems also required that the analysis and tests be performed in the same location. Recently, the benefits of using multiple locations have been explored through the concept of 'Internet testing' or 'distributed testing' (NSF 2001; Tsai 2003). However, there still remains a need to standardize and simplify the interface between subsystems so that these systems can be more effective.

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In order to further improve upon the effectiveness of substructural online hybrid testing, the Peer-to-Peer (P2P) Internet online hybrid test system has been developed at Kyoto University. This system allows the full structure to be divided into multiple substructures which are considered equally and independently. Thus, the equations of motion of each individual substructure are only required to be solved rather than that of the full structure. This allows the individual substructures to be considered in parallel. The substructures are highly encapsulated and require only a standard input/output for the exchange of force and displacement values at the boundary providing a means of implementing existing finite element programs for the numerical portion. A Coordinator program is then used in order to ensure compatibility and equilibrium at the boundaries through the use of a two round quasi-Newton iterative procedure. The use of the Internet and a proxy for data exchange allows for both the numerical and experimental portions of the test to be conducted in multiple locations.

A series of tests have been conducted in order to validate the P2P Internet online hybrid test system. The P2P system is applied to a base isolated structure in order to study its effectiveness and applicability for a simple linear system (Pan 2006). The ability to support multiple finite element programs and accurately account for significant nonlinearity in a complex structure is studied through the examination of a steel-encased reinforced concrete (SRC) structure (Wang 2007). As a final part of the test series, a four-story steel moment frame is studied where the plastic hinge behavior at the base of the two columns is taken as the experimental portion in the P2P test, allowing for the ability of the system to accurately handle multiple experiments in multiple locations to be determined.

### System Design

A detailed formulation of the P2P Internet online hybrid test system is given in the paper by Pan et al. (2006). A summary of the system design and key components is provided as follows.

#### System Overview

The P2P Internet online hybrid test system allows a full structure to be separated into a number of independent subsystems which can be evaluated in parallel either through numerical analysis or experimental testing. The equations of motion for these substructures are formulated for each independently. Thus, the only interaction between the substructures is with respect to compatibility and equilibrium at their boundaries. Fig. 1 provides a schematic of the substructuring associated with the P2P system where a central program provides the coordination between the separate substructures. The 'Coordinator' is the central program which ensures the compatibility and equilibrium at the boundaries between the substructures. Since the equations of motion are formulated independently for each substructure, only the boundary displacements and corresponding forces need to be exchanged between the Coordinator and the substructures providing a simple input/output interface for data exchange. In this way, each substructure acts as a highly encapsulated separate system.

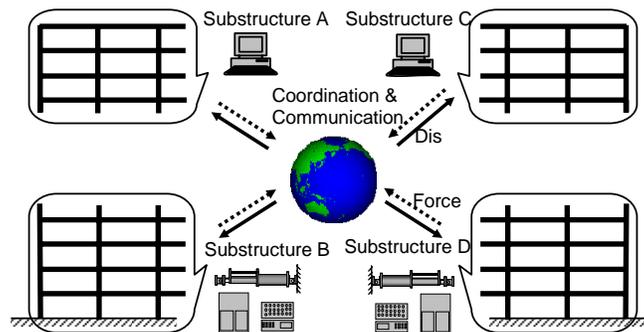


Figure 1. Substructuring technique used for the P2P Internet online hybrid test system (Pan 2006).

The P2P system can be described considering a structure that has been divided into two substructures, one evaluated numerically and the other evaluated through experimental testing. At the beginning of a given step, the Coordinator determines a trial boundary displacement and sends this to both substructures. At this point, the boundary displacement is such that compatibility is ensured between the substructures. These displacements are then imposed analytically and experimentally to each respective substructure independently. The resulting forces from each are returned to the Coordinator where equilibrium at the boundary is checked. If equilibrium is satisfied, the process continues on to the next step. If not, the Coordinator uses the unbalanced force to determine new boundary displacements and the procedure is repeated until equilibrium is satisfied. In order to take advantage of this system, an iterative method must be used, but it must be ensured that multiple loadings for a single step are not necessary for the physically tested substructure.

### Implementation of the Quasi-Newton Method

The family of quasi-Newton methods provides iterative techniques for the solution of non-linear systems. Because of the advantages with respect to convergence in linear and non-linear problems, the Broyden-Fletcher-Goldfarb-Shanno update is adopted for the P2P Internet online hybrid test system (Bathe 1996). This procedure is adopted because it allows for the use of an approximate secant stiffness matrix in order to find equilibrium rather than requiring the tangential stiffness matrix which is difficult to obtain due to the resolution associated with the physically tested substructure. The iterative predicting-correcting quasi-Newton procedure thus uses a set of trial displacements to determine the unbalanced forces in each substructure. The resulting unbalanced forces are then used to update the secant stiffness matrix and recompute the displacements. These iterations continue until displacement tolerances are met.

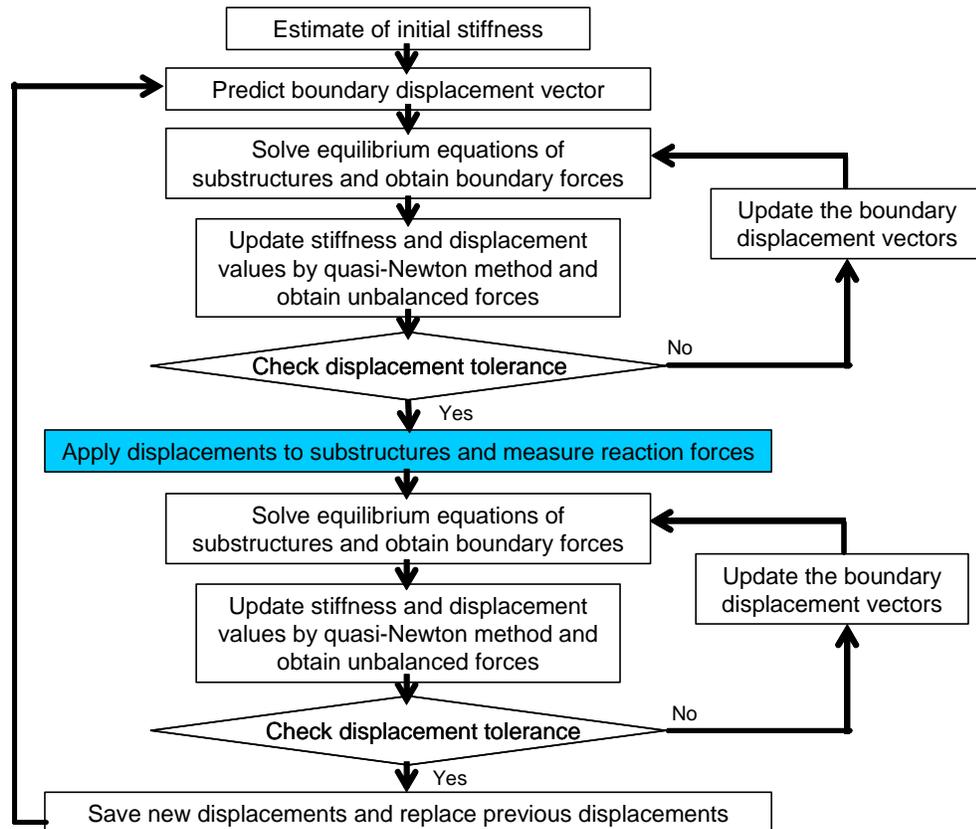


Figure 2. Flow chart of the P2P Internet Online Hybrid Test System implementing a two round quasi-Newton procedure (Pan 2006).

In order to implement this method into the P2P system, the limitation of only being able to load the physical test once during each step due to path dependence of the physical behavior needs to be considered. For this reason, two rounds of the quasi-Newton iteration procedure are adopted for each step. The first round of quasi-Newton iterations uses the elastic stiffness of the tested substructure without applying the physical load to the tested substructure to determine the reaction forces for the tested substructure. For the numerically simulated substructure, the restart function of the finite element program is used with each iteration in order to avoid the effects of path dependence. Once the correct displacements are obtained from the first round of iterations, they are applied to the physically tested substructures and numerically simulated substructures to get the actual reaction forces. The second round of quasi-Newton iterations then compensates for the unbalanced forces which arise as a result of the nonlinearity of the physical specimens to determine the final displacements for the step. The iteration process for the second round again uses the elastic stiffness of the tested specimen in determining the final displacement. For later tests (4-story steel moment frame study), the secant stiffness rather than the elastic stiffness of the physical specimen is used to improve accuracy and reduce the number of iteration. A flow chart outlining the two round quasi-Newton procedure for the P2P Internet online hybrid test system is given in Fig. 2.

### **Data Exchange**

The use of the Internet for data exchange alleviates the need to have all substructures in the same location and allows for parallel computation of each substructure. In order to increase the speed of data transmission, a socket mechanism is adopted with either direct data exchange, where the Coordinator is considered the Server and the substructures the Clients, or data exchange through a proxy, where the proxy is the Server and the substructures and the Coordinator are the Clients. Data exchange through a proxy is used in the case where there are strict firewalls present.

### **Verification Studies for the P2P Internet Online Hybrid Test System**

A series of test are conducted to verify the applicability and efficiency of the presented P2P Internet online hybrid test system. A comparison of the P2P system with conventional hybrid test procedures is first undertaken to verify the accuracy of the system using a simple linear system when multiple locations are used. The effect of more complex nonlinear behavior is then evaluated along with the ability to use multiple finite element programs for specific substructures. Finally, the applicability of the P2P system is evaluated when multiple experimental substructures are used for an innovative approach in which only the plastic hinge is taken as the experimental substructure.

### **Base-Isolated Structure Study**

The P2P Internet online hybrid test system is used to simulate the response of a base-isolated structure subjected to the fault-normal component of the JMA Kobe ground motion. The structure is an eight-story, two-span by six-span steel moment frames isolated with high-damping rubber bearings. For this test, only a planar frame in the two-span direction is considered as shown in Fig. 3(a). The structure was divided into three substructures. The steel moment frame is divided into two substructures which are analyzed numerically in order to show the ability of the system to handle multiple computed substructures, while the base isolation layer is experimentally tested. The division of the substructures is shown in Fig. 3(b). A linear mass-spring system is used to model the behavior of the steel moment frame (i.e. computed part). The fundamental period of the base-isolated structure is 3.76 s.

The test set-up for the experimental substructure can be seen in Fig. 3(c). A horizontal jack and vertical jack are used to provide the required horizontal displacement and a constant vertical load is applied to account for the weight of the structure. The horizontal jack is connected to an inverted T-shaped loading frame. The two identical high-damping rubber bearings are then connected at the top to the T-shaped

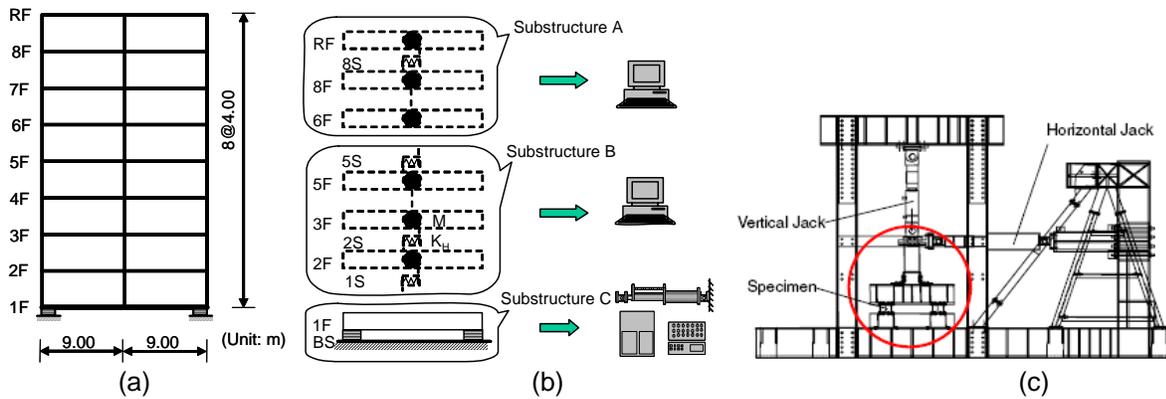


Figure 3. (a) Elevation view of the base-isolated frame with basic dimensions, (b) division of substructures, (c) diagram of test setup for tested substructure (Pan 2006).

loading frame and at the bottom to the base steel beam using high strength bolts. The use of the inverted T-shape loading frame allowed for the effects of overturning moment to partially be considered. Scale ratios of 1-to-4 and 1-to-40 are adopted for the horizontal displacement and horizontal force, respectively, based on the properties of the prototype and tested dampers.

Two separate personal computers are used to perform the numerical simulation of the substructures representing the steel moment frame. The base isolation layer is tested physically in the laboratory using the described setup. The Coordinator program operates on one of the personal computers controlling the physical test and thus does not require data exchange through a proxy. The proxy is setup up on a separate personal computer connected to a different subnetwork than all of the other computers.

The accuracy and effectiveness of the P2P Internet online hybrid test system is determined by comparing the results to an online hybrid test of the same system using a conventional substructuring technique in which the equations of motion are solved for the entire system. Both tests are performed using the same physical specimen. The horizontal force versus displacement curves and displacement time histories for the base-isolation layer are shown in Fig. 4(a) and (b). The solid line represents the conventional system and the dashed line represents the P2P system. The results show similar behavior from both systems with the difference reaching a maximum of only 5% suggesting the accuracy of the P2P system when multiple substructures in multiple locations are used. In general, the first round of the quasi-Newton procedure only requires at most two iterations while the second round required a maximum of three iterations for those cases when the displacements are large. These results suggest that P2P system is viable in terms of accuracy, speed, and stability. However, this test only looked at a system that had a low number of degrees of freedom, only a single physically tested substructure, and a linear superstructure.

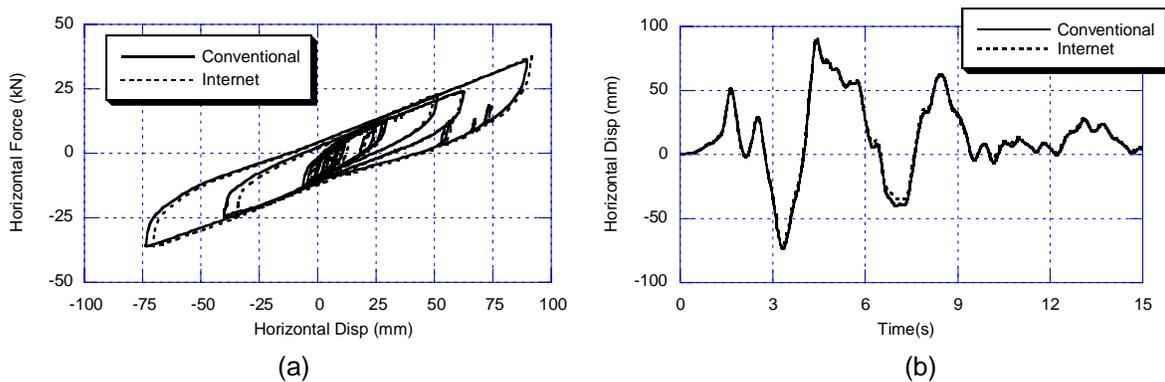


Figure 4. Base isolation layer: (a) hysteresis curves and (b) displacement time history (Pan 2006).

## Steel-Encased Reinforced Concrete (SRC) Structure Study

To further evaluate the P2P Internet online hybrid test system in terms of accuracy and efficiency, a study is performed for the case where one of the substructures undergoes significant nonlinear behavior. For this purpose, the seismic response of an SRC structure with a steel tower on top is evaluated through the use of the P2P system. The presence of the steel tower suggests that this structure may undergo significant plastification during a severe earthquake. Given the presence of both an SRC system and the steel tower, two different finite element programs are implemented. OpenSEES is adopted for the SRC system and ABAQUS is adopted for the steel tower to best take advantage of the strength of both programs. Further details in regards to this study can also be found in Wang et al. (2007).

### **SRC Structure with Steel Tower**

The SRC structure is a seven-story frame with a penthouse where the columns and beams are made of steel-encased reinforced concrete. Two shear walls spanning the height of the SRC portion of the structure are used to provide added stiffness. The steel tower is an eleven-story steel braced frame which is connected to the top of the SRC frame. The only concrete slab in the steel tower exists at its second-story for the placement of special facilities. As a result, most of the weight of the structure is attributed to the SRC frame, 220 MN, while the steel tower is relatively light, 5 MN, with most of its weight being concentrated in the first story due to the presence of the slab above. An elevation view of the structure can be seen in Fig. 5 which represents the planar frame whose response is analyzed in this study. Assuming a based fixed condition for both the SRC frame and the steel tower, the natural periods are found to be 0.6 sec and 0.7 sec, respectively.

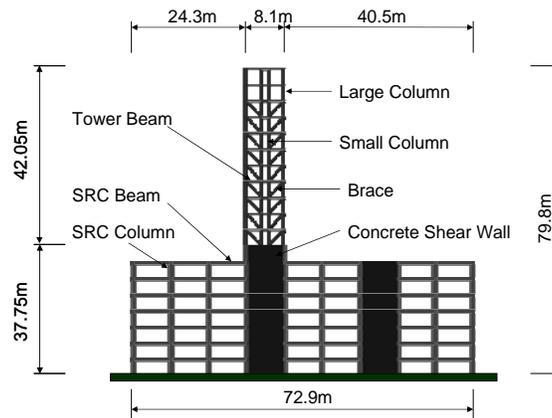


Figure 5. Elevation view of the SRC structure with the steel tower (Wang 2007).

### **Substructures and Test Specimen**

The discontinuity between the tower and the SRC frame along with the large mass concentrated at the first story of the tower suggest that this first story may be susceptible to large deformations. For this reason, it is reasonable to use the first story of the tower as the physically tested substructure. The remaining structure is divided into two parts consisting of the SRC frame and the upper portion of the steel tower. These two parts are analyzed numerically as two separate substructures.

For the numerical substructures, two available finite element codes are used to accurately model the complex structures. The SRC frame is modeled using OpenSEES because of the availability of fiber beam-column elements which can accurately account for the steel-encased reinforced concrete members. The shear wall is modeled using a beam-column element where the plastic hinge represents the nonlinear shear force versus story drift angle relationship. For the steel tower, ABAQUS is used

because of its ability to accurately handle both material and geometric nonlinearities. Brace buckling behavior was accounted for by imposing an initial imperfection. The model of the SRC frame contains 177 elements and 178 degrees of freedom while the model of the steel tower contains 334 elements and 867 degrees of freedom. Representations of the two models are shown in Fig. 6(a) and (b).

Because of limitations of the loading facilities, only the horizontal displacement is considered as the boundary degree of freedom, both at the top and bottom of the tower's first story. For the test, the horizontal displacement is applied at the top of the test specimen with the bottom of the specimen fixed to a foundation beam. A vertical jack is used to apply a constant vertical load representing gravity. External control is used to directly measure the specimen displacement. The tested specimen consists of a one-quarter scale prototype shown in Fig. 6(c). Similitude between the prototype and the actual first story of the tower are maintained through the proper selection of the force scale ratio, 1-to-11. A "virtual loading" scheme is also developed to account for the control precision of the loading system. This allows for loadings less than a set tolerance to be skipped with the force being updated based on the initial stiffness of the specimen.

For the P2P online hybrid test, the substructures are distributed to three geographically different locations. The Coordinator program is run on a separate computer at one of these locations. Because of the use of different subnets, a proxy computer is also used to transfer all data between the Coordinator and the substructures.

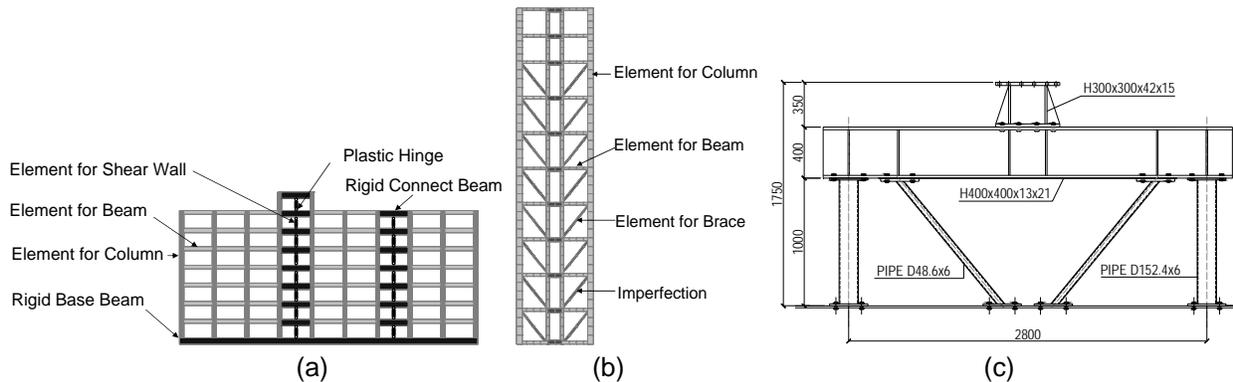


Figure 6. Substructures: (a) SRC frame (b) Steel tower and (c) Scaled steel tower first-story (Wang 2007).

## Results

The same fault-normal JMA Kobe ground motion as the base isolation study is adopted here, but enlarged by two times in order to study the P2P system when highly nonlinear behavior occurs and large models are used for the substructures. A comparison of the response of the structure is made between the results when the P2P system is used and when the entire structure is simulated numerically only using OpenSEES. It should be noted for the simulated case, buckling behavior of the steel braces is not considered.

Fig. 7 shows the time history results of the top story of the SRC frame and the first story of the steel tower for both the P2P system test and the entire numerical analysis. Comparing the results for the top story of the SRC frame, the difference in the maximum displacement is only approximately 2.2 mm suggesting the use of large finite element models with the P2P system is feasible given that the models for both cases are the same. The maximum displacements for the first story of the tower are also similar; however, the buckling behavior of the tested specimen causes some deviation in the behavior during continued cycling. This is further confirmed by comparing the hysteretic behavior of the first story of the steel tower shown in Fig. 8. These responses indicate the effectiveness of the P2P system and suggest increased accuracy due to the ability to simulate the buckling behavior of the tower.

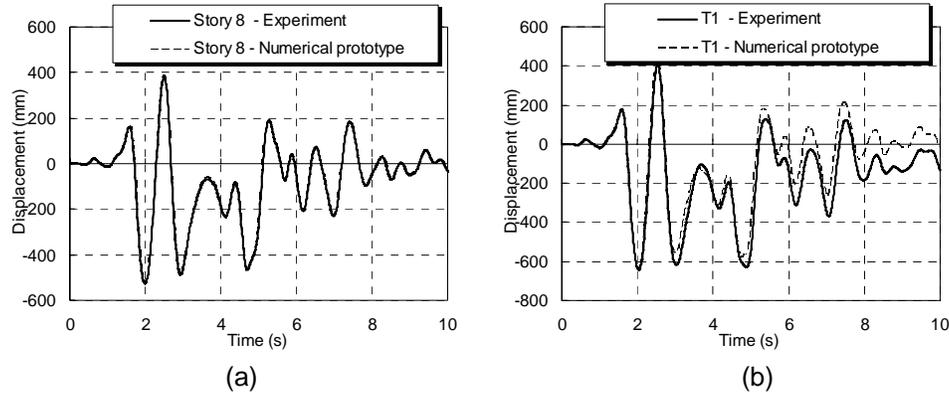


Figure 7. Response Comparison: (a) Top story of SRC frame (b) First-story of steel tower (Wang 2007).

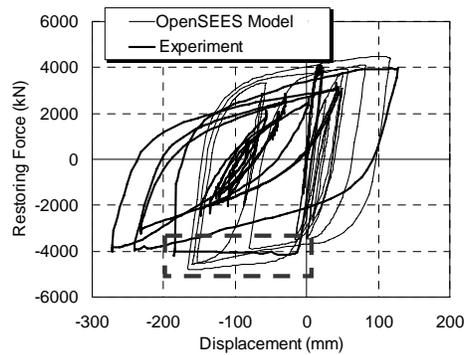


Figure 8. Hysteretic behavior of the first-story of the steel tower (Wang 2007).

#### Four-Story Steel Moment Frame Study

As the final part of this test series, a four-story steel moment frame is studied in order to evaluate the P2P Internet online hybrid test system under conditions where the boundaries are more complex and multiple experimental substructures are used. Only the plastic hinge behavior at the column bases is taken as the experimental substructures requiring that both vertical and horizontal loads be applied. The two round quasi-Newton method is also modified during this test series to use the secant stiffness rather than the elastic stiffness of the tested specimen during the iteration process.

#### Steel Moment Frame Structure

A two-span by one-span steel moment frame structure is selected for this study. The length of the spans in the two-span direction is 5 m and the length of the single span is 6 m. The floor heights remain constant along the height of the structure at 3.5 m. Column members consisted of steel tube sections and beam members are H-sections consistent with typical Japanese design of low-rise moment frames. The structure is similar to the one which will be tested to collapse at E-defense (Japan) in the future. The interior single-span frame is selected for this study where a preliminary analytical analysis shows that plastic hinges first develop at the column bases.

#### Substructures and Test Specimen

The steel moment frame is divided into three substructures. The plastic hinge at each of the column bases is used for the experimental substructure. These are set in two geographically different locations, Kyoto Universities' Katsura and Uji laboratories, while the rest of the frame is numerically modeled. The use of only the plastic hinge behavior as the experimental substructure is a unique part of this test which

removes the necessity of having to estimate the plastic hinge length. For the numerical substructure, ABAQUS is adopted as the finite element program. Since the more complex plastic hinge behavior in the column bases due to axial load interaction is handled experimentally, the beams and columns are modeled with beam-column elements using discrete plastic hinges at their ends as shown in Fig. 9(a).

Although only the plastic hinge behavior is used as the experimental substructure, columns of a given length are required to be tested in order to obtain this behavior. Two prototype 200x200x6 steel tube sections with welded base plates at each end are used for the experimental substructures. These represent a 2-to-3 scale ratio and a 4-to-9 force ratio. The length of the two specimens is slightly different due to the constraints of the test setup in the two different laboratories. Since the plastic hinge behavior is highly dependent on the axial load, both the vertical load and the horizontal displacement are controlled as part of this test. The changing vertical loads are obtained from the numerical substructure and account for the effect of the overturning moment. The test setups are shown in Fig 9(b) and (c).

The boundaries between the experimental substructures and the numerical substructure are taken as the moment and rotation at the column base. However, the physical test can only apply a horizontal displacement and return a horizontal reaction force. Thus, an algorithm is developed to convert the required applied rotation into a horizontal displacement based on the length of the test specimen, the moment associated with the previous step, and the elastic stiffness of the specimen. The resulting reaction force can then be turned into a moment based on the length of the specimen and returned to the Coordinator program. The implementation of the P2P system is similar to that used for the SRC frame test.

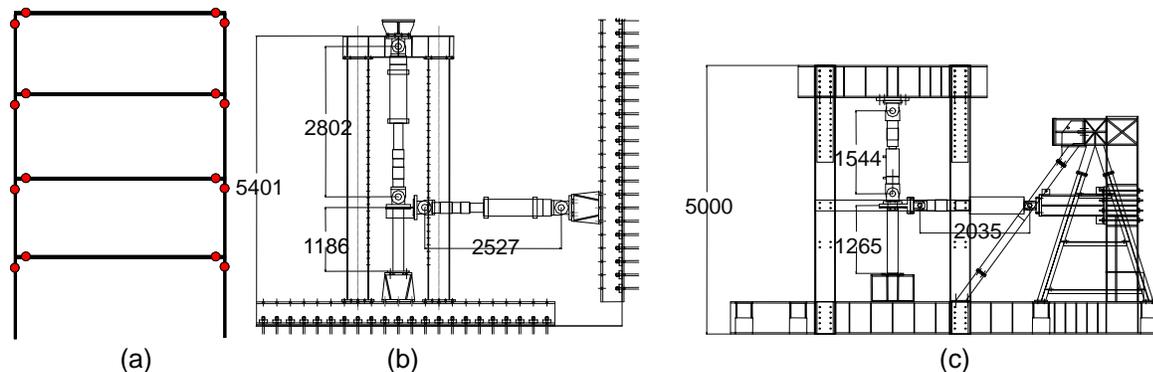


Figure 9. Substructures: (a) Numerical model, (b) Experimental portion at Katsura, (c) Experimental portion at Uji.

## Results

The JMA Takatori ground motion is adopted as part of this study with the magnitude scaled by 1.5 times. The ground motion is applied twice to the structure with a short period considering free vibration of the structure in between. The application of the ground motion the second time is to show the ability of the P2P system to predict the collapse behavior.

Fig. 10(a) shows the time history of the rotation at the base of the two columns. The results show a similar behavior for the two tested column bases as expected up until a rotation of 0.15 rad when the displacement limit of the jacks is reached and collapse is assumed. At this point, the column bases have experienced significant buckling and even tearing of the steel tube for one of the substructures. The moment-curvature hysteretic behavior for one of the plastic hinges is shown in Fig. 10(b). This figure shows a highly nonlinear behavior which would be difficult to model accurately in a finite element analysis further supporting the use of the P2P system. The test results confirm the ability of the P2P system to provide reasonable results even when multiple experimental substructures are used. They further suggest that complex boundary conditions with multiple loadings can be handled efficiently.

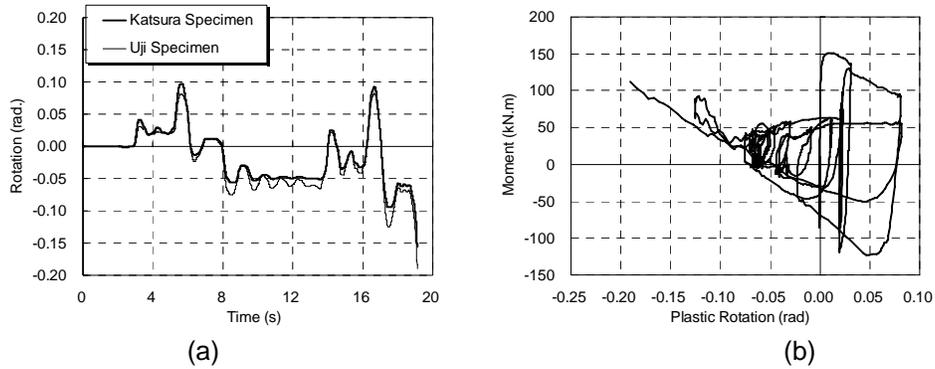


Figure 10. Results: (a) Rotation time history at the column base (b) Moment-curvature relationship for one of the experimentally tested substructures.

### Conclusions

The Peer-to-Peer Internet online hybrid test system expands upon the advantages of typical hybrid testing systems by treating substructures as highly independent systems and thus requiring only the equations of motion for each substructure to be solved rather than for the structure as a whole. A two-round quasi-Newton iteration method is used to efficiently achieve equilibrium and compatibility through a trial and error process while only requiring the tested substructure to be loaded once at each step. The P2P system is shown to be feasible through the test of a linear base-isolated structure. The ability of the P2P system to simulate complex structures is proven through the test of an SRC frame structure where multiple available finite element programs are used. Finally, the P2P system is tested when complex boundary conditions and multiple experimental substructures are present through the test of a four story steel moment frame. This test series shows the ability and benefits of using the developed P2P system for a wide variety of situations allowing for complex responses to be more accurately and efficiently simulated.

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