Collaborative Research:

Behavior of Braced Steel Frames with Innovative Bracing Schemes

A NEES Collaboratory Project

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The 1994 Northridge and 1995 Kobe earthquakes showed that new technologies and structural configurations are needed to limit damage to steel structures subjected to moderate and large ground motions. In this context, the need to provide additional stiffness to modern frame configurations is clear, leading to a renewed interest in braced frame configurations. Braced frames, however, are regarded as not being very ductile because buckling of individual braces quickly leads to formation of story mechanisms. The additional need for stiffness and ductility for modern structures is compounded by the trends towards lighter structures, more compact lateral-load resisting systems and the advent of performance-based design.

To solve the traditional problems associated with conventional braced frames, a new class of bracing systems, known as a zipper frames, will be developed and tested as part of this proposed work. This proposal represents the first phase of a two-phase collaborative approach to the problem. In the experimental portion of the first phase, four laboratories (Georgia Tech (GT), U. at Buffalo (UB), U. of California at Berkeley (UCB), and the U. of Colorado at Boulder (CU)) will conduct studies on the behavior of whole systems, subassemblages, and individual elements. These will be tested under a variety of load regimes, ranging from shake table tests to quasi-static ones, in order to provide comprehensive data on which to base design recommendations. In the analytical part of the first phase, the four universities listed above, plus Florida A&M (FAMU) and Imperial College-London (IC), will conduct extensive analytical studies to provide (1) a basis and a complement to the experimental work, (2) a testbed for the NEESgrid portion of the NEES Consortium, and (3) new, simplified and comprehensive models for use in design. As the final task for the first phase, GT and FAMU researchers will develop the proposal for the second phase, which will deal with the use of advanced materials and active controls in braced steel structures.

The intellectual merit in the proposed research is that it will provide a unique database of information on the behavior of zipper frames, and will provide results from proof-of-concept studies on a new class of bracing systems. In addition, the research will lead to the development of analytical models that can be implemented into existing seismic analysis programs. The research will develop analytical tools and methodologies to allow practicing engineers to determine potential benefits of a variety of applications of zipper frames.

The project also intends provide initial shakedown studies for the NEES Consortium and in particular to test the flexibility and robustness of the NEESgrid system. In addition, it will provide valuable lessons from both the logistical and technical standpoints for future NEES collaborations. The project will link three NEES sites, one well-established program (GT), one developing program (FAMU) and international partner (IC) as a test case for future grand challenge collaborations. The project has been divided into two phases so that two younger remote researchers (Dr. DesRoches from GT and Dr. Abdullah from FAMU) will benefit from the work on the first phase in order to develop the technical expertise in pseudo-dynamic and shake table testing that they will need for the second phase. This intends to be a model for future NEES projects in which researchers from remote sites will be able to gain valuable experience and mentoring from established researchers/sites.

The research proposed depends strongly on the collaboration between researchers at five sites. To fully maximize the potential impact of this project, a strong education component of the program is proposed. To complement the collaborative research program, that includes a very large exchange of graduate students, a NEES undergraduate research program will be developed. The program will consist of three components; an undergraduate research experience at the sites, a summer undergraduate research exchange program, and a 2-day student symposium. Students from traditionally underrepresented groups will be specifically targeted for the undergraduate research program.

The broader impact of the proposed research is that is will provide important information for the design community on the performance of braced frame construction. In addition, the proposed study will serve as a model for future collaborative research using NEES.

models for shear strength, deformability, and axial load collapse, including implementation of nonlinear models and solution algorithms for seismic simulation of collapsing frames. Relevant publications include:

1. "Gravity Load Collapse of Building Frames during Earthquakes," J. Moehle, K. Elwood and H. Sezen, ACI SP 197, "*Behavior and Design of Concrete Structures for Seismic Performance*," ACI, 2002.
2. "Seismic Behavior of Shear-Critical Reinforced Concrete Building Columns, H. Sezen and J. Moehle,, 7US Nat'l. Conference on Earthquake Engineering, Boston, Earthquake Engineering Research Institute, July 2002.

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1. Introduction

This proposal intends to generate data on the behavior of braced steel frames with emphasis on a novel configuration called a zipper frame. In a zipper frame, the unbalanced forces set up as a result of buckling of the inverted V-braces in compression are taken by an additional vertical element, leading to nearly simultaneous buckling of all stories. To the best of the knowledge of the proposers, tests on such structural systems have not been carried out even though the concept is outlined in the steel seismic design provisions and structures following this concept have been built in California. In a future second phase, the work will be extended to the use of elements containing energy dissipation elements based on innovative materials (shape memory alloys), which have been tested recently at Georgia Tech and have shown superior energy dissipation and re-centering capabilities under seismic loads.

In addition to its innovative technical content, the project will showcase the capabilities and potential of some of the newly installed NEES facilities and the NEESgrid web-based collaboration tools. The project intends to link three of the NEES facilities (U. of Colorado - Boulder (CU), U. of California at Berkeley (UBC), and the U. at Buffalo (UB)) with a non-NEES site (Georgia Tech (GT)) to demonstrate the advantages of integrating new advanced control algorithms for testing and analysis. An international partner, Imperial College (London) will also participate actively in the project to test the potential international extensions to the NEES initiative. In addition, the program will bring in at least one partner from an HBCU (Florida A&M University (FA)) who will be actively involved in the research and will be one of the lead proposers for the second phase of the research.

The project intends to test the flexibility and robustness of the NEESgrid system and to provide valuable lessons from both the logistical and technical standpoints for future NEES collaborations. To conduct this work, a simple but innovative structural configuration for a braced steel frame, known as a zipper frame, has been selected. This configuration allows for the economical reuse of the test structure as it will be designed such that only certain elements are damaged (the braces and zipper elements, in this case). This will permit the evaluation of whether a design methodology that aims for the yielding of all or a few of the zipper elements after initial buckling of the first story braces, the buckling of only the braces throughout the height, or a combination of both deformation modes represents the best structural solution for this system. A braced frame is an ideal structure to test the NEES infrastructure because its relative low degree of redundancy, its inherent two-dimensional behavior, and the relatively simple stress-strain characteristics of steel under cyclic loads simplify the analytical modeling and minimize differences between specimens built at different laboratories. On the other hand, the use of this system preserves some of the complexities due to stiff system behavior, non-linear geometry effects, and buckling, thus posing significant challenges to new control algorithms. In addition, braced frames have begun to receive much attention from the design community both because moment frames proved to be less reliable than expected in recent earthquakes and the perceived need to provide more stiffness to structures to minimize damage under the proposed performance-based design specifications.

2. Braced Frames

Conventional bracing systems (Figure 1) include typical diagonal and chevron bracing configurations, as well as innovative concepts such as strut-to-ground and zipper braced frames (Khatib et al. 1988, Bruneau et al. 1998). Seismic provisions for the analysis, design, and detailing of concentrically braced frame (CBFs) were gradually introduced into seismic regulations and guidelines in the United States in the early 1970s. Newer regulations and guidelines for the seismic design of CBFs can be found in the Structural Engineers Association of California (SEAOC) Recommended Lateral Force Requirements (SEAOC 1996), the International Building Code (IBC 2000), the NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings (BSSC 2000), and the AISC Seismic Provisions for Structural Steel Buildings (AISC 2002). The rules presented in these codes and resource documents are similar, with the exception that nonlinear analysis procedures are included in the Guidelines for the Seismic Rehabilitation of Buildings (FEMA 1997).

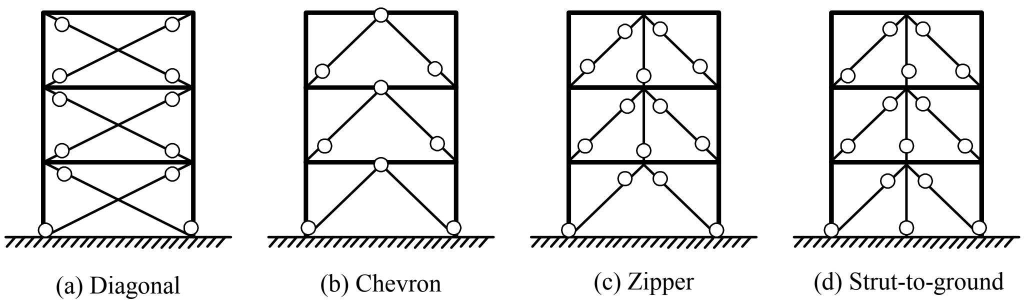


Figure 1 – Typical braced frame configurations (circles denote possible locations for energy dissipators).

Diagonal and chevron systems can provide large lateral strength and rigidity but do not provide great ductility as buckling of the diagonals leads to rapid loss of strength without much force redistribution (Goel 1992). In chevron configurations, this is due primarily to the unbalanced vertical forces that arise at the connections to the floor beams due to the unequal axial capacity of the braces in tension and compression. In order to prevent undesirable deterioration of lateral strength of the frame, the provisions require that the beam should possess adequate strength to resist this potentially significant post-buckling force redistribution, in combination with appropriate gravity loads (AISC 2002). This results in very strong beams, much stronger than would be required for ordinary loads.

The adverse effect of the unbalanced vertical force at the beam-to-brace connections can be mitigated by adding zipper elements, as proposed by Khatib et al. (1988) and shown in Fig. 1(c). If the compression brace in the first story buckles while all other braces remain elastic, a vertical unbalanced force is then applied at the middle span of the first story beam. The zipper elements mobilize the stiffness of all beams and remaining braces to resist this unbalance. The unbalanced force transmitted through the zipper elements increases the compression of the second story compression brace, eventually causing it to buckle. A comparison between the development of the zipper column effect and the behavior of a conventional braced frame is shown schematically in Figure 2.

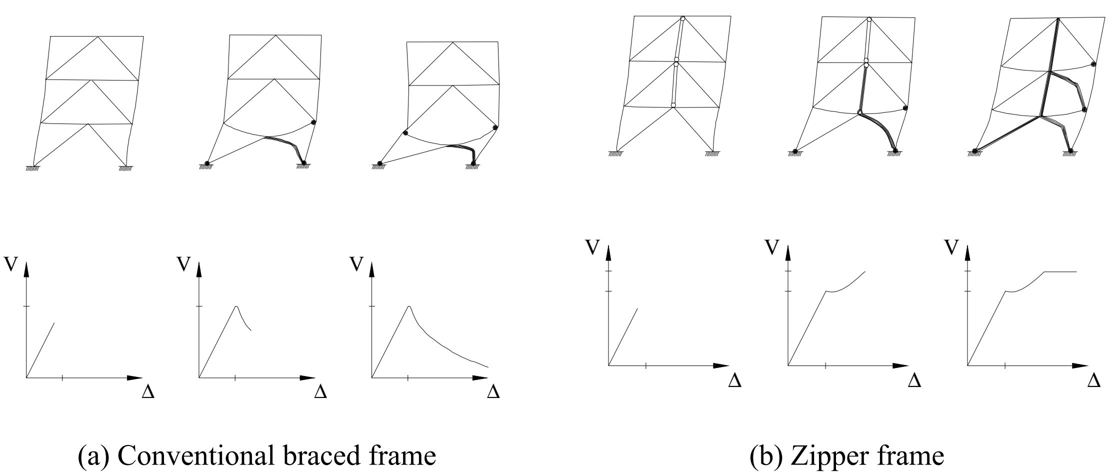


Figure 2 – Comparison of the collapse mechanism and load-displacement relationships for zipper and conventional braced frames (Khatib et al. 1988).

The intent of the zipper elements is to tie all brace-to-beam intersection points together, to force all compression braces in a braced bay to buckle simultaneously and then activate formation of the plastic hinges on the beams, and thereby to distribute the energy dissipation (damage) over the height of the building. Simultaneous brace buckling over the height of a building will produce a single-degree-of-freedom mechanism and result in a more uniform distribution of damage over the height of the building (Bruneau et al. 1998). However, during the period of the external excitation, the zipper columns in the frame can be in tension or compression, which makes the design for the zipper columns very complex.

Khatib et al. (1988) studied the behavior of a zipper frame using nonlinear response-history analysis. Comparing the response of the zipper frame with that of the other frame configurations, such as inverted-V-, V-, X-, split-X-, and strut-to-ground-braced frames, Khatib concluded that the response of the zipper frame was less sensitive to ground motion characteristics and that the zipper frame achieved a more uniform distribution of damage over its height. Khatib also showed that the zipper frame developed a trilinear story shear force-displacement relation, and that the zipper frame concept could be successfully implemented with flexible beams and braces of intermediate slenderness. However, there are still several important questions to be resolved before the zipper frame can be safely recommended for practical use:

- What happens if the first brace to buckle is not in the first story?
- What if the structure is not in the first mode deflected shape when the zipper effect is activated?
- How does the designer proportion the braces to maximize the effectiveness of the zipper effect?
- How does the designer choose the relative stiffness of the zipper elements and beams?
- What are the expected axial forces in the zipper elements and in the columns?
- What would be the effect of simultaneous horizontal and vertical excitations?

These and similar questions will be addressed in this research project from the analytical and experimental standpoint. An interesting item to be investigated is a new design strategy that posits that some disadvantages of the original "zipper frame" design can be overcome by introducing suspension system, labeled a "suspended zipper frame." For the configuration of the bracing members in this frame, the top floor bracing members are designed to be bigger than the lower floor ones so as to "suspend" the zipper struts from the roof of the structure (See Section 3). Accordingly, the suspended zipper struts undergo the unbalanced vertical forces induced by lower floor bracing members in combination with gravity loads collected from the beams when the structure enters the nonlinear range. Since the function of the suspended zipper struts is to sustain only tension forces, and the suspended zipper struts support the beams at the middle span, the beams can be designed to be flexible. This results both in significant savings in the amount of steel (up to 40%) and a clear force path that considerably simplifies design.

In addition, the zipper frame behavior can be significantly improved if additional damping and energy dissipation is built into the braces. For example, bracing elements made of shape-memory alloys (SMA) can provide significant additional energy dissipation in addition to re-centering capabilities after a large earthquake. SMAs have the ability to display a wide range of cyclic behaviors, from fully re-centering to high energy dissipation by slightly varying the types of alloys, heat treatment, and finishing used. Recent work by the two of the co-PIs has established the feasibility of using large diameter SMA elements in seismic applications (Ocel et al. 2002, DesRoches and Delemont, 2002). This issue will be studied analytically at the end of this project using devices in the positions shown in Fig.1. Not all SMA elements will be used concurrently and it is likely that a mix of SMA materials with different characteristics will be used in different locations within the same frame. The aim of that work will be to propose a second phase where zipper frames with active control and passive SMA devices will be tested. Such structures will present a significant increase in the difficulty of the testing control, algorithms and collaborative tools.

3. Specimen Design

Following the concept of a suspended zipper frame, three different 3-story prototypes were designed for a high seismic area. The intent of this initial effort was to show the potential benefits of a zipper frame. Fig. 3 shows the comparison of the pushover response for the three frames. The three responses shown correspond to a conventional braced frame, a zipper frame and a suspended zipper frame, all meeting the requirements of the 2003 AISC Seismic Specification.

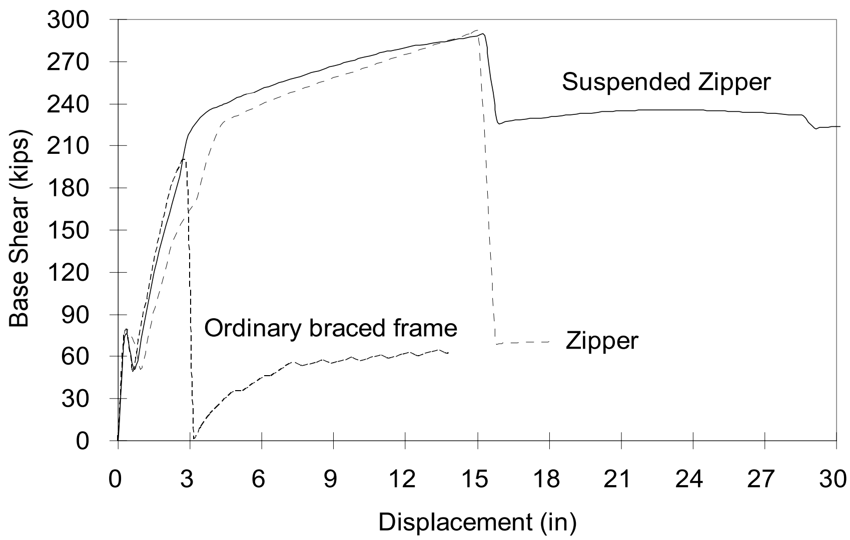


Figure 3 – Comparison of pushover curves

From similar non-linear dynamic studies for the suspended zipper frame, conducted using OpenSEES and using the El Centro ground motion, the left bottom brace sustains more tension than the right bottom brace, while the latter sustains more compression. In addition, the zipper elements are subjected to tension only. At maximum response, the second-floor zipper strut had yielded and the third-floor zipper strut was in an incipient yielding state. Once the unbalanced vertical forces form, they are transmitted up to the top floor through the struts, and then sustained by the third-floor bracing members. As a result, the analysis shows that those third floor bracing members are always subjected to compression and remain in the elastic range. Finally, some yielding occurs in the columns due primarily to bending, while the beams remain in the elastic range. For the suspended zipper system, the nonlinear static pushover analyses indicate that this structural system has a more ductile behavior than the conventional zipper frame. Since the force path is easily recognizable, the capacity of each member can be fully utilized. For the El Centro ground motion, the maximum base shear is 301 kips at about 11.7 in, which is close to the result from the static pushover analysis shown in Fig. 3. These analyses were carried out using OpenSEES, for which a suitable bracing element has been developed by Yang (2003) and which has already been extended to incorporate the SMA hysteretic characteristics. Elements incorporating some active control characteristics are currently being developed.

4. Project Integration

The project will proceed along parallel tracks at four laboratories, testing scaled models of a three-story prototype. The frame has been designed so that several bracing schemes, ranging from a conventional braced frame to a zipper frame, can be tested without damaging the columns and beams. The project will proceed in four phases:

- ***Phase 1: Preliminary Analytical Studies:*** The work will begin with extensive non-linear modeling of zipper frames using OpenSEES (GT, CU, UCB and UB), ABAQUS (CU and UB), and ADAPTIC (GT and Imperial College, London, an international partner). This step will involve extensive contacts via the NEESGrid network by the PIs and their graduate students to coordinate issues related to analysis and load history to be imposed. These results will be used first to design the final prototype structure and the four variants to be tested. It is anticipated that one conventional braced frame, one conventional zipper frame, one suspended zipper frame with yielding zipper elements and one suspended zipper frame with buckling braces will be designed. However, these final configurations may change based on the advanced analysis results. Later in the project, these analytical platforms will be used to assess the robustness of the programs, simulate the experiments, and determine the sensitivity of the pseudo-dynamic tests to the analytical platform. Simplified models using commercial design software (SAP2000, ETABS, ROBOT and others) will also be used to assess the accuracy of those programs in predicting non-linear behavior for an unusual structure.
- ***Phase 2: Final Prototype Design:*** The final design for the prototype structure will be conducted by the PI at GT, in extensive consultation with the co-PIs at the other NEES sites. This stage will also entail extensive use of web-based collaboration tools to finalize the loading histories, instrumentation, data archiving and dissemination issues.
- ***Phase 3: Material Ordering, Distribution and Testing:*** Once the design is finalized, the main steel components, those designed to yield, will be detailed and fabricated by GT. This is necessary to ensure the

fabrication similarity of the specimens, to remove as much of the uncertainty associated with material strengths and ductility, and to mimic the need in future NEES cooperative programs to fabricate and ship large specimens between laboratories. Cost studies will be conducted to relate the cost of doing this versus having each lab provide the materials independently. The final designs will be checked against these material properties to ensure that the expected behavior will be achieved

- ***Phase 5: Shake Table Tests:*** A model of the prototype structure will be constructed and tested on the new shaking table at the UB. The specifics of this phase are described in Section 6. These tests will be conducted immediately after the table qualification testing, which is expected to be finalized in early April 2004. The shake table tests will provide benchmark information for the fast hybrid tests to be run at CU and UCB. It is assumed that two GT graduate students will spend about three months at Buffalo as part of the setup of this experiment, and that graduate students from both CU and UCB will spend three to four weeks at Buffalo, immediately before and after the main test. This interchange of students will also take place as tests are run at the other laboratories. In is assumed that once each of the four variants is tested at UB, the corresponding tests at the other sites will start.
- ***Phase 6: Tests at Other Sites:*** Coordinated work at UCB and CU will initiate with efforts to integrate and synchronize the pseudo-dynamic testing algorithms at the two schools. It is anticipated that this will require a significant amount of effort as this is the first attempt at multi-site simultaneous testing under NEES. Once this preparatory work is completed and the first shake table test run at UB, CU will test the two bottom story braces as shown in Fig. 6 and UCB will test both individual braces and a complete one-story subassemblage using the displacements obtained at UB. The details of the work at UCB and CU are given in Sections 7 and 8, respectively. UCB will test individual brace components to assess the ability of different pseudo-dynamic test algorithms to handle buckling of the brace and the associated changes in brace stiffness. CU and UCB will cooperatively test the one-story subassemblages in two ways: 1) as identical sub-structures to evaluate the accuracy and identify the differences between the two laboratories; and 2) as first- and second-story models of the three-story prototype structure tested at UB and GT. The specimens at UC and UCB will be as similar as practically possible. Both tests will be conducted using the geographically distributed versions of the pseudo-dynamic test method implemented on NEESgrid. Due to the complexity of the models and the latency issues in the network, true real-time interaction will probably not be achieved, although the test will be relatively fast compared to the quasi-static test conducted at GT. Both labs have virtually identical hybrid test control hardware and software and similar hydraulic actuators: this will make conducting a geographically distributed test much easier. The work at Georgia Tech will entail the testing of two braced zipper frames in a quasi-static fashion, as shown in Fig. 4 and described in Section 5. The first test, for which a prescribed displacement history from the UCB and CU work will be used, will be conducted in early 2004, while the second, for which the UB displacements are needed will follow in the early summer.
- ***Phase 7: Synthesis of Experience*:** In this phase of the work, the project team, will synthesize their experiences related to joint cooperation and collaborative tools. This feedback will be channeled through the Committee on Shared Use and Site Operations of the NEES Consortium. It is expected that this will occur in the summer of 2004, so that future NEES proposers will benefit from the experience. It is intended that a log will be maintained online throughout the project documenting both positive and negative aspects of the collaboration, conflict resolution techniques used, and similar issues. Since it will not be possible to maintain anonymity within the project given that each site is conducting fairly unique research, access to this site will initially be granted by special permission to other potential NEES researchers.
- ***Phase 8: Analysis and Synthesis of Results:*** The PIs and graduate students involved will synthesize the results of the experiments and produce technical reports and refereed publications on (a) the experimental and analytical test results and their comparison, (b) the comparison of the test techniques and their relative merits, (c) the design procedure for zipper frames, and (d) code-format design recommendations. The latter will be sent to both BSSC/NEHRP and the AISC Seismic Committee for implementation. Two of the PIs serve in these committees, so implementation of the results should be immediate.
- ***Phase 9: Development of Second Phase Proposal*:** Two of the co-PIs in this proposals, Drs. R. DesRoches and M. Adbullah will take the lead in developing a follow-up proposal dealing with active control and the use of shape memory alloys.

5. Georgia Tech

The experimental work at Georgia Tech will center on testing four zipper frame configurations under quasi-static loads. Two sets of tests will be conducted on each configuration, using different load histories. One set of tests will be run using the live input from the slow-rate pseudo-dynamic test at CU and UCB., while the other will use an incrementally increasing cyclic load history using an appropriate distribution of displacements along the height of the structure. Such displacement distribution will be derived using the UC Berkeley and CU Boulder slow pseudo-dynamic test data. In both cases, the structure will be loaded in a quasi-static fashion with three actuators at the floor levels (Figure 4). As the GT site is not a NEES ES at this point, a NEES POP machine will be purchased and installed at the GT site. These tests will serve to assess the efficiency of quasi-static tests versus the more advanced techniques in the new NEES ES.

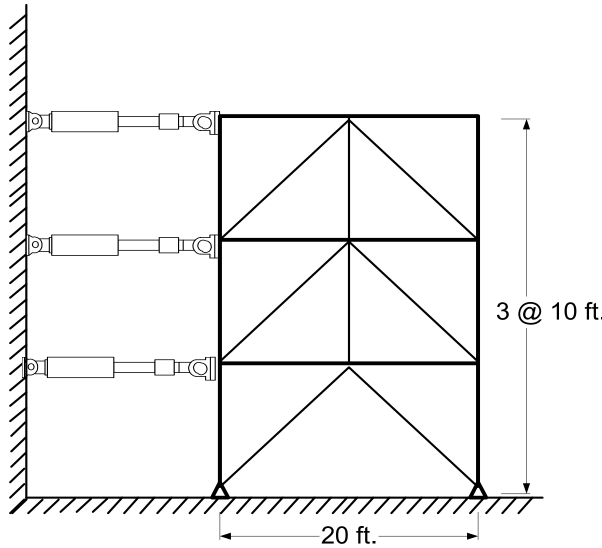


Figure 4 - Proposed prototype structure

The analytical work at GT is well underway, using ABAQUS, OpenSEES and SAP2000. A proposal on a similar set of tests (but including testing of SMA elements) was submitted to NSF by the GT team last year. Although the proposal obtained good reviews, it was not funded. However, the PIs have continued to explore the feasibility of zipper frames with an unfunded student, with the result that much of the preliminary analytical work for this project has been completed.

6. University at Buffalo

The University at Buffalo work will focus on the development of a complete model of the structural systems, intended to provide results on the behavior of the full structure assembly with and without the special energy dissipating elements, as well as corresponding table motions that will be used as input for the fast hybrid tests to be conducted at UC-Berkeley and University of Colorado and story displacements that will be used as input in the second test at Georgia Tech. The following steps will be required to provide these outcomes:

(a) Preliminary design of the full scale specimens: The specific characteristics and scale of a specimen to be subjected to shake table testing are obviously dictated in part by the desired performance objectives for the project at hand, and by the experimental constraints due to the equipment, sensors, and overall testing environment. An additional complexity exist in this project in that part of the results have to be used directly by three other investigators located in three different universities. This additional coordination introduces a few cycles of design iterations.

The basic concept to be considered uses a modular reconfigurable structural frame system (developed as part of another recent project that required inelastic structures for the study of fragility of steel frame buildings (Kusumastuti, 2003)) which provides for a most convenient framework within which the sacrificial elements can be introduced. This modular system consists of separate lateral load resisting frames, doubled hinged gravity load-resisting columns, and steel floor plates (Fig. 5). The lateral load resisting frames are attached to the floors supported by the gravity columns through side connections which allow for free deformations of the frames. The frames are made of removable beams and columns with provisions for attachments of diagonal braces. “Fresh” members can successively replace the components of the frames damaged in a testing sequence. The model is reconfigurable from multiple bays to single bay, producing regular or irregular configurations.

Frames designed and constructed in collaboration with the GT team, as well as the previously described various bracing and zipper–bracing configurations, will be inserted in the three-story configuration of the modular system considered in this project. By using this model, it will be possible to test all specimens (with or without braces) to large inelastic deformations. This design phase includes selection, in collaboration with all partners, of an appropriate standard and common ground motion time history that will allow the structure to exhibit the desired ultimate behavior.

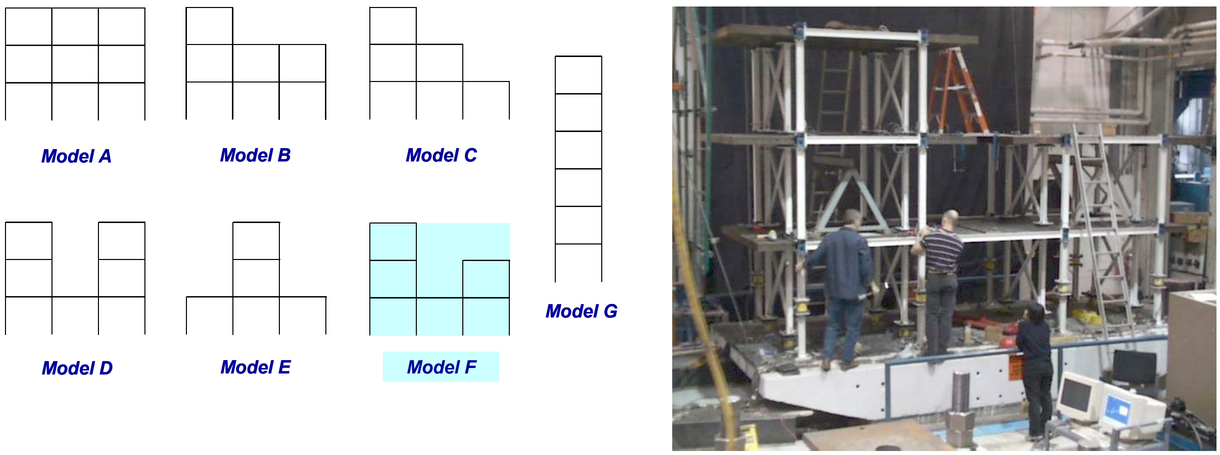


Figure 5: Reconfigurable modular structural system

(b) Typical testing procedure: Three phases of testing are planned for each different specimen to be tested on the shake table. The first phase of testing consists of small amplitude shake table testing, mostly for system identification purposes and performance verification of the instrumentation. Such test will be also repeated after each major test in phases two and three.

In the second phase of testing, the specimen will then be subjected to the selected ground motion, scaled to progressively increasing amplitude (incremental dynamic testing), up to the largest amplitude of response possible at safe operation of the system. As the structure progressively undergoes more severe inelastic excursion for each earthquake excitation, each subsequent test will start with a different state of initial residual deformations (and inherent residual forces locked into the system). Therefore, this series of tests, while conventional for shake table testing, could make coordination with the other sites difficult, as replication of the entire suite of time-histories might be required to properly capture the progression of inelastic behavior, with the inherent drawback of accumulated numerical errors and solution discrepancies between the experimental solutions at the various laboratories. To overcome this limitation, for the third phase of testing, the few selected structural elements that will have been designed to contain all inelastic deformations for this frame will be removed and replaced with new virgin members, and the final test of the last series (i.e. the test with largest amplitude of response) will be repeated, albeit this time without initial residual deformations/forces.

In the third phase of testing, all results will be distributed in real-time to the other equipment sites. On one hand, this will provide a measure of the network latency and of the fluctuation in regularity of data streams. This data could be stored at the remote sites for later use, or attempted to be used in near-real time if network latency and irregularity is found to be manageable. This decision is dependent on the observed throughput rates that will be observed. On the other hand, the Buffalo tests will provide the benchmark data required for the fast hybrid tests, slow pseudo-dynamic tests, and quasi-static tests, to be conducted at Berkeley, Boulder, and Georgia Tech, respectively. Table motions from these tests will be used as input for the fast hybrid tests. Structural displacements and forces will be used for the other tests. Note that while only input from the third phase will constitute the “official” data set per which other tests will be calibrated, data from all tests in the second phase of testing will also be streamed, for the sake of analysis the network capacities and better planning of the important third phase tests. Moreover, the data from phase two will serve as the basis for refinement of the analytical models at all sites for their further use in the hybrid tests.

The following tasks will be also accomplished by the University at Buffalo team:

1. Joint development of models of the frame assembly and ductile components to be tested, in collaboration with Georgia Tech, also accounting for data generated by (and needed for) the UCB and CU single component tests.
2. Planning, calibration, and integration into the networking platform of the instrumentation protocols for monitoring cyclic inelastic behavior of braces and zipper members.
3. Monitoring global and local structural behavior in real-time, with simultaneous transmission of information to the project partners. Package the information for archival and latter use of displacement histories of frames by GT and of base motions for use by UCB and CU in hybrid testing.
4. Post-processing of data and discovery of actual system behavior, in collaboration with other project partners, using the available GRID tools, and comparison with results expected per the proposed design concepts.
5. Re-analysis of system model and adjustments to analytical computational cyclic inelastic models as new data is progressively collected, using OpenSEES, ABAQUS, and other in-house software (IDARC-3D).
6. Formulation of capacity design procedures for zipper and suspended-zipper brace configurations, for submission and possible integration into the seismic design provisions of the BSSC/NEHRP and AISC Seismic Provisions for Structural Steel Building, in collaboration with Georgia Tech.

7. University of California at Berkeley

The University of California, Berkeley (UCB) NEES Equipment Site is uniquely equipped to conduct multiply-substructured pseudo-dynamic tests at rates ranging from slow to real-time. The pseudo-dynamic test algorithms for such tests are implemented using an event-based controller strategy suitable for controlling multiple processes running at different rates and handling random amounts of time delay. As such, the UCB lab is uniquely equipped to conduct geographically distributed hybrid simulation in cooperatation with other NEES equipment sites and laboratories not directly involved in the NEES building effort.

UC Berkeley work on the proposed zipper-frame concepts focuses on the application of NEES hybrid simulation methods to: (a) verify the analytical assumptions about brace and memory shape allow component behavior, used to design the structural system; and (b) examine the interaction of structural components in the zipper-frame structure to verify the fundamental design assumption on simultaneous spreading of inelastic deformation. Facilities of the nees@berkeley NEES Equipment Site will be fully utilized to achieve these two goals. In particular, the ability of the nees@berkeley laboratory to conduct geographically distributed multiply-substructured as well as conventional pseudo-dynamic testing will be used. The following tasks will be accomplished by the UC Berkeley Principal Investigators and a Graduate Student Researcher with assistance from an undergraduate student:

1. Development of the model for simulating the hybrid simulation tests. A conventional analytical model of the zipper-frame structure will be developed in cooperation with GT and other participants. This model will then be incorporated into the analytical model of the nees@Berkeley laboratory. The simulation-of-simulation model involves the tested structure, the dynamic model of the hydraulic and control systems, and the dynamic model of the reaction wall and floor and enables complete analytical simulation of the planned tests.
2. Evaluation and tuning of pseudo-dynamic test algorithms. An existing test setup, used to test buckling-restrained braces, will be used to do sub-structured pseudo-dynamic tests of individual zipper-frame structural element that are expected to behave in an inelastic manner (braces) or dissipate energy (memory-shape alloy elements). In addition to fulfilling the first structural test objective (verification of the analytical assumptions), these tests will be conducted using different integration algorithms and at different rates to evaluate the errors induced by the inelastic behavior of critical structural elements, to evaluate the ability of the pseudo-dynamic test algorithms implemented at the UC Berkeley NEES laboratory to handle sudden stiffness changes, and choose an optimal testing algorithm for the next test phase.
3. Geographically-distributed hybrid simulation. This task will be done in close cooperation with CU Boulder NEES laboratory, following the same test phases in parallel and using the same test setup. First, analytical-only simulations will be done to verify the function of NEESgrid and individual laboratories and their ability to communicate data during a geographically distributed test. Second, identical elastic and inelastic tests on a single-story model will be conducted to compare results with CU Boulder. The same test specimen, shown in

Fig. 6, will be used. Identical tests, using the same algorithms and rates in two laboratories will serve to directly compare the results. Tests using different rates and algorithms will be used to further verify the ability of the laboratories to conduct pseudo-dynamic testing. Third, geographically distributed hybrid simulation of the three-story structure will be done. The two single-story sub-structures at UC Berkeley and UC Boulder will be used to model two lower stories of the three-story zipper-frame prototype, where inelastic action is expected, while the third (top) story will be modeled analytically. Elastic simulations will be conducted first to estimate the delays in NEESgrid connection between UC Berkeley and UC Boulder. An inelastic test will be conducted next to simulate the response of the zipper-frame to the same ground motion used at Buffalo and provide input for the quasi-static test at GT. In addition to fulfilling the second structural test objective (examining the interaction of structural components), these tests will serve to compare the accuracy of essentially identical tests conducted at different NEES laboratories and to demonstrate the viability of geographically distributed testing. Results from the University of Buffalo shaking table tests will be used to verify the accuracy of the conducted tests. Finally, a cooperative test involving a slow pseudo-dynamic test at UC Berkeley and a quasi-static test at GT, with the UC Berkeley test providing live displacement commands for the GT test, will be conducted. Three single-story sub-assemblies and the associated lateral stabilization and fixed-frame-of-reference measurement structures will be used in this task.

4. Analysis and comparison of results of various hybrid simulation tests. These comparisons will be conducted jointly with other participants in order to evaluate the accuracy of developed pseudo-dynamic testing algorithms, and effectiveness of different hybrid simulation methods used in this project, and, most important, the ability to perform geographically distributed pseudo-dynamic testing using the NEES infrastructure.

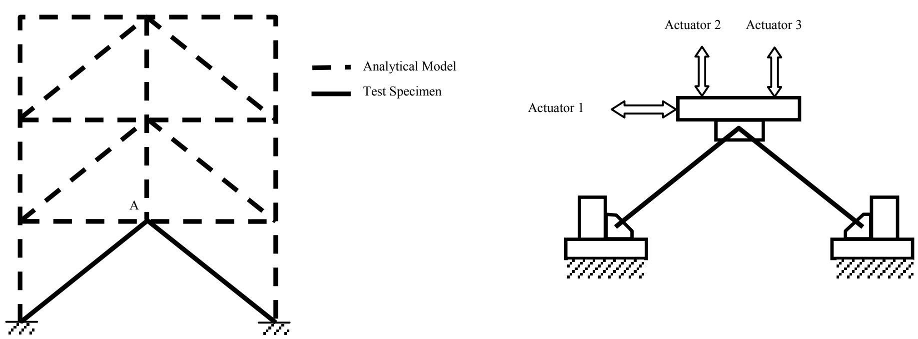
8. University of Colorado

The Fast Hybrid Test (FHT) system at the University of Colorado at Boulder (CU) is based on the pseudodynamic test concept, with which the dynamic behavior of the test structure is simulated in a computer by solving the equations of motion during the test using the structural restoring forces measured from the structural specimen. Since the inertia effect is simulated, a pseudodynamic test can be carried out at a very slow rate. The FHT system is an improvement over the conventional pseudodynamic test method by having the rate of loading approaching the real-time response of a structure in an earthquake. Furthermore, the FHT system allows the testing of a critical structural component or subassemblage with the rest of the structure modeled in a computer, the testing of multiple structural components and subassemblages of a single structure in geographically distributed laboratories that are linked by a single simulation program through the Internet. The latter application is an extension of the substructuring method and is referred to as multi-site tests in this proposal. Hence, the FHT system combines physical testing and model-based simulation in a flexible manner for an efficient and realistic evaluation of the seismic performance of a structural system. The work to be conducted at CU is to demonstrate these salient features of the system for the evaluation of the seismic performance of a zipper frame. For the tests to be conducted at CU, a three-story zipper frame identical to those tested in the other laboratories will be considered. However, instead of testing the entire frame, only the two braces at the bottom-story will be tested while the rest of the structure will be modeled in a computer as shown in Fig. 6. The test setup is shown in Fig. 6b. A set of three dynamic actuators will be used to control the two translational and one rotational degrees of freedom at the connecting node (node A) of the braces. The displacement compatibility and force equilibrium between the experimental and analytical substructures will be enforced in the computer model. The equations of motion for the three-story frame will be formulated and solved in real time during a test using appropriate ground motion histories including those obtained from the shake table tests conducted at the University at Buffalo. The displacements computed at node A will be imposed on the specimen by the actuators, and the restoring forces measured will be fed back to the analytical model and used to compute the response in the next step.

For analytical substructure modeling, the program OpenSEES will be used. The program will be run in a real-time environment in a target PC, which will communicate with the actuator controller via a high-speed shared memory network. Hence, the previous experience of the Georgia Tech team in the analysis of zipper frames with OpenSEES will greatly benefit this task.

The proposed tests provide an efficient means to evaluate the performance of individual braces in a zipper frame as well as the impact of individual brace behavior on the performance of the frame as a whole. Such tests are especially suited for evaluating the effectiveness of innovation energy-dissipation devices in enhancing the seismic performance of steel braced frames. Four series of tests are proposed here.

- The first series will use small amplitude ground motions so that all structural elements including the two bracing specimens will remain linearly elastic. The purpose of these tests is to validate the testing procedure. Results of these tests will be compared to those obtained from purely numerical simulations as well as results from UCB, where similar tests will be conducted.
- In the second series, validation tests will be conducted with the structure subjected to strong ground motions. The bracing elements are expected to buckle and deform inelastically in these tests. The testing procedure will be validated by comparing to numerical simulations and to results from UCB on similar tests. The system will be tuned to handle the drastic changes in the load resistance of the structure due to brace buckling.
- The third series will use the ground motions obtained from the shake table tests conducted at the University at Buffalo to validate the fast hybrid test procedure with the shake table test results. Once validated, tests will be repeated with different sizes of bracing elements to evaluate the influence of the strength and stiffness of the bracing elements on the performance of a zipper frame.
- In the fourth series, linked multi-site tests will be carried out with UCB. In this series, the bottom story braces will be tested at CU and the second-story braces will be tested at UC-Berkeley (or vice versa) with the structural frame and the braces in the top story modeled analytically in the simulation program. Test information from the two sites will be exchanged via the NEESgrid. The structural restoring forces measured at individual sites will be fed back to the simulation program run at CU or UCB, which will in turn generate displacement commands for the local site as well as the remote site. Because of the limitation of the Internet speed and possible network latency, it is expected that such tests can only be carried out at a loading rate lower than that in a single-site test. The purpose of these tests is, however, to demonstrate the multi-site testing capabilities of the two NEES facilities and calibrate the performance of the NEESgrid in terms of bandwidth and data transmission rate.



(a) Analytical and Experimental Substructures (b) Test Setup

Figure 6 – Fast Hybrid Tests at the University of Colorado

MANAGEMENT OF PROPOSED RESEARCH

The team consists of eight PIs from five different institutions. The Lead P.I. is Dr. Roberto Leon, P.E., Professor and Interim Chair of the School of Civil & Environmental Engineering at Georgia Tech. His research interests center on dynamic behavior and design of structures with partially-restrained composite connections, bond of reinforcement under cyclic loads, and testing of full-scale and model structures in the laboratory, and field instrumentation of structures. Among his many professional activities, he is chairman of the Building Seismic Safety Council (BSSC) TS11 – Composite Construction in Steel and Concrete, of the American Institute of Steel Construction (AISC) TC-5 Composite Design, and a member of the AISC Specification Committee.

Dr. Leon, with two graduate research assistants, will coordinate all project tasks. The project intends to use the numerous collaborative tools provided by the NEESGrid to conduct web-based project meetings on a bi-weekly basis throughout the project. NEESgrid is envisioned as a distributed virtual laboratory for earthquake experimentation and simulation. Its integrated tools will enable earthquake engineering simulation -- both physically