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SUBSTRUCTURING TECHNIQUES FOR HYBRID SIMULATION OF COMPLEX STRUCTURAL SYSTEMS

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ABSTRACT

Hybrid simulation is an effective structural test technique combining numerical simulation of substructures with predictable behavior, and experimental testing of complex components that are difficult to model. Consequently, hybrid simulation is prone to modeling assumptions in addition to experimental and numerical errors. Particularly when simulating the response of complex structural systems, the boundary conditions between substructures are often simplified to reduce the number of required actuators. For example, pin connections are assumed at boundaries to avoid the challenges of controlling stiff moments and rotations in the experiment. Numerical studies examining the effects of boundary condition assumptions on the global and local structure response are presented in this paper. The numerical simulation of a steel moment frame with added hinges at desired boundaries indicate that while the global structural response remains unchanged, the local element response near the boundaries is modified substantially. Alternatives for substructuring are investigated and their suitability for application to hybrid simulation is assessed. The results of these studies were used to select the substructures for an internationally distributed hybrid simulation examining the seismic response of a steel moment frame building to collapse. The results from the hybrid simulation are then compared with shake table tests of the complete structural model to evaluate substructuring assumptions through a detailed analysis of stress distributions.

Introduction

A key objective of seismic design for buildings is life-safety, particularly collapse prevention during a major earthquake. Recent earthquakes, however, have exposed deficiencies in knowledge about the progress of damage in buildings and the margin of safety against collapse provided by current codes. One notable example of such unanticipated failure are the fractures to welded connections in steel buildings during the 1994 Northridge earthquake (Bertero et al., 1994) and the 1995 Kobe earthquake (Nakashima et al., 1998). Further, recent experiments of full-scale frames to failure have demonstrated modeling deficiencies and the difficulties capturing the behavior of steel structures in the very large deformation range (Nakashima et al., 2006). Previous numerical studies and proposed procedures to predict collapse

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of structures under seismic loads (Villaverde 2007), have relied on empirical data and mechanical component models that have not been validated at the system-level through experimental data of realistic structural models or subassemblies. Earthquake simulator facilities such as the Hyogo Earthquake Engineering Research Center of Japan (E-Defense) provides the capabilities for realistic full-scale testing of structures through collapse and are currently being used for this purpose. Alternatively, hybrid numerical and experimental simulation provides significant potential for realistic, safe and economical evaluation of complex structural systems with more widely available laboratory capabilities.

In this paper, a hybrid simulations framework is presented and applied to evaluate the seismic performance of large-scale steel structures from the onset of damage through collapse. In this approach, only the critical subassemblies of the structural system leading to the collapse mechanism are evaluated experimentally while the global response of the remaining structure is captured numerically. The selection of the subassemblies (number of stories, number of bays, etc) and the sensitivity in enforcing boundary conditions between experimental and numerical substructures in order to capture the initiation of collapse are the focus of this paper. The numerical studies are validated by performing an internationally distributed hybrid simulation and comparing the results to the E-Defense test of the full-scale steel moment resistant building that was tested to collapse in September 2007 (Suita et al. 2008). A companion paper (Wang et al. 2009) provides a detailed description of the test and the software framework for distributed testing. The focus of this paper is on the numerical and experimental studies conducted to examine the effectiveness of the substructuring techniques.

Substructuring Techniques

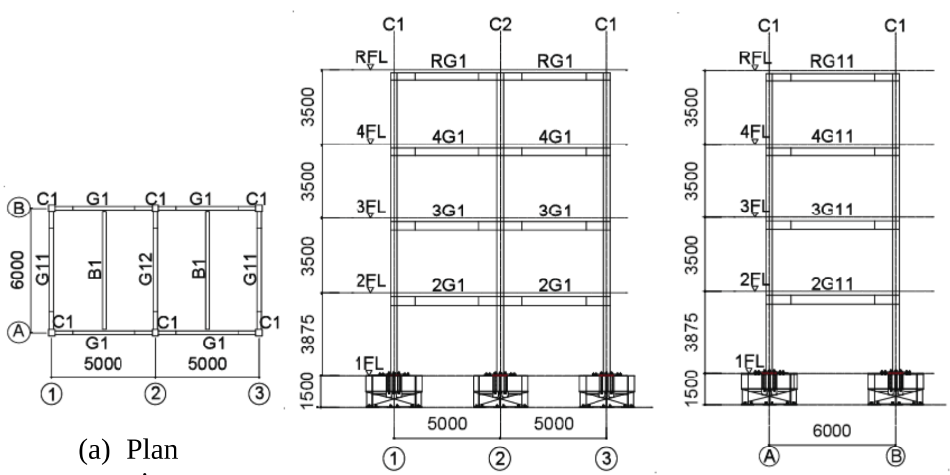
One advantage of using hybrid simulation to test structures to collapse is the ability to test experimentally the key elements where damage is expected to occur while the parts with predictable behavior can be modeled in the computer. The substructuring techniques follow procedures from conventional structural analysis. Hybrid simulation with substructuring has been investigated in the past by Dermitzakis and Mahin (1985), Shing et al. (1996), and Schneider and Roeder (1994).

Substructuring requires that both force equilibrium and displacement compatibility be satisfied at the boundaries between the analytical and experimental substructures. This can be accomplished by positioning actuators at strategic positions in the experimental substructure to enforce these boundary conditions. To minimize the number of actuators, points of inflections may be assumed at the boundaries, typically in the centers of beams and columns (Schneider and Roeder 1994), or rotations may be omitted. Schneider and Roeder (1994) proposed a substructuring technique for non-linear structures where the measured forces were treated as unbalanced forces. Further, they conducted numerical studies to examine the effects on structural response by assuming hinges. Inflection point locations were calculated through an inelastic dynamic analysis to identify the preferred location for the hinges. These studies showed that there were only a slight variation in global frame response (drift) in assuming plastic hinges in the middle of the beams but for column hinges the variations in response was larger. Only the global structural response was examined in this study. This study also concluded that the experimental component should have a significant portion of the total inelastic energy dissipated by the structure since the hysteretic degradation experienced by the test specimen is difficult to represent in the mathematical models.

Numerical Studies on Substructuring

In order to validate the substructuring techniques discussed in the previous section, analytical models were developed using as a prototype of the E-Defense full-scale steel moment resistant building that was tested through collapse in September 2007 (Suita et al. 2008). The objectives of this numerical study were to select the substructures for a hybrid simulation that would minimize the error in response introduced by simplified boundary conditions while limiting the experimental degrees of freedom. This was accomplished by assuming pin connections at the boundaries of presumed inflection points and also by the simplification of the physical boundary implementation using closed and/or open control in the flexible test scheme as described by Wang et al. (2010).

The E-Defense steel moment frame structure is selected for the studies presented here because experimental data from the seismic response of the full structural system is available to compare and validate the results of the numerical studies and experimental substructured hybrid simulations. In the earthquake simulator tests, the two-bay by one-bay four story steel moment resistant frames was excited by the JR Takatori Station ground motion in the three principal directions at amplitude levels of 5, 20, 40 , 60 and 100%. The member sections and materials are listed in Table 1. This structure was designed following the typical Japanese seismic design procedures (BCJ, 1997). The frame collapsed in the longitudinal direction at a target level of 100% Takatori. The prototype for the analytical models was chosen as one of the longitudinal steel moment resistant frames as shown in Fig. 1(b).



(a) Plan view. (b) Longitudinal Direction- Elevation. (c) Transverse Direction- Elevation.

Figure 1. E-Defense Test Specimen Layout and Framing.

Table 1. E-Defense Test Specimen Section Properties.

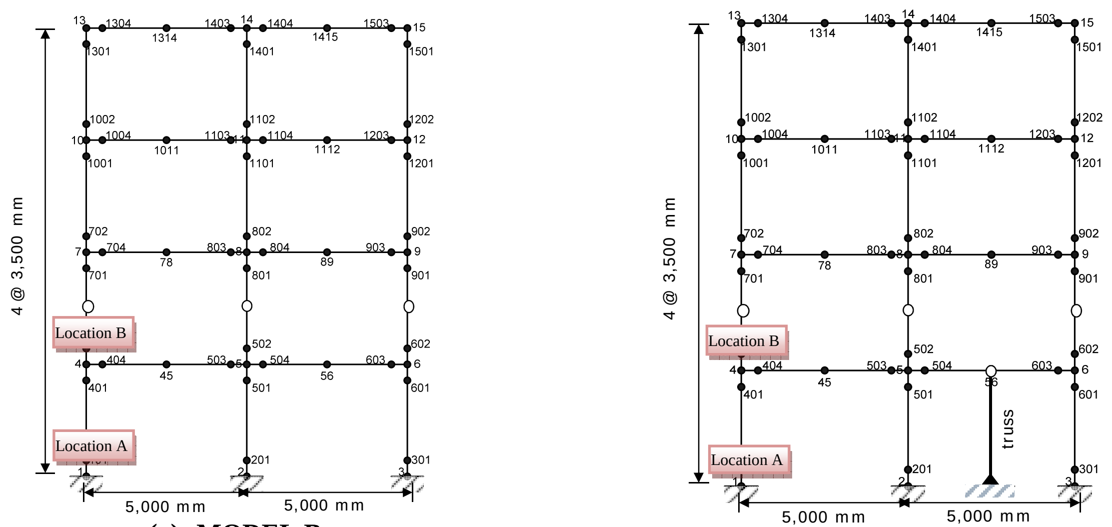
Beam (SN400 B)				Column (BCR295)	
Story	G1	G11	G12	Story	C1,C2
R	H- 346x174x6x9	H- 346x174x6x9	H- 346x174x6x9	4	□-300x300x9
4	H- 350x175x7x11	H- 350x175x7x11	H- 340x175x9x14	3	□-300x300x9
3	H- 396x199x7x11	H- 400x200x8x13	H- 400x200x8x13	2	□-300x300x9
2	H- 400x200x8x13	H- 400x200x8x13	H- 390x200x10x16	1	□-300x300x9

The selected prototype frame was modeled and analyzed in 2-D using OpenSees (Mazzoni et.al, 2006). The model was calibrated using the experimental results from the E-Defense 60% and 100% Takatori simulations. The nonlinear behavior of the beams and column was modeled assuming concentrated plasticity, with the rotational springs at the ends of the elements defined by tri-linear degrading hysteresis**.**

Different substructures were modeled and analyzed with different combinations of hinges to identify which hinges or combination of hinges caused the least change in the structural behavior. Hinges were added to the original frame where it may be partitioned into one or two substructures. Table 2 describes two models that gave the most desirable response with practical substructure models able to capture story mechanism that may form. Fig. 2 shows the location of the hinges for the two modified models described in Table 2.

Table 2. Description of substructures analyzed.

MODEL	DESCRIPTION
A	Original moment frame model calibrated to 60% Takatori
B	Single substructure model with hinges on center of all second story columns.
C	Two substructure model with hinges on center of all second story columns plus additional hinge at 1st level beam of the right bay. Beam hinge includes truss to limit vertical movement.



(a) **MODEL B** (b) **MODEL C**

Figure 2. Models with hinges examined for substructuring.

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Numerical Results

Simulations of the models described above were analyzed to determine a suitable substructure that would provide minimal response modification as a result of substructuring. The response was assessed by comparing the global response (story displacements and accelerations) and local response (energy dissipated by concentrated plasticity elements). It should be noted that the fundamental elastic period of the models examined with various hinge combinations changed by less than 0.2%. For time history analysis, the different models were excited by the

JR Takatori ground motion at 60% amplitude. The maximum displacement errors found from the analysis were up to 7.5%. It should be noted that residual displacements were very sensitive to the added hinges and difficult to control. Maximum floor acceleration errors up to 5% were observed. Overall both models demonstrated acceptable global behavior as shown by the comparison in Figure 3, of the first floor displacement subjected to 60% Takatori record**.** The displacement time history matches the original model very closely up until 10 seconds, thereafter there appears to be an offset in residual displacement.

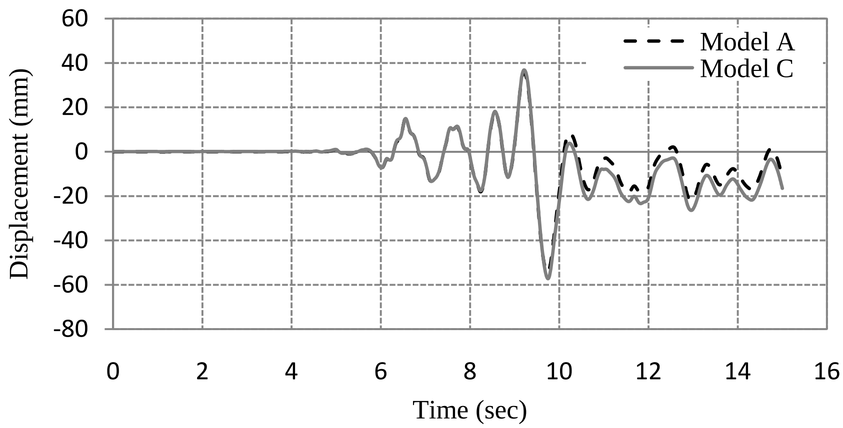
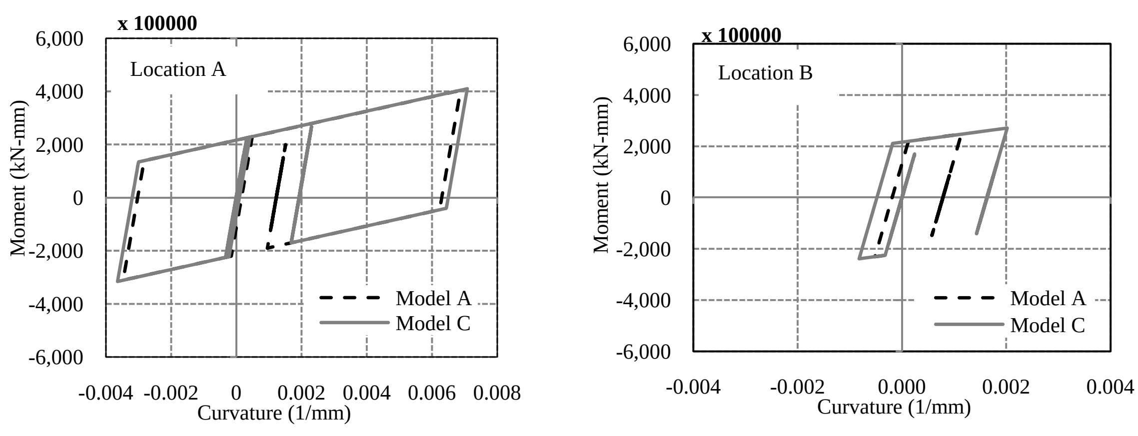


Figure 3. First story global displacement response.

Larger differences in response were observed in the local behavior of the models, where in some cases the maximum plastic hinge deformation errors were as large as 85%. From examining the moment-curvature response, the maximum differences occurred near the location of the hinges, particularly at the ends the beams or columns to which hinges were added. Figure 4, shows the moment-curvature relationship for the exterior column of **Model B** at two locations shown in Fig. 2. At location A (away from the hinges) the model matches well but at location B (near the hinges) the peak deformations change substantially.



(a) Location A (b) Location B

Figure 4. Local behavior of plastic hinges for 60% Takatori.

Both substructure models provided a reasonable approximation to the response of the original model and provide practical boundaries that could be applied in an experimental setup.

The global behavior and local behavior response were in general in good agreement with the original model. Model C lends itself to two substructures of different sizes that will further allow for an experimental comparison of their response and was selected for the experimental study.

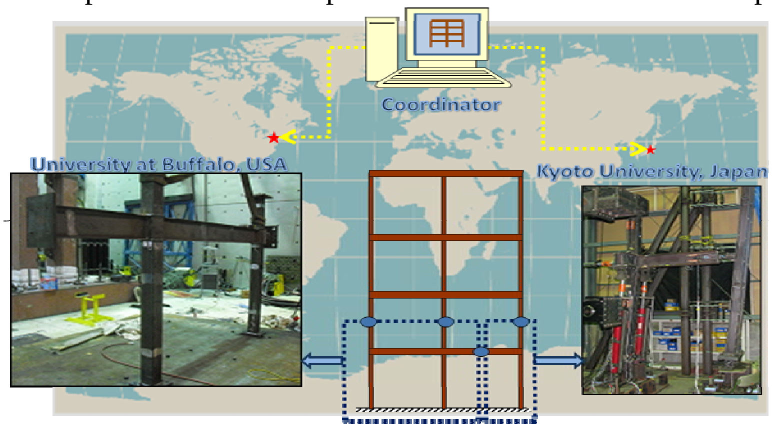


Figure 5. Illustration of geographically distributed hybrid simulation.

Distributed Hybrid Simulation

A distributed hybrid simulation was carried out with two substructures in an effort to reproduce the results of the E-Defense earthquake simulator test. The substructuring objectives were to simulate experimentally the first story columns of the structure, where the collapse mechanism formed in the earthquake simulator experiments. Figure 5 illustrates the prototype frame and the locations of hinges for the distributed test and also identifies the partitioning of the substructure. The left substructure tested at the University at Buffalo, USA consists of one and half bay by one and one-half story frame with a support link at mid- bay of the beam. The right substructure tested at Kyoto University, Japan consists of one-half bay by one and one-half story frame with a support link at mid-bay. A length scale factor of two was selected for the substructure specimens to satisfy economical and physical constraints in the laboratory facilities. The structure was designed based on similitude requirements and to match the strength and stiffness of the E-defense frame. While the columns where scaled based on the geometry of the section, the beam section was increased to include the effect of the floor slabs. The beam section was selected to match the stiffness of the composite section with a reduced beam section at the ends to also match the estimated composite strength. Table 4 illustrates the sections and materials used for the design of the specimens.

Table3. Beam and column section for substructure specimens.

	Buffalo		Kyoto	
Story	**Beam**	**Column**	**Beam**	**Column**
2	-	HSS6x6x3/16 (152.4x152.4x4.8mm)	-	150x150x6
1	W10x15 (W250x22.3)	HSS6x6x3/16 (152.4x152.4x4.8mm)	H200x150x9x6	150x150x6

The test-setup for the two substructures is shown in Figure 6. Both frames were loaded by two horizontal actuators to control the story drift of the first and second level, with additional force-controlled actuators applying axial loads in each column.

(a) University at Buffalo, USA. (b) Kyoto University, Japan

Figure 5. Experimental setup of two substructures.

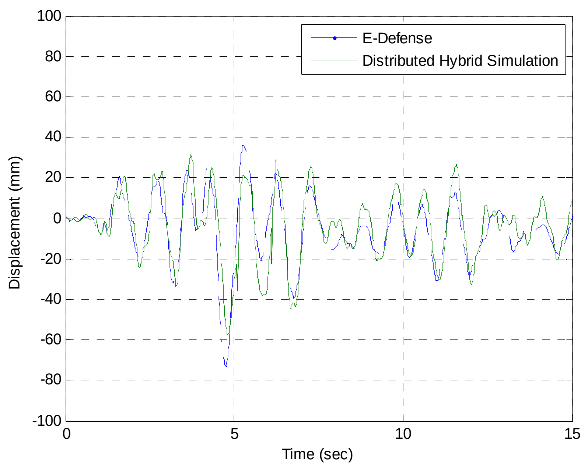
Comparison with E-Defense Tests

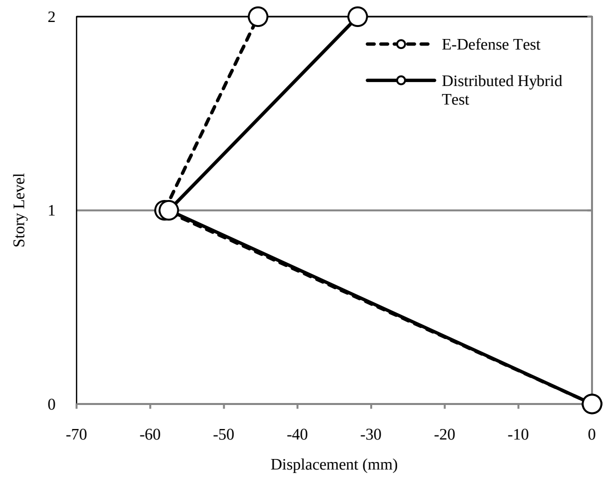
The results from the internationally distributed hybrid simulation test were compared to the E-Defense test of the full-scale steel moment frame building (Suita 2008). Figure 6 shows the displacement time history for the first floor and the displacement profile for the first two stories at the maximum peak displacement for the 60% Takatori hybrid simulation. The profile shown for the E-Defense test was obtained was at a similar first story displacement, not at the peak which is approximately 23% larger. Note that the deformed shape of the structure is also different. Due to these differences in global response, it proved difficult to obtain a point at which to compare the local response. It should be noted that larger errors were observed in the lower level simulations because the numerical model in the hybrid test were calibrated to the measured behavior of the E-Defense specimen for the 60% tests, which likely included degradation in behavior of the concrete slabs and nonstructural wall elements. Fourier Transform of the displacement time histories for the first and second floor indicated that the predominant period of vibration did not change, with both models having a fundamental frequency response of 1.12 Hz for the 60% simulation.

Distribution of Stresses

In order to further examine the selected substructures and the modeling assumptions, the distributions of stresses in the frame were compared during the distributed test and the E-defense tests by means of moment diagrams. The moment diagrams were calculated at the peak displacement response for the distributed tests using the experimental strain data. For the E-Defense test, the moments were calculated at the same time step that the moments for the

Distributed test were calculated with both having similar displacements. In both tests, strain gauges were located at the one-third and two-thirds length of the beams and columns where the members are assumed to remain elastic. A linear moment diagram is then fitted to these two points to obtain the moment diagram for the member and extrapolate the moment at the member ends. The member end moments calculated for the 60% and 100% Takatori tests are listed in Table 5, with Figure 7 illustrating the moment diagram at peak displacements profile shown in Fig. 6b. The moment *Mij* corresponds the moment at end *i* of the element connecting nodes *i* and *j*. The maximum differences in the member end moments were observed at the second floor near the boundaries and at the beams, while smaller errors occurred at the first floor. It is important to note that the focus of the experiment is on the first story, thus extending the boundaries beyond the critical substructure may be advantageous towards achieving realistic distribution of stresses in the key portion of the experiment. In the actual hybrid simulation, the second story response was modeled numerically (Wang et. al, 2009).





(a) Displacement Time History (b) Displacement snapshot

Figure 6. First floor displacement response for target level: 60%.

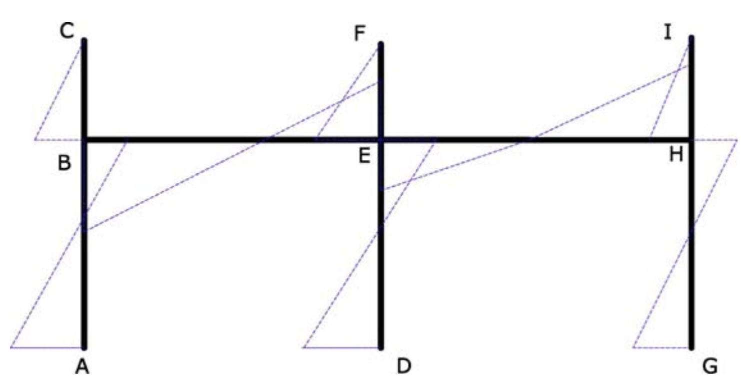


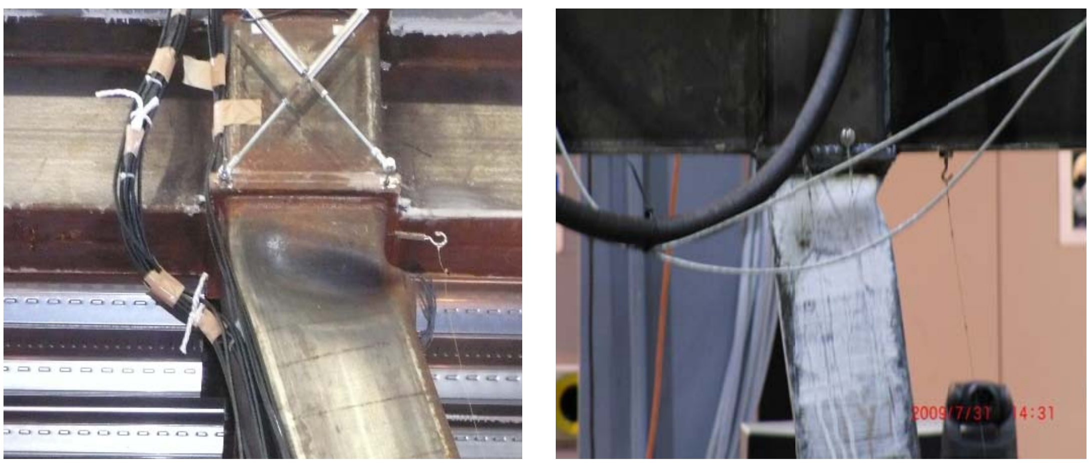
Figure 7. Moment at diagrams for hybrid test at peak displacement.

Table 4. Comparison of moments between distributed test and E-Defense test.

Target Loading	**60% Takatori**		
Location	Hybrid Simulation	Shake table	% Error
M_{AB}	362	370	2.2
M_{BA}	217	295	26.4
M_{BC}	323	265	21.9
M_{BE}	531	620	14.4
M_{EB}	417	296	40.9
M_{DE}	371	350	6.0
M_{ED}	301	327	8.0
M_{EF}	460	377	22.0
M_{EH}	655	476	37.6

Collapse Mechanism

The collapse mechanism for the internationally distributed hybrid simulation test was a first story mechanism with local buckling and hinging at the top and the bottom of the first story columns. Figure 8 compares the collapse mechanism for the E-Defense test and the distributed hybrid simulation test. It can be seen, that similar failure modes were observed for the center column of the frame. The difference in hinge rotations is due to the different limits set for each test; the hybrid simulation was not allowed to exceed 10% drift, whereas twice the drift was allowed on the shake table test.



(a) E-Defense Test (b) Distributed Hybrid Test

Figure 8. Comparison of collapse mechanism at top of center column

Conclusions

An internationally distributed hybrid simulation with two half-scale substructures was used to simulate the seismic response of a steel moment frame to collapse. The frame model was based on a full-scale frame tested to collapse using the E-Defense shaking table. Numerical studies conducted prior to the experiment and a comparison of the hybrid and earthquake simulator test verified that hybrid simulation with substructuring techniques provide reasonable approximations to the structural response. The substructures selected simplified the loading mechanism, allowing for the simulation of a realistic structural model to collapse. The assumed hinges at the boundaries produced large errors near the boundaries. The distribution of stresses away from the boundaries compared reasonably well even though there was noticeable differences in the global response. Overall, a similar collapse mechanism was observed in both tests consisting of local buckling and hinging at top and bottom of the first story columns.

Acknowledgments

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