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PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 04-23

NSF 06-504 **01/25/06**

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TITLE OF PROPOSED PROJECT **NEESR II; SYSTEM BEHAVIOR FACTORS FOR COMPOSITE AND MIXED STRUCTURAL SYSTEMS**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ **374,998**	**36** months	**10/01/06**	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW
☐ BEGINNING INVESTIGATOR (GPG I.A)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.B, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ____________
☐ HUMAN SUBJECTS (GPG II.D.6)
Exemption Subsection ____________ or IRB App. Date ____________
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____
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

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Civil and Environmental Engineering

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CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-23. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix C of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix D of the Grant Proposal Guide.

Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME		

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

Project Summary

This proposal intends to develop system performance factors (R, C_d, and W_o) for composite frame structural systems and to provide practical guidelines for the analysis and design of such structures. The project will develop advanced computational models to (a) conduct parametric studies on composite frames to develop rational systems factors and (b) develop simplified recommendations for the equivalent rigidities to be used for composite beam-column elements and their connections in braced and unbraced mixed and composite frames subjected to large cyclic drifts. The project will use the NEES MAST Facility at the University of Minnesota to test a series of 20 full-scale slender composite beam-columns in order to develop data on the evolution of the stiffness and strength of these elements when subjected to large lateral displacements. This data will fill gaps in our current databases and provide a unique series of well-controlled tests to allow for the calibration of advanced, fiber-based analytical models for composite beam-columns. In addition, experimental data will be collected on the behavior and performance of connections of composite beam-columns to beams and foundations in order to calibrate component models. The main deliverables will be two-fold: (a) a series of design recommendations formatted in code language for direct incorporation into the revised structural system tables being developed for the 2010/11 cycle of ASCE 7 and the AISC *Seismic Provisions*, along with design examples to illustrate and clarify their applicability; and (b) a detailed description of the advanced models developed that will help researchers pursue similar studies for other composite and mixed structural systems.

Intellectual Merit

The proposal addresses directly Basic Research Needs #1 (development of rational elastic design parameters), #4 (connections to column bases), #12 (use of high strength steel), #19 (mixed and composite structures), #22 and #23 (composite columns) in the BSSC Research Needs document referenced in this solicitation. The project will provide a unique set of data to verify advanced analytical models and provide support for the development of both simplified and advanced analysis techniques for composite and mixed structures. Some of the more challenging experimental and computational tasks to be solved as part of this work include development of models for the progressive cyclic deterioration of strength and stiffness of beam-columns and their connections within composite frames, the effect of long-term effects such as creep and shrinkage, the force transfer along the composite interface and at column bases and connections, and the necessary instrumentation to discriminate between the many mechanisms of strength, stiffness, and deformation capacity that will be necessary to properly understand the behavior of composite beam-columns systems.

Broader Impact

The results of this project will be in a format that can be directly incorporated into design codes and will span a wide range of material properties (3 ksi < f'_c < 15 ksi and 36 ksi < F_y < 80 ksi), a range of material strengths that is not currently contemplated by design specifications. The objective is to encourage the use of composite systems in buildings in the 5 to 20 story range in areas of low, moderate, and high seismicity. In addition, the project will interface with the FACES/AGEP project at Georgia Tech to provide minority undergraduates with research experience and involve two very young faculty members at predominantly undergraduate institutions into the research project. The impact of the research is assured by the leadership provided by the two senior investigators on the pertinent AISC and BSSC Committees. Finally, the project will provide preliminary guidelines suitable for being adapted to the upgrading of existing structures through the use of external confinement (FRP and similar) for encased sections and infilling with lightweight cementatious materials for hollow structural sections.

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Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

D. PROJECT DESCRIPTION

1. PROJECT TEAM

Table 1. Project Participants

Name and Title	**Affiliation**	**Expertise**	**Role in Project**	**Time Commitment (mos./year)**
Roberto T. Leon ***Professor*** ***Principal Investigator***	School of Civil and Environ. Engineering The Georgia Institute of Technology Atlanta, GA 30332-0355	Seismic behavior and design of steel and composite steel/concrete structures; large-scale experimental testing; performance-based earthquake engineering; development of building code provisions. Member of the AISC Specification Committee and technical committees (TC) including AISC TC5 – Composite Structures, AISC TC9 – Seismic Design, and BSSC TS6 – Steel and Composite Structures.	Project coordination (PI); planning, design, and execution of experimental tests; development of design recommendations; interaction with FACES/AGEP project; project website; education and outreach activities.	0.5-0.5-0.5
Jerome F. Hajjar, ***Professor*** ***Co-Principal Investigator***	Department of Civil and Environ. Engineering University of Illinois at Urbana-Champaign Urbana, IL 61801-2352	Computational analysis, experimental testing, and design of steel and composite steel/concrete structures; performance-based earthquake engineering; development of building code provisions. Member of the AISC Specification Committee and technical committees (TC) including AISC TC3 – Loads, Analysis, and Systems, AISC TC5 – Composite Structures, AISC TC9 – Seismic Design, and BSSC TS6 – Steel and Composite Structures.	Development of computational models for composite structures; prediction of specimen response; development of design recommendations and examples	0.25-0.25-0.30

2. RESOURCES AT NEES EQUIPMENT SITES

Table 2. NEES Site and Other Experimental Facilities Used

Site	Special Requirements	Time
NEES Multi-Axial Subassemblage (MAST) Large-Scale Testing System at the University of Minnesota (UMN)	None envisioned; tests will be very similar to those envisioned in original MAST proposal	6 months, in two periods of three months, the first starting approximately May 2007 and the second starting approximately February 2008

The investigators have both worked at the University of Minnesota and are very familiar with the personnel and equipment there. The co-principal investigator spearheaded the development of the IT infrastructure through August 2005. This proposal has been discussed with both the Operations Manager and the Principal Investigator of the MAST Laboratory.

3. INTRODUCTION

Composite columns, in the form of either encased shapes (steel reinforced concrete, or SRCs, as seen in Figs. 1 and 2) or concrete-filled steel tubes (CFTs), have demonstrated in past earthquakes and through careful analytical and experimental studies that they are robust, tough, and ductile structural members [1-8]. Composite construction exploits the synergistic action in a single structural member of steel in tension and shear and concrete in compression. Additional constructional advantages accrue from the fact that concrete has relatively low material costs, good fire resistance, and is easy to place, while the steel offers high ductility, toughness, and high strength-to-weight and stiffness-to-weight ratios [9].

Figure 1- Composite column in which steel section is used mainly for carrying construction loads (low reinforcement ratio).

Figure 2- Composite column in which steel section provides most of the strength and stiffness (high reinforcement ratio).

Composite columns are very common in low- to high-rise construction in Japan and China, where they constitute the majority of the vertical members in modern braced and unbraced frames. Since often most or all the columns in a given floor are used in the lateral-resistance systems in those countries, this results in structural systems with great redundancy, with approximately equal biaxial resistance, and without significant eccentricities in either plan or elevation. Composite columns have also been used in many high-rise construction areas such as Hong Kong, Singapore, Seattle, and the Gulf coast of the U.S. to limit drifts and accelerations due to hurricane/typhoon winds [10-14]. In these cases, the SRC columns consist of a steel section used for construction and later embedded in concrete with significant additional steel bar reinforcement used, often as part of mixed systems (e.g., composite columns with steel girders, see Fig. 1), and the CFT columns consist of a large, thin steel tube (often much larger and thinner than ever tested as a CFT) filled with normal or high strength concrete.

As new areas of the U.S. are reclassified to higher design accelerations and the need to limit non-structural damage becomes more important, replacement of more congested concrete columns and more flexible steel columns with composite columns is a clear solution. In this case the steel column would play a more dominant role (Fig. 2) and will form part of a mixed structural system. Use of composite and mixed systems in low to moderate height construction (3 to 20 stories) in seismic areas of the U.S. is less common than in Japan and China. The primary reason for the lack of use of composite columns in the U.S. is that while current American and foreign design codes [15-23] allow their use, there are major gaps in the provisions due to lack of targeted/coordinated prior research on composite columns and frames using U.S construction practices, and there is little data available to justify the structural system factors (e.g., R, C_d, and Ω_o) given in the specifications. Two examples of areas where much additional work and synthesis are needed are:

- From a practical standpoint, the designer of a composite frame does not have guidance on how to calculate the equivalent stiffness (EI_{eq}), deformation capacity, and ultimate/residual strength of composite members. These quantities are needed to compute realistic interstory drift values, to properly assess the reliability of any proposed design procedure, and to ensure the stability of the system during and after a major seismic event (i.e., its capacity to carry gravity loads). Currently designers will typically default to the EI_{eq} and strength values for similar reinforced concrete columns as given in ACI 318 (ACI, 2005) because this is the only document providing some explicit, recommendations in this area. As the resulting analysis is that for a reinforced concrete structure, the performance advantages of composite columns are not recognized.
- From a more fundamental standpoint, there are a number of issues that still need to be carefully investigated. For example, there is insufficient guidance on how to assess bond in the presence of combined cyclic shear and tension along the steel-concrete interfaces. PCI [16] and ACI [17] provide the only relevant anchorage provisions for combined stresses, with a focus on reinforced, prestressed or precast concrete, but they are not as relevant for the steel-concrete interfaces of composite columns and connections. Advanced computational work is especially needed in this area to permit the development of efficient and economical connection details.

This proposal intends to 1) determine improved system response factors (R, C_d, Ω_o) for composite systems; (2) develop comprehensive guidelines for the calculation of equivalent composite column stiffness to be used in simplified seismic analysis and design of composite braced and unbraced frames; and (3) substantially upgrade the computational models available for analyzing complete composite systems by developing formulations suitable for connection modeling to complement prior research on beam-column models. These objectives will be attained through the use of the advanced testing and data acquisition facilities at the NEES MAST Laboratory at the University of Minnesota, which will permit for the first time the comprehensive testing of a wide range of composite beam-columns subjected to three-dimensional (3D) loading at a realistic scale. The MAST configuration, moreover, makes the testing of numerous specimens possible at a very economical cost. In addition to the testing of the beam-columns, significant experimental and analytical effort will be dedicated to the development of component models for connections between beams and columns and columns and foundations. The testing will be complemented by advanced computational research aimed at developing, calibrating and validating models for the evolution of the damage of composite frames under large random cyclic loads.

The project is unique in at least three aspects. The first is that it couples the scientific and practical aspects of an important and challenging problem through a program that is only possible because of the new NEES facilities. The MAST system makes possible the economical 3D testing of complex beam-columns and connection elements and the available instrumentation means that a carefully coordinated set of tests will provide sufficient data for the calibration of robust, high fidelity computational models suitable for analyzing complete 3D composite frames. The second aspect is that the results of this research will have immediate practical impact on U.S. construction, as attested by the strong support from both industry and designers. The latter is particularly important as this research intends to develop recommendations for the synergistic use of high-strength and other advanced materials in composite construction. Strong industry input in the form of a Designer Advisory Panel (DAP) that will be formed to advise this project, and the Research Committee of the American Institute of Steel Construction, which will help guide this work. The third unique aspect is that the products of this project will be directly applicable to design and the intent is to have them ready by the time the next round of U.S. composite seismic codes is completed (thus, the data will need to be ready by the middle of 2008 if the deadlines for the 2010 codes are to be met).

The overall objective of the project is to facilitate the use of composite systems in buildings in the 5 to 20 story range in areas of low, moderate, and high seismicity. This project intends to utilize the large amount of data on composite columns and beam-columns developed in the US-Japan Cooperative Research Program in the 1990's [1, 2, 5, 8], as well as related research conducted over the last twenty years (e.g., as summarized in part in Hajjar [9, 51]), and which has never been properly synthesized for use of U.S. designers. The project counts on strong financial backing from the American Institute of Steel Construction (AISC, see attached letter) and materials donations from the Technical Committee on Structural Shapes (TCSS).

4. INTELLECTUAL MERIT

This proposal intends to develop system performance factors (R, C_d, and Ω_o) for composite frame structural systems and to provide practical guidelines for the analysis and design of such structures. Currently such structural systems have been arbitrarily assigned response parameters based on a perceived equivalence to either concrete or steel systems, with little data or no data to assess the rationality of these values. The project will develop advanced computational models to (a) conduct parametric studies on composite frames to develop rational systems factors and (b) develop simplified recommendations for the equivalent rigidities to be used for composite beam-column elements and their connections in braced and unbraced mixed and composite frames subjected to large cyclic drifts. The proposed work addresses directly Basic Research Needs #1 (development of rational elastic design parameters), #4 (connections to column bases), #12 (use of high strength steel), #19 (mixed and composite structures), #22 (response of slender SRC beam-columns with high strength concrete), and #23 (CFT members and connections with high strength concrete and steel) in the BSSC *Research Needs* document referenced in this solicitation. The project will provide a unique set of data to verify advanced computational models and provide support for the development of both simplified and advanced analysis techniques for composite and mixed structures. There are very challenging experimental and analytical tasks to be solved as part of this work, including development of models for the progressive cyclic deterioration of strength and stiffness of beam-columns and connections within composite frames, the effect of long-term effects such as creep and shrinkage, the force transfer along the composite interface and at column bases and connections, and the necessary instrumentation to discriminate between the many mechanisms of strength, stiffness, and deformation capacity that will be necessary to properly understand the behavior of composite beam-column systems.

5. BROADER IMPACT

These recommendations will be in a format that can be directly incorporated into design codes and will span a wide range of material properties (3 ksi < f'_c < 15 ksi and 36 ksi < F_y < 80 ksi); high strength materials are currently not contemplated within current design specifications. The impact of the research on design codes is assured by the leadership provided by the two investigators on the pertinent AISC and BSSC Committees. In addition, the project will interface with the FACES/AGEP project at Georgia Tech to provide minority undergraduates with research experience and involve two very young faculty members at predominantly undergraduate institutions into the research project. Finally, the project will provide preliminary guidelines suitable for being adapted to the upgrading of existing structures through the use of external confinement (FRP and similar) for encased sections and infilling with lightweight cementitious materials for hollow structural sections.

6. BACKGROUND

The new AISC 2005 Specification [19] contains substantial changes from previous editions in Chapter I – Composite Construction for non-seismic design. The overall goals of the new provisions were two-fold:

1. To develop a design procedure for composite beam-columns that provided a seamless transition from a typical reinforced concrete column [17] to a steel one [18-19]. The new provisions allow for the

design of a composite column with reinforcement ratios based on the area of the steel section ranging from 1% to a practical upper limit in the vicinity of 16-18%.

2. To improve and modernize the AISC composite column provisions. An example of the radical changes brought in by the new provisions is the considerable liberalization of the width-to-thickness ratios for CFTs, which now reflect more reasonably the stiffening effect of the concrete infill, and almost doubled the local buckling limits on tubes.

The former non-seismic design provisions for composite columns [72] were based on work developed in the 1970s for allowable stress design [24]. They utilize an approach in which the composite column is converted into an equivalent steel one. This approach was logical as the provisions originally intended to address columns with relatively high reinforcement ratios (>4%) and it was necessary to tie their stability design to the established column curves for steel members. At least two limitations of this approach are now clear. First, it has long been recognized that composite members exhibit a different stability curve than all-steel ones. In the process of making composite members "fit" the steel stability curve, distortions were introduced into the design equations in order to make the data fit. Second, this approach has been shown to yield comparatively low reliability indices [25-26], with particularly large dispersions for some types of beam-columns.

The new provisions addressed these shortcomings by first developing comprehensive databases of composite columns test results [25-27, 32] and then utilizing these databases to calibrate new design provisions. The development of these databases required extensive reviews of tests from throughout the world, including close cooperation with leading international researchers in this area (primarily Dr. R. Bergmann from Germany [27], who led the efforts to develop composite column provisions for the Eurocode, and Dr. R. Bridge from Australia [29], who has conducted pioneering work on composite beam-columns and who wrote most associated provisions in the Australian building code). This means that a very significant portion of the background material is already in hand and has been examined thoroughly. Extensive literature reviews on research and practice on composite beam-column, connections, and frames are present in the original reports [30-33], and will not be repeated here for brevity. Only a few citations will be used in this proposal, but bibliographic indices with several hundred citations and many original reports are already in possession of the investigators.

The next code-related effort, which this proposal addresses, is to extend the 2005 AISC composite column provisions [19] to seismic design [18, 20]. Four important points need to be made:

1. The databases used for the development of non-seismic provisions [30, 33] contain numerous cyclic tests, including the complete data set from Japan developed as a result of the preliminary work for the U.S.-Japan Cooperative Research Program on Composite Construction [1, 5, 7, 8]. The principal investigator will spend an extended leave later this year in Japan under the auspices of the Japan Society for the Promotion of Science, and will take that opportunity to update the databases with the most recent work from that part of the world. Thus, database development can be considered to be largely finished and will be completed before this proposal is funded. The investigators are in close contact with leading researchers in Japan, China, Korea, Australia, Canada, Europe, South Africa, and other locations who are working on this topic, and the project will endeavor to work with them to reduce design differences in international codes.

2. Careful descriptions of a number of full-scale tests [34-36] and component tests on composite systems [37-48, 65-68, to name a few] only have just begun to appear in the literature and will provide excellent additional calibration data for this study. There are a number of major differences between such previous work and the test proposed here, including:

    a. Much of the previous work was not conducted on slender members or with large axial loads.

    b. The number of tests in an individual series was too small to properly calibrate advanced models.

c. In many cases the tests were at reduced scale and with local buckling slenderness ratios well below those permitted in CFTs by the new AISC Specification,

d. The details of the connection tests often connections do not accurately represent U.S. practices, particularly for tests conducted outside the U.S.

e. A complete synthesis of all the work for design applications has not been carried out.

3. The mechanistic approach taken in the development of the composite column provisions in AISC 2005 [18-19] and the elimination of any significant differences between the new steel and concrete design procedures mean that the extension to the seismic case can be made without major inconsistencies between design codes. The principal investigator is currently a member of a joint ACI-AISC Task Group aimed at eliminating design differences between codes, and there is considerable interest from both organizations in harmonizing design procedures. Note that currently the ACI seismic provisions do not address composite columns directly.

4. For the case of CFTs, one of the co-investigator has been modeling the cyclic behavior of rectangular concrete-filled steel tubes (RCFTs) for over a decade [49-51]. Recent work has included establishing a comprehensive database of worldwide test results that includes documenting the detailed progression of damage in the tests so as to establish deformation-based and energy-based damage functions that predict the progression of damage within RCFT beam-columns, connections and frames (e.g., concrete cracking, steel yielding, local buckling). Figure 3 shows the results of a parametric study of an energy-based damage index calculated for sixteen RCFT beam-columns with varying geometry and material properties subjected to non-proportional monotonic loading, half having relatively low ductility, and half having relatively high ductility. The graph exhibits the intricate relation in the progression of damage for composite members, e.g., the varying effects of whether yielding in the steel tube tension flange (YTF) occurs before or after local buckling of the steel tube flange (LBF), and the resulting affect on the ductility. Figure 4 shows results of a recently developed comprehensive distributed plasticity mixed fiber-based finite element for RCFT beam-columns, developed in OpenSEES, comparing computed results with measured results from Morino et al. [38]. The specimen consists of a pin-pin RCFT column with girders framing in to three of the four flanges. A monotonic axial compression is applied along with a tip load to one out-of-plane girder. The two in-plane girders are then cycled antisymmetrically. The RCFT is thus subjected to cyclic biaxial flexure plus axial force. The plot, in which the computational and experimental results match well, shows the average shear in the in-plane girders versus the chord rotation of the specimen. This formulation accounts for all significant cyclic phenomena within an RCFT beam-column, including interlayer slip of an arbitrarily oriented 3D beam-column (through separation of the axial degrees-of-freedom in the steel and concrete), concrete cracking, concrete confinement, local buckling, etc. This background will be invaluable to establish new formulations for SRC and CFT connections to enable more comprehensive studies of the progression of damage in complete composite frames composed of SRC or CFT beam-columns. These studies are necessary to determine the structural system factors for composite systems, as well as to assess the validity of the simplified models for use in design. Similar work, but not as refined for the cyclic case, also exists for SRC columns [52-54].

One objective of the research will be the derivation of a simplified, mechanistically based equation for the prediction of the EI_{eq} for composite beam-columns. Statistical analysis of the databases has led to best fit curves such as the ones proposed by Mirza and Tikka [55] for encased sections:

$$EI_{eq} = (0.313 + 0.00334\frac{L}{h} - 0.203\frac{e}{h})\, E_c(I_g - I_{ss}) + 0.729E_sI_s + 0.788E_sI_{sr} \quad (1)$$

where L is the length of the member, h is the dimension perpendicular to the axis of buckling, e is the eccentricity, $\underline{E_c}$ and E_s are the modulus of elasticity of the steel and concrete, and I_g, I_s and I_{sr} are the gross moment of inertia of the entire section, of the steel section, and of the reinforcement bars, respectively. This equation shows the main parameters that influence the buckling behavior of these members, but gives little or no insight into mechanistic behavior. The intent of this project will be to derive equations similar to the current ones for buckling of composite sections in the 2005 AISC Specification [19]:

$$EI_{eff} = E_s I_s + 0.5 E_s I_{sr} + C_1 E_c I_c \tag{2}$$

In which a simple parameter C_1, based on the reinforcement ratio, is used for predicting global behavior.

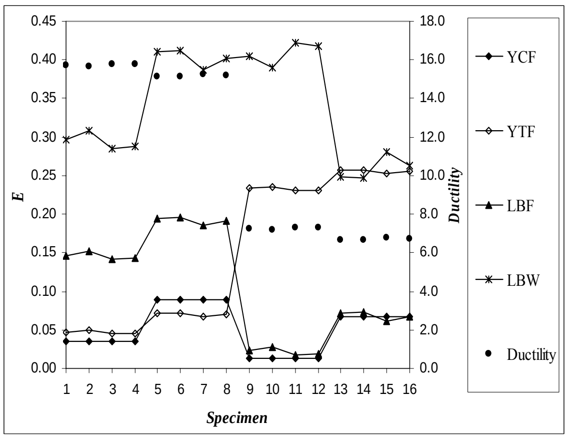

Fig. 3: Comparison of Energy-Based Damage Index for Monotonically-Loaded Beam-Column Tests (after Tort and Hajjar, 2004)

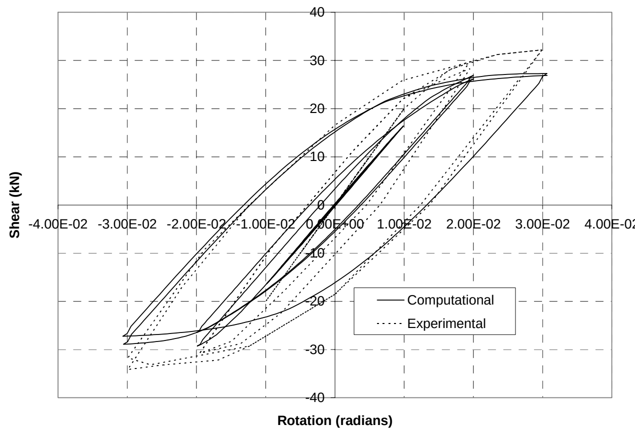

Fig. 4: Comparison of Computational and Experimental Results for Eccentrically-Loaded Beam-Column Tests (after Tort and Hajjar, 2006a)

7. PROPOSED RESEARCH

The research program is divided into 8 tasks:

Task 1: Determination of Pertinent Parameters and Data Gaps: This phase of the project will:

- Utilize the existing databases to extract a subset of representative, well-documented cyclic tests on large-scale composite columns that can be used to ascertain the relevant parameters to be used in their seismic design. The use of genetic algorithms and expert systems is contemplated as part of this effort. The principal investigator has been working with a colleague [56] on applications in this area, particularly on developing connection models, and a companion individual proposal on this topic has been submitted to NEESR. The intent is develop a mock-up of what the final provisions may look like in order to better focus the experimental and analytical work to follow.
- Examine the databases for gaps in test data for combinations of interest in seismic design, i.e., there are insufficient tests of cyclically-loaded large-scale shear-critical circular CFTs with combinations of high strength concrete and steel and thin steel sections, such as have been used numerous times on the west coast of the U.S. [11, 69]. Figure 5 shows a 3D plot of available monotonic tests of SRC beam-columns for different combinations of steel yield stress, concrete strength and total reinforcement ratio [33]. The data shows that majority of the data is for combinations of low concrete and steel strengths. Similar plots will be made for cyclic tests, and their examination may lead to changes in the experimental matrix discussed in Task 3.
- Augment the databases with recent full-scale and component tests that can be used to calibrate and verify the models to be developed.

Task 2: Preliminary Development of Frame Models and Theme Structures: This task will use current design specifications [18-19] to select a series of prototype structural configurations, similar to the theme structures used for the U.S.-Japan Cooperative Research Program [1, 2, 5, 8] and with extensive input from the DAP. These frames will be used in the parametric studies of Task 8 and to determine the validity of the member sizes in the experiments. The emphasis will be on developing a series of composite SRC unbraced frame and CFT braced and unbraced frame structural systems that can compete with traditional steel and concrete frame systems in the 3 to 20 story range. A wide range of geometric and material properties will be used so as to ensure proper breadth in the results for generating system response parameters for these systems in Task 8.

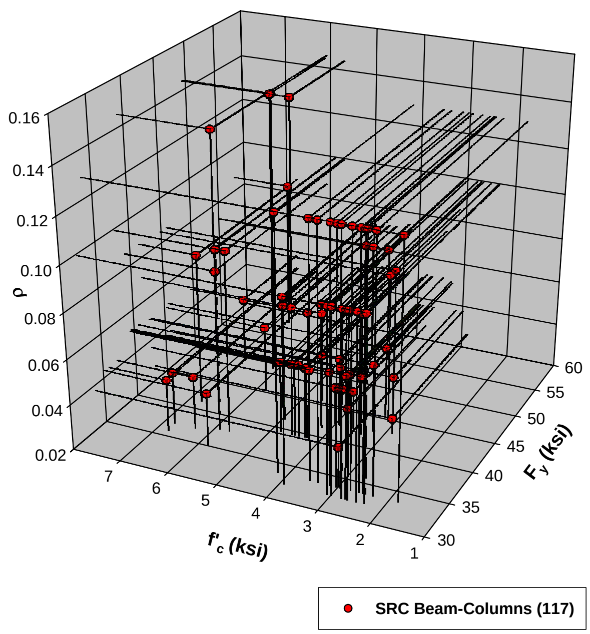

Figure 5 - Scatter plot of data available for SRC beam-columns based material strengths and reinforcement ratios.

A number of important insights will be gained by these studies. Three examples are:

1) The major remaining difference between how AISC [18-19] and ACI [17] treat column design relates to creep and shrinkage effects. In the ACI specification, the equivalent rigidities of a concrete column are considerably reduced by these long term effects. Measurements by the principal investigator [57] and others [e.g., 58] indicated that this may not be so significant for SRC columns with high reinforcement ratios.

2) While there are many possible combinations of material properties to be used in these frames, these studies will narrow the choices to those that seem to provide the beast combination of stiffness and deformation capacity

3) These studies will help assess the likely combinations of shear and bond forces that will arise in practice. This, in turn, will direct the need and level to which such interactions will need to be included in the models.

Task 3: Testing of Encased Sections: A series of eight full-scale encased composite columns will be tested at the MAST facility. Two types of columns, one with a low reinforcement ratio, ρ (representing the case of the steel section being an erection column) and one with a high reinforcement ratio (a column in a low-rise frame, intended to have a high reinforcement ratio) will be tested at two different lengths (slenderness, $\lambda = \sqrt{P_e / P_o}$, where P_e and P_0 are the composite column buckling strength and axial cross section strength, respectively) each (SRC1 through 4). In addition, one specimen of the low reinforcement ratio type will be loaded along the weak axis and one of the high reinforcement ration specimens will be loaded biaxially (SRC5 and 6). Two other specimens will be designed after consideration of the results of Task 1, and are shown as combination of high strength materials in Table 1 (SRC7 and 8).

The sizes in Table 3 were selected as a preliminary matrix of what the investigators intend to test, and are based on (1) preliminary studies which suggest maximum axial loads around the balanced point (or about $0.4P_0$) and (2) the vertical load limitations of the MAST facility. Based primarily on the results of Task 1 and the input of the DAP, it is possible that the specimens will be slightly redesigned.

Table 3 – Preliminary SRC Test Series

Label	Concrete Section	Steel Section	Axis	f'_c (ksi)	F_y (ksi)	Long. Reinf.	Trans. Reinf.	ρ	L (in.)	λ
SRC1	24" x 24"	W10x49	Str	5	50	8#8	#4@12"	2.3	168	1.0
SRC2	24" x 24"	W10x49	Str	5	50	8#8	#4@12 "	2.3	240	2.0
SRC3	16" x 16"	W10x100	Str	5	50	8#6	#4@12"	10.3	168	1.25
SRC4	16" x 16"	W10x100	Str	5	50	8#6	#4@12"	10.3	240	2.50
SRC5	16" x 16"	W10x100	We	5	50	8#6	#4@6"	10.3	168	1.25
SRC6	16" x 16"	W10x100	Bia	5	50	8#6	#4@12"	10.3	240	2.50
SRC7	16" x 16"	W10x100	Str	8	65	8#6	#4@12"	10.3	240	2.50
SRC8	16" x 16"	W10x100	Str	12	65	8#6	#4@12"	10.3	240	2.50

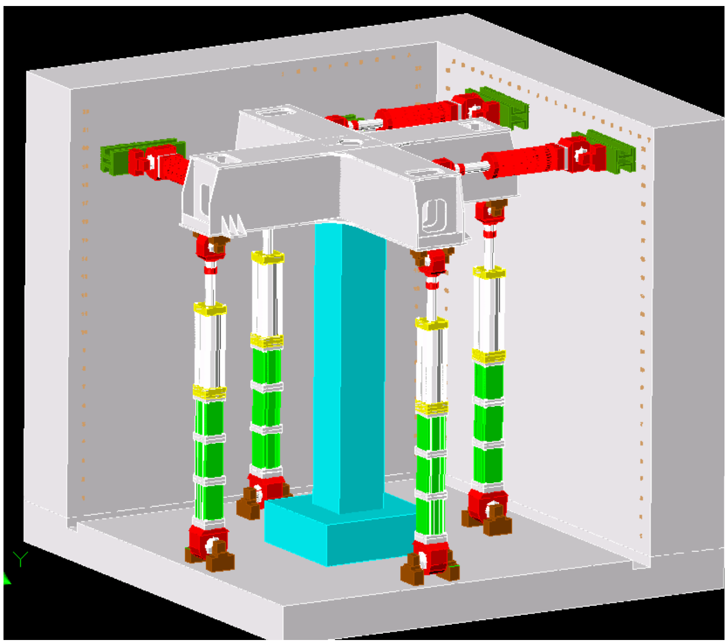

Figure 6 – SRC Column in MAST testing facility

Figure 6 shows the proposed loading scheme for these encased tests. The specimens will be fixed at the bottom into a large, rigid anchor block bolted to the reaction floor to simulate the foundation connection (a variety of connection topologies at the base may be explored with this configuration). The top of the column will be nominally "pinned" by utilizing the 6 DOF of the MAST system to minimize the moment at the top. A 2D pin arrangement will be used at the top, but the large axial loads to be imposed will require slight adjustments of the rotations of the MAST crosshead to reduce frictional forces and keep the moments at the top close to zero. The fixed-pinned arrangement will result in an effective length factor close to 2, allowing slender columns to be tested.

Because of the very large axial capacity of composite columns, it will not be possible to test reasonable size specimens to their design axial load at low eccentricities. Moreover, since the interest is to look at the rigidity of the column at large displacements and under relatively low axial loads, the loading path shown in Fig. 7 will be used. The initial cycles at eccentricities (*e/h*) of 0 (Path A), 0.4 (Path B), and about 0.6 (Path C) will be single cycles to the capacity of the testing machine, the onset of yield in the steel, or strain in the concrete of 0.0.02 to avoid extensive damage. A cyclic test following the AISC Seismic testing protocol to 5% drift (Path D) will be followed by a final test to ultimate bending strength (Path E).

In addition to conventional strain gage and displacement transducers, the specimens will be heavily instrumented using the Krypton system at the MAST Laboratory to measure 3D displacements and thus discern detailed curvature assessments at several cross-sections along the length of the specimen. Two experimental techniques will be used to monitor concrete cracking. The investigators will actively solicit payload projects to validate new techniques of monitoring cracking in concrete.

Task 4: Localized Testing for Force Transfer Mechanisms in Composite Sections: Test data from (a) bond-slip instrumentation used during the main tests and (b) subsequent tests on components will be used in this task to develop component models for connections and foundation behavior. For the latter, a number of connection elements (plates, T-stubs, angles) will be welded and embedded near the top of the encased columns during their construction. In this region, the concrete is expected to remain relatively undamaged after the tests in Task 3. After the beam-column tests are completed, a number of localized test will be conducted on these elements using the ancillary actuators available at MAST. Localized tests on the column bases will also be carried out to provide data to calibrate component models (i.e., models made up of simple springs with nonlinear characteristics, [59]). In the SAC project, the principal investigator demonstrated the validity of such an approach for the design of steel T-stub connections [60]. In other recent work [61], this approach has been extended to column bases and has proven its ability to predict yield and failure mode magnitude and sequence. These models can provide substantial computational savings in modeling connection behavior. Similar approaches have been or are being applied to these components by other researchers [37, 40]

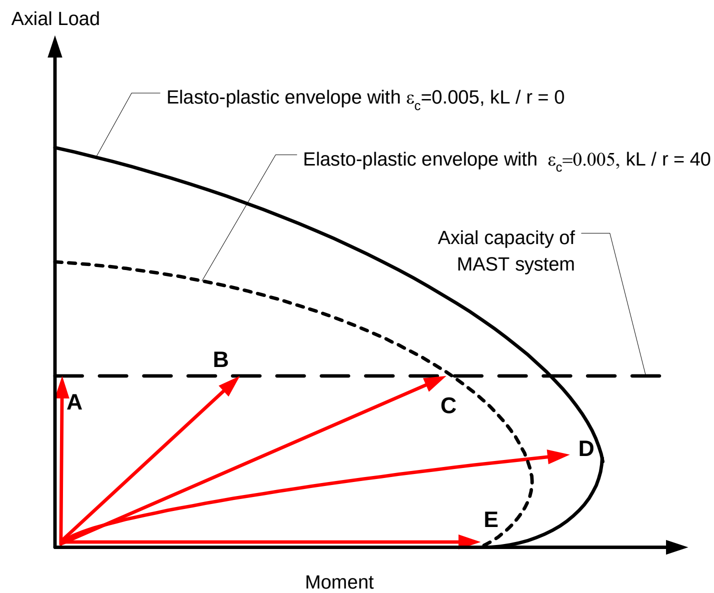

Fig. 7 – Loading paths for composite beam-column specimens.

Task 5: Advanced Cyclic Modeling of Steel Reinforced Concrete Members, Connections and Frames: El-Tawil and Deierlein [52] and Elnashai and Broderick [4] have developed three-dimensional distributed plasticity formulations for SRC beam-columns. This prior research will provide background for adapting a new formulation to be implemented in OpenSEES. The robust constitutive models developed for concrete-filled tubes and introduced in Section 6 will be adopted and recalibrated for SRCs to properly account for concrete cracking, confining effects, differences in stress-strain curves for high-strength materials, interface slip and the resulting affects on force transmission, and large deformations. Fig. 7 shows the constitutive formulations under development for RCFT fiber models [62, 63], based on prior research by Mizuno et al. [6] and Chang and Mander [64] for the steel and concrete, respectively. New components of these models include accounting for local buckling and residual strength after large deformation in the steel, and residual strength, confinement, and robust cycling from tension into compression and back into tension in the concrete. These models are thus comprehensive in scope and may be calibrated for SRC members as needed. In addition, interlayer slip between the steel and concrete will be included similar to the formulation of Tort and Hajjar [62, 63]. This is especially important in the connection region so as to understand the force transfer mechanism between the constituent materials. The bulk of the research will then focus on developing new component-based formulations within OpenSEES for connections between steel girders and SRC columns, as well as accounting for creep and shrinkage where appropriate, particularly within the interlayer slip and confinement components of the formulation [28]. Such formulations have not been developed previously to interface with fiber-based beam-column elements that account for interlayer slip between the steel and concrete in 3D composite frames. Prior experimental research [35, 40] will be used to calibrate the components of the connection model. These elements will be used in parametric frame behavior studies aimed at developing system response factors (R, C_d, and Ω_o) in Task 8.

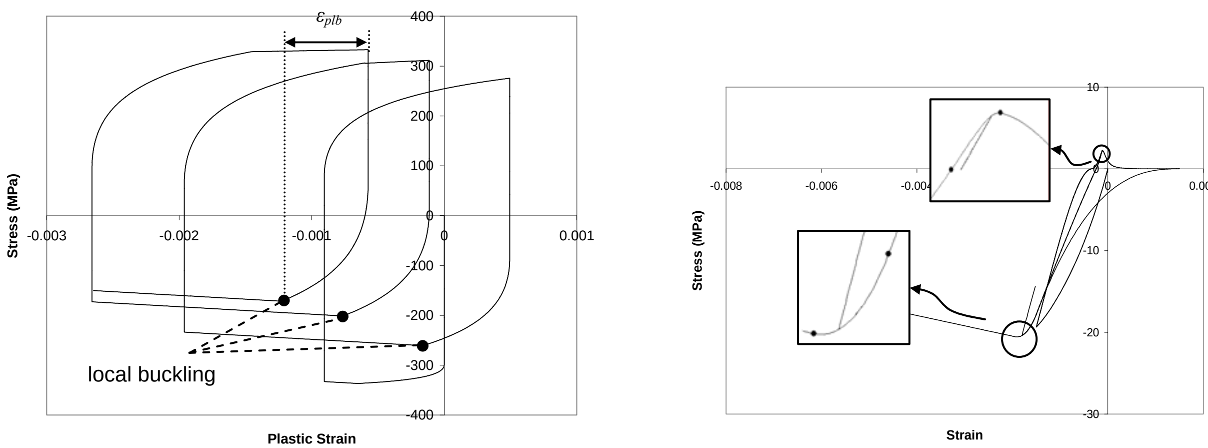

Fig. 7 Steel and Concrete Constitutive Formulations for RCFTs (after [63])

Task 6: Testing of Concrete Filled Rectangular and Circular Tubes: A series of tests on both rectangular and circular concrete-filled tubes will be conducted to develop parallel information to that for encased sections described in Task 3. In these tests the emphasis will be on the use of thin steel tubes (b/t of 50 for rectangular and 90 for circular tubes) and high strength materials. The preliminary test matrix is shown in Table 4. The specimens in this series are somewhat smaller than those for the SRC series so that higher compressive stresses can be reached, an important parameter in the high-strength specimens and for braced frames.

Task 7: Advanced Cyclic Modeling of Concrete-Filled Tube Members, Connections and Frames: The prior research of Tort and Hajjar (2006) on analysis of rectangular CFTs will be adapted to circular CFTs within OpenSEES, accounting for the effects of creep and shrinkage where appropriate within the constitutive formulation [42], to provide a comprehensive scope of analysis capabilities needed to determine system response factors (R, C_d, and Ω_o). In addition, component-based connection models that account for the force transfer between steel girders and CFT beam-columns for both braced and unbraced connections will be developed within OpenSEES. Prior research by Azizinamini and Schneider [48] has documented the force transfer common in circular CFT moment-resisting connections, and prior research in Japan has done similarly for rectangular CFT moment-resisting connections. These behavioral studies will provide a basis for development of the component connection models. These models will be calibrated and verified versus experimental research conducted in the U.S. both for braced [65] and unbraced [45, 46, 48, 66] connections. These elements will be used in parametric frame behavior studies aimed at developing system response factors (R, C_d, and Ω_o).

Task 8: Development of Analysis and Design Recommendations: Based on the results of the computational studies (Tasks 5 and 7), parametric studies to determine simplified expressions for the equivalent rigidities of composite beam-columns will be conducted using the structures designed in Task 2. The effect of different assumptions and the effect of over- and underpredictions of the member stiffness on the system behavior will be studied. This will result in the development of simplified expressions for the equivalent rigidity of composite beam-columns to be used in frame analysis. So as to limit the scope of this research, the intent here is to propose values to be used to capture global behavior (interstory drift, maximum rotational demands, etc.). A large series of parametric studies on the behavior of 3-, 9- and 15-story composite frames in areas ranging from low to high seismicity will be conducted. Following the procedures proposed by BSSC TS2, system behavior factors (R, C_d, and Ω_o) will be developed for the two types of structural systems selected in Task 2. Finally, the project will do preliminary work to prepare to augment these design recommendations for the use of advanced materials and composite action in retrofit of structures, towards identifying potential additional uses of this research, and towards the development of additional innovative composite systems.

Table 4 – Preliminary CFT Test Series

Label	Tube Section	b/t	f'_c (ksi)	F_y (ksi)	L	P_0 (kips)
CCFT1	10 x 0.125(1)	80	5	42	120	472
CCFT2	10 x 0.125	80	5	42	240	472
CCFT3	10 x 0.125	80	12	42	120	1040
CCFT4	10 x 0.125	80	12	42	240	1040
RCFT1	12x12x0.25	48	5	50(2)	120	1030
RCFT2	12x12x0.25	48	5	50	240	1030
RCFT3	12x12x0.25	48	12	50	120	1510
RCFT4	12 x12x0.25	48	12	50	240	1510
RCFT5	14 x 6 x 1/4	56	5	50	240	900
RCFT6	14 x 6 x 1/4	56	12	50	240	1480
RCFT5	14 x 6 x 1/4	56	5	50	240	900
RCFT6	14 x 6 x 1/4	56	12	50	240	1480

8. DELIVERABLES

There will be two main deliverables for this project in addition to the NEES reporting requirements for projects of this type, one for the professional community and one for the research community:

- In close collaboration with the DAP and members of both AISC TC9 and BSSC TS6 on steel and composite seismic design of structures, a design document consisting of proposed code language and four complete design examples illustrating the use of those proposals will be produced.
- A detailed document outlining the development of any new beam-column and connections elements for OpenSEES.

9. INTEGRATED EDUCATION AND OUTREACH PROGRAM

Although the individual investigator nature of this project does not allow for extensive education, outreach, and training efforts, two approaches will be used this project to fulfill these requirements:

a) Undergraduate students will be involved in all phases of the work through the FACES program at Georgia Tech (Drs. Gary Mays and Regnald DesRoches, P.I.s), an AGEP program (see supporting letter in supplemental documents). Facilitating Academic Careers in Engineering and Science (FACES) is a National Science Foundation-sponsored effort between Georgia Tech, Morehouse, Emory University and Spelman College. Its aim is to increase the number of African-Americans attaining doctorates in engineering and science. The ultimate goal of the FACES program is to alter the "face" of the engineering and science professoriate, such that it includes a greater number of African-Americans (http://www.faces.gatech.edu/)

b) Two very young faculty members (assistant professors with less than two years in rank) at predominantly undergraduate or minority institutions, selected in consultation with the AGEP program, will be invited to join the project as full members of the team in order to gain experience and insight into the NEES program and to assist with both the experimental and computational components of the research program.

10. PROJECT IMPLEMENTATION PLAN

Project Team: The project team consists of Dr. Roberto Leon (Georgia Tech) and Dr. Jerome Hajjar (UIUC). At least two Ph.D. students (one at Georgia Tech and one at University of Illinois) and one or two undergraduates at Georgia Tech will be part of the project. Efforts will be made to recruit these students from minority groups. The project team is diverse and comprises a principal investigator from a non-NEES site and a co-principal investigator from a NEES site. In addition, the familiarity of the investigators with NEES Inc. procedures (Dr. Leon led the Site Operations Committee and currently sits on the NEES Board of Directors and Dr. Hajjar has been a key member of its Information Technology Strategy Committee) ensures that all requirements relative to data sharing and shared use will be fulfilled. A Designers Advisory Panel (DAP) made up mostly of design representatives in AISC TC9 (Seismic Design) and BSSC TS6 (Steel and Composite Structures) will help guide the project. In addition, participation from structural shape and tubes manufacturers (TCSS) will ensure that manufacture and fabrication issues are properly addressed.

Project Schedule: The project is scheduled to last three years as shown in Table 5.

Table 5. Proposed Schedule

Tasks	*Year 1*				*Year 2*				*Year 3*			
Determination of Pertinent Parameters and Data Gaps:												
Preliminary Development of Member Models/ Theme Structures:												
Testing of Encased Sections:												
Localized Testing for Force Transfer Mechanisms												
Advanced Modeling of Encased Sections												
Testing of Concrete Filled Rectangular and Circular Tubes												
Modeling of Concrete-Filled Tubes												
Development of Analysis and Design Recommendations												

Management Plan: Dr. Leon will provide the leadership on the experimental research and overall management of the project, while Dr. Hajjar will provide the leadership for the computational research (see also page 1 for a listing of their roles on the project). This team has cooperated very successfully in the past [70-71] and has considerable experience in the testing and analysis of composite elements and systems.

Plan for Experimental Planning: The investigators have extensive experience with large experimental projects involving multiple organizations. In this project, much of the instrumentation will be installed by graduate and undergraduate students at Georgia Tech. Experience with similar projects in the past indicate that cost of shipping may be more than offset by the cost of having the same students instrument while at MAST or having MAST staff perform that task. The specimens and ancillary formwork will be shipped to MAST, where the specimens will be assembled for casting and any external instrumentation support hardware added. The specimens will then be cast and cured for 30 days. The specimens will be in a vertical position and will take up relatively little space. For each of the two runs of testing, there will be two crosshead positions, and a one week period has been set aside for moving the crosshead. It is expected that each test will take about 3 to 4 days from start to finish. The specimens will then be disposed off and proper account has been taken of that in the experimental budget.

Risk Mitigation: The investigators have experience with large projects involving multiple organizations, large-scale testing, and international collaboration. As such, they appreciate the challenges and risks to successful completion of the project. While a formal and detailed risk management plan will be established upon the project award, the primary strategy for risk mitigation will be through (a) careful planning of the research activities, (b) paying careful attention to activities that can be impacted by external factors (e.g., laboratory delays) and are on the critical path, (c) continuous monitoring of our own progress, and (d) effective communication with team members, equipment sites, NEES, Inc, contractors, and others whose work progress will affect the overall project schedule. Budgeting of large tests is another concern. The investigators have been in contact with the MAST Laboratory staff and think an accurate assessment of the testing expenses have been built into the budget. In the event of unforeseen cost over-runs (e.g., larger than expected bids from contractors to build the specimens), there are contingency plans to reduce test specimen sizes and modify the testing scope if necessary.

Use of NEESgrid Resources: NEESgrid resources are integrated into this research and education plan in four fundamental ways: (a) telepresence activities; (b) data sharing and archiving plans as discussed below; (c) education and outreach plans, specifically through the establishment of a public telepresence website; and (d) extensive utilization and model development for the OpenSEES platform, which has been adopted as part of NEESGrid, and use of supercomputer as needed at NEESit.

Data Sharing and Archiving Plan and Dissemination to Earthquake Engineering Community: The MAST Laboratory provides outstanding facilities related to archiving of all sensor data (including resistance strain sensors, displacement and rotation sensors, and 3D deformation data measured by a Krypton LED-based system), video and audio data, and still image data. The investigators have been leaders in advising on the establishment of data models and policies for data curation within NEES (Hajjar sat on both the NEES Information Technology Committee and the NEES Data Sharing and Archiving Committee up until 2005, and is currently the chair-elect of the NEES Information Technology Strategy Committee; Leon is on the NEES Board of Directors and was the chair of the NEES Site Operations Committee from its inception until recently). Leon has already posted most of the data from his pre-NEESR project to the data repository and this project is being used by NEESit as a demonstration project for data archiving. The team will ensure that the data and metadata is posted to the NEES national data repository, consistent with the policies of the NEES, Inc. Staff and student time at the equipment sites have been budgeted for this effort. A similar archiving of OpenSEES data will be executed for all significant structural analyses conducted in this research. Significant findings will be promptly submitted for publication in journals, workshops, seminars and conferences, and comprehensive documentation will be published in report series (such as the proposed NEES electronic journal). Both investigators are currently members of BSSC TS6 and AISC TC9, the committees in charge of developing new seismic design provisions for steel and composite structures, the AISC Specification Committee, and NEES, Inc. committees. Membership in the first three committees ensures that the results of this research will be discussed with a broad cross-section of potential users during their development, and that the implementation of the results remains the primary objective of the research.

11. BUDGETS

The experimental test series proposed herein and the related advanced analyses will be accomplished by leveraging there sources of funding: (1) the NEESR funding from this proposal; (2) research support from the American Institute of Steel Construction (minimum of $50K per year, see attached letter); and in-kind donations of materials from the steel industry (cost of steel is estimated at about $35K). A breakdown of these funds by major category is shown in Table 6 (see next page).

12. RESULTS FROM PRIOR NATIONAL SCIENCE FOUNDATION SUPPORT

Prof. Roberto T. Leon has been funded by the National Science Foundation (CMS-9710238: Three-Dimensional Slab Effects in PR Composite Frames; $253,000 with D. White, 10/97-8/00) and through the MAE Center (CMS-9701785: ST-7-Performance of Rehabilitated Steel Connections; $80,000, 10/97/10/00) for work in the area of steel and composite structures and unreinforced and rehabilitated masonry structures (CMS-9701785: ST-11- Full-Scale Test of a Masonry Structure; $400,000 with L. Kahn; 9/99-10/02). He is the P.I. on a recently awarded pilot NEES project linking Georgia Tech, U. of Buffalo, U. of California at Berkeley, U. of Colorado at Boulder, and Florida State for testing innovative bracing configurations (NSF 0324542 -NEES Collaborative Research; $218,000, 10/03-9/06). He was co-principal investigator in the proposal funding the maintenance and operations of NEES Inc. (NSF 0402490: $12.4M for FY04-05) His work has elucidated the role of floor slabs in providing additional strength and stiffness to low-rise steel buildings, has provided robust and comprehensive strength, ductility and stiffness evaluation for bolted steel connections, and has provided code-type provisions that have been incorporated into both the AISC and NEHRP. Recent relevant publications may be found at http://www.ce.gatech.edu/~rleon/ and in Section E.2.

Prof. Jerome F. Hajjar has been funded by the National Science Foundation to conduct computational, experimental, and design-oriented research on composite-steel concrete structures. In "Three-Dimensional Nonlinear Cyclic Analysis of Concrete-Filled Tube Beam-Columns and Composite Subassemblies" (Hajjar, J. F., CMS-9410473, 9/15/94-8/31/98, $110,000), both a stress-resultant-based concentrated plasticity beam-column finite element formulation and a stress-based distributed plasticity beam-column finite element formulation were developed for rectangular concrete-filled steel tube members subjected to seismic loading as part of complete 3D composite frames. In "Performance Assessment and Performance-Based Design Methodology for Composite Construction with Application to Concrete-Filled Steel Tube Structural Systems" (Hajjar, J. F., CMS-0084848, 9/15/00-8/31/06, $206,142), these formulations were augmented to develop a mixed hybrid distributed plasticity beam-column finite element that captures more robustly and with fewer elements the detailed progression of damage that occurs at the stress-strain level in rectangular CFTs as part of complete 3D composite frames. A comprehensive database of worldwide experimental results on RCFTs was also compiled and damage measures were produced for all relevant limit states of RCFT members, connections, and frames. Details of these projects were discussed in the project description. In "Seismic Behavior of Steel Moment-Resisting Frames with Composite RC Infill Walls," (Schultz, A. E., Hajjar, J. F., and Shield, C. K., CMS-9632506, 9/15/96-8/31/00, $253,896), an experimental and computational research program were executed to study steel moment-resisting frames with composite reinforced concrete infill walls subjected to seismic excitation. A one-third scale frame was tested quasi-statically to determine the cyclic behavior of steel frame-RC infill composite wall systems. Twelve full-scale cyclic shear specimens, comprised of steel wide-flange sections connected with shear studs to a concrete panel, were tested to quantify the strength of stud connections under cyclic shear and axial tension. Data analysis coupled with linear and nonlinear system analyses and prototype structure design served to establish preliminary analysis and design recommendations, including recommendations for the system response factors for this structural system. Two Ph.D. students and eight M.S. students were graduated on these projects. Selected references are in Section E.2.

Table 6. Functional Budget

	NSF			AISC + TCSS			
Item	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Total
Experimental Research	$45,670	$67,490	$53,890	$40,000	$45,000	$25,000	$277,050
Non-Experimental Research	$52,450	$32,670	$42,380	$15,000	$23,000	$3,000	$168,500
Education and Outreach	$24,880	$21,260	$17,450	$10,000	$5,000	$18,000	$96,590
Data Archiving/Sharing	$2,000	$3,580	$11,280	$0	$2,000	$4,000	$22,860
Total	$125,000	$125,000	$125,000	$65,000	$75,000	$50,000	$565,000
Notes: Total corresponds to $375K from NSF and $50K from AISC per year, plus $15K in the first year And $20K in the second year in in-kind material donations from TCSS and tube manufacturers							

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E.2 SELECTED REFERENCES FROM RESULTS FROM PRIOR NSF RESEARCH

R. T. Leon

Refereed Journal Publications

1. Rassati, G. A., Leon, R. T. and Noe, S., (2004). Component Modeling of Partially Restrained Composite Joints under Cyclic and Dynamic Loading, *Journal of Structural Engineering*, *ASCE,* 130(2).
2. Green, T., Rassati, G. A., and Leon, R .T., (2004). Bidirectional Tests on a Partially Restrained Composite Connection, *Journal of Structural Engineering*, *ASCE*, 130(2).
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J. F. Hajjar

Refereed Journal Publications

1. Tong, X., Hajjar, J. F., Schultz, A. E., and Shield, C. K. (2005). "Cyclic Behavior of Composite Steel Frame-Reinforced Concrete Infill Wall Structural System," *Journal of Constructional Steel Research*, 61(4), 531-552.
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1/95- present Professor, Georgia Institute of Technology
9/89 - 12/94 Associate Professor, University of Minnesota
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C. Publications:

1. Leon, R.T., 2005. Recent Developments in Composite Construction in the USA, *Advances in Structural Engineering*, Vol. 8, No. 3 pp. 259-274
2. Rassati, G.A. and Leon, R.T., Component Modeling of PR Composite Frames under Cyclic and Dynamic Loading: Numerical Modeling, *International Journal of Steel Structures*, Vol. 4, No. 3, pp.131-140.
3. Linzell, D., Leon, R.T., and Zureick, A., 2004. Experimental and Analytical Studies of a Horizontally Curved Steel I-Girders During Erection, *Journal of Bridge Engineering*, Vol.9, No.6, pp.521-530
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5. Linzell, D., Zureick, A., and Leon, R.T., Comparison of Measured and Predicted Response of Manufactured Circular Steel Tube Members under Concentric and Eccentric Compressive and Tensile Loads, *Engineering Structures*, v. 25, n. 8, July 2003, pp. 1019-1031
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7. Rassati, G.A., Leon, R.T., and Noe, S. Component Modeling of Partially Restrained Composite Joints under Cyclic and Dynamic Loading, *Journal of Structural Engineering*, v. 130, n. 2, pp. 343-351
8. Green, T. P., Leon, R.T. and Rassati, G.A., Bidirectional Tests on partially Restrained, Composite beam-Column Connections, *Journal of Structural Engineering*, v. 130, n. 2, pp 320-327
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10. Swanson, J. and Leon, R.T., 2001. "Stiffness Modeling of T-stub Connection Components," *ASCE Journal of Structural Engineering*, Vol. 127, No.5, pp. 498-505.

D. Synergistic Activities:

American Concrete Institute (ACI): Former Chairman and Member, Committee 408 - Bond and Development of Reinforcement; Member, Joint ACI-ASCE 352 - Monolithic Joints; Member ACI 335 – Composite Construction

American Institute of Steel Construction (AISC): Member, Specification Committee; Chairman, TC5 – Composite Construction; Member TC9 – Seismic Design

American Society of Civil Engineers (ASCE): Member, Load and Resistance Factor Design (LRFD) Committee (Chairman 1998-1994); Member, Composite Construction Committee, Chair, Executive Committee, Technical Activities Division, Structural Engineering Institute

Building Seismic Safety Council (BSSC): Chairman, TS 11 – Composite Construction; Member, Code Resources Support Committee; Member, Provisions Update Committee

Comite Eurointernationale du Beton (CEB, now FIB): Member, TG 2/5 - Bond Models; Member, TG 2/3 – Design by Testing

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EDUCATION

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1982 B.S., Engineering Mechanics, *cum laude*, Yale University, New Haven, CT.

TECHNICAL SPECIALIZATION

- Steel and composite steel/concrete structures: analysis, experimental testing, design.
- Nonlinear static and dynamic subassemblage and system-wide frame finite element formulations.
- Use of advanced nonlinear analysis directly for structural design.
- Analysis, design, and field measurement of steel and composite steel/concrete bridges.
- Parallel processing of nonlinear static and transient dynamic finite element analysis of frame structures.
- Information technology: Data archiving, telepresence, geometric modeling, scientific visualization.

PROFESSIONAL CAREER

2005-present	Professor, Dept. of Civil and Env. Engineering, Univ. of Illinois, Urbana, IL.
2005-present	Deputy Director, Mid-America Earthquake Center, Univ. of Illinois, Urbana, IL.
2004-2005	Professor, Dept. of Civil Engineering, Univ. of Minnesota, Minneapolis, MN.
2000-2001	UPS Found. Visiting Prof., Dept. of Civil and Env. Eng., Stanford Univ., Stanford, CA.
1998-2004	Associate Professor, Dept. of Civil Engineering, Univ. of Minnesota, Minneapolis, MN.
1992-1998	Assistant Professor, Dept. of Civil Engineering, Univ. of Minnesota, Minneapolis, MN.
1990-1992	Structural Engineer and Associate, Skidmore, Owings & Merrill, Chicago, IL.
1988-1990	Structural Engineer, Skidmore, Owings & Merrill, New York, NY.

PROFESSIONAL LICENSURE

2000-present	Professional Engineer, License No. 40498, Minnesota

SELECTED AWARDS

2005	T. R. Higgins Lectureship Award, American Institute of Steel Construction
2004	Special Achievement Award, American Institute of Steel Construction
2003	Walter L. Huber Civil Engineering Research Prize, American Society of Civil Engineers
2001	Charles E. Bowers Faculty Award, Institute of Technology, U. of Minnesota
2000	Norman Medal, American Society of Civil Engineers.
1998	Taylor Career Development Award, Institute of Technology, U. of Minnesota.
1996, ’97	Bonestroo, Rosene, Anderlik and Assoc. Undergraduate Faculty Award, Dept. of CE, U. of Minnesota.
1995, ‘96	Outstanding Instructor Award, Dept. of CE, Institute of Technology Student Board, U. of Minnesota.
1995	Minnesota Young Engineer of the Year, Minn. Soc. of Prof. Eng. and Minn. Fed. of Engrg. Societies.
1995	Minnesota Young Civil Engineer of the Year, American Society of Civil Engineers, Minnesota Section.

SELECTED PROFESSIONAL SOCIETY MEMBERSHIPS

Co-Chair, *Comp. Constr. in Steel and Concrete IV*, United Eng. Fnd. Conf., Banff, Canada, May 28-June 2, 2000.
American Institute of Steel Construction (AISC), Member.

- Member.: AISC Committee on Specifications (2006-).
- Chair: AISC Specification Commentary Team (2002-2005).
- Vice-Ch.: AISC Spec. Task Comm. 3 on Loads, Analysis and Systems; subcommittee chair (1997-).
- Member: AISC Spec. Task Comm. 5 on Composite Construction (2001-), AISC Spec. Task Comm. 10 on Stability (1997-), AISC/SSRC Specification Task Comm. on Stability; subcommittee chair (2000-2002).

American Society of Civil Engineers (ASCE), Structural Engineering Institute (SEI), Member.

- Chair (2001-2004), Member (1994-2000): ASCE Technical Administrative Committee on Metals.
- Chair (1994-2000), Ctrl. Grp. Mem. (1992-2001): ASCE Tech. Comm. on Load and Res. Factor Design.
- Chair: ASCE Task Committee on Effective Length (1993-1996).
- Officer: ASCE Minnesota Section Board of Directors (1998-2006; President, 2004-2005).

- Advisor: ASCE Student Chapter, University of Minnesota (1993-1997).
- Member: Several other national and local ASCE Technical Committees.

Building Seismic Safety Council (BSSC).

- Member: BSSC Prov. Update Comm. (2001-2004), Task Subcom. 6 on Steel (2006-), Task Subcom. 11 on Composite Construction (1998-2004).

Network for Earthquake Engineering Simulation (NEES) Consortium, Inc., Member.

- Chair-Elect: NEES Information Technology Strategy Committees (2005-).
- Member: NEES Information Technology and Data Sharing and Archiving Committees (2003-2005).

Structural Stability Research Council (SSRC), Member.

- Member: SSRC Task Group 4 on Frame Stability (1991-).

ACI, CUREE, EERI, IABSE, PCI, Sigma Xi, Chi Epsilon, Member.

FIVE REFEREED PUBLICATIONS MOST CLOSELY RELATED TO PROPOSED PROJECT

1. Tort, C. and Hajjar, J. F. (2004). "Damage Assessment of Rectangular Concrete-Filled Steel Tubes for Performance-Based Design," *Earthquake Spectra*, 20(4), 1317-1348.
2. Hajjar, J. F. (2002). "Evolution of Stress-Resultant Loading and Limit Surfaces in Cyclic Plasticity of Steel Wide-Flange Cross Sections," *J. of Constructional Steel Research*, 59(6), 713-750.
3. Hajjar, J. F. (2002). "Composite Steel and Concrete Structural Systems for Seismic Engineering," *J. of Constructional Steel Research*, 58(5-8), 703-723.
4. Hajjar, J. F., Molodan, A., and Schiller, P. H. (1998). "A Distributed Plasticity Model for Cyclic Analysis of Concrete-Filled Steel Tube Beam-Columns and Composite Frames," *Engineering Structures*, 20(4-6), 398-412.
5. Hajjar, J. F., Gourley, B. C., and Olson, M. C. (1997). "A Cyclic Nonlinear Model for Concrete-Filled Tubes. I. Formulation. II. Verification," *J. of Struc. Eng*, ASCE, 123(6), 736-754.

FIVE ADDITIONAL REFEREED PUBLICATIONS

6. Lee, D., Cotton, S., Hajjar, J. F., Dexter, R. J., and Ye, Y. (2005). "Cyclic Behavior of Steel Moment-Resisting Connections Reinforced by Alternative Column Stiffener Details: I. Connection Performance and Continuity Plate Detailing. II. Panel Zone Behavior and Doubler Plate Detailing," *Engrg. J.*, AISC, 42(4), 189-238.
7. Tong, X., Hajjar, J. F., Schultz, A. E., and Shield, C. K. (2004). "Cyclic Behavior of Composite Steel Frame-Reinforced Concrete Infill Wall Structural System," *J. of Constructional Steel Research*, 61(4), 531-552.
8. Hajjar, J. F., Gourley, B. C., O'Sullivan, D. P., and Leon, R. T. (1998). "Analysis of Mid-Rise Steel Frame Damaged in Northridge Earthquake," *J. of Performance of Constructed Facilities*, ASCE, 12(4), 221-231.
9. Hajjar, J. F., Leon, R. T., Gustafson, M. A., and Shield, C. K. (1998). "Seismic Response of Composite Moment-Resisting Connections. I. Performance. II. Behavior," *J. of Struc. Eng*, ASCE, 124(8), 868-885.
10. White, D. W. and Hajjar, J. F. (1997). "Buckling Models and Stability Design of Steel Frames – A Unified Approach" and "Accuracy and Simplicity of Calculations for Stability Design of Steel Frames," *J. of Constructional Steel Research*, 42(3), 171-261.

SYNERGISTIC ACTIVITIES

- Computational methodologies: development of two finite element formulations for concrete-filled steel tube beam-columns, including one macro formulation and one fiber formulation; source code is public domain.
- Teaching: created and taught several times a new graduate course on Nonlinear Analysis of Structural Systems.
- Broadening participation of underrepresented groups: advisor to four graduate students and ten undergraduate research assistants who were women; co-authored several publications with these students.
- Service on national boards and committees: see Selected Professional Society Memberships, above.

RECENT COLLABORATORS

A. Elnashai, D. Kuchma, B. Spenser, *U. of IL*; B. Chen, D. Du, D. Ernie, C. French, A. Schultz, C. Shield, *U. of MN*; D. Veazie, *Clark-Atlanta U.*; R. DesRoches, B. Ellingwood, R. Haj-Ali, R. Leon, C. Pu, *GA Tech*.; *J. Ricles*, Lehigh U.; G. Deierlein, H. Krawinkler, S. Billington; *Stan. U.*; A. Aref, M. Bruneau, A. Filiatrault, A. Reinhorn, *U. of Buff.*.; G. Rassati, *U. of Cinn.*; B. Stojadinovic, *U.C.Berkeley*.; B. Kutter, *U.C./Davis*; C.-M. Uang, U.C.S.D.; S. El-Tawil, S. Goel, *U. of MI, A. Itani*, U. of Nevada; M. Engelhardt, *U. of TX*, E. Sotelino, *VA. Tech.*

GRADUATE STUDENT ADVISING (WITH YEAR OF GRADUATION)

Post-Doc. (3 total): Lee, D., *Korea* (2002); Rassati, G. A., *U. of Cinn.* (2002); Forcier, G., *Canada* (1995).
Ph.D. (6 total): 3 current; 3 grad. incl. X. Tong (2001), W. Huang (1996); M.S. (37 total): 3 current; 34 grad.

I. FACILITIES, EQUIPMENT, AND OTHER RESOURCES

FACILITIES, EQUIPMENT & OTHER RESOURCES

Georgia Institute of Technology

The School of Civil and Environmental Engineering at Georgia Tech is equipped with state-of-the-art structural and geo-technical engineering laboratories, instrumentation facilities and machines shops. The laboratories include a broad range of equipment and instruments appropriate for research in all aspects of modern structural engineering and structural mechanics research problems.

Laboratory Facilities

Structural and Earthquake Engineering: The earthquake engineering testing capabilities at Georgia Tech were significantly enhanced by the addition of a new Structural Engineering Laboratory (SEML), with a total area of just under 18,000 $ft.^2$. The facility opened in early 1999 and is shown in Figure C-1. It includes a strong floor 55 m (180 ft.) long by as much as 18.3 m (60 ft.) wide, for a total strong floor area of about 8,000 $ft.^2$. The floor has 900 kN (200 kip) anchor points on a 1.2m (4 ft.). The anchor points consist of an embedded grid of Dwydag bars that permit prestressing forces of over 8000 kN (400 kip) per load point in addition to the external loads. The floor is 1.8 m (6 ft.) thick near the wall and 1.2 m thick in the area away from the wall.

The facility includes an L-shaped reaction wall, with anchor points on a 1.2 m (4 ft.) grid and capacities ranging up from 450 kN (100 kip) along the wall sections to 1350 kN (300 kips) on the buttresses. The EW wall is 17 m (56 ft.) long and 10.4 m (34 ft. high), while the NS wall is 18.3 m (60 ft.) long, with the first 11 m (36 ft.) having a 7.9 m (26 ft.) high wall, and the remaining 7.3 m having a 10.4 m (34 ft.) high wall. The system is designed to carry over 90,000 kN-m (50,000 kip-ft) of overturning moment in the NS wall and 49000 kN-m (36,000 kip-ft) on the EW wall. This bi-directional wall system permit the full-scale testing of full-sized three-story buildings, and has comparable characteristics to the ATLASS facility at Lehigh University.

Hydraulic distribution and data acquisition systems modular ports are distributed throughout the testing bay to facilitate testing setup. Near the walls, a hardline hydraulic system capable of peak flows of 1300 lpm (350 gpm) provides power to five substations. Along the long NS axis of the testing bay, a similar system with half the flow capacity is available. Currently, the hydraulic power comes from a 570 lpm (150 gpm) unit running at 20.7 MPa (3000 psi) pressure. Two 400 kN (30 ton) cranes service the main testing bay. The cranes have access to a width of about 16.5 m (54 ft.), and a clear height of to the lifting hook of 10.9 m (36 ft.).

Modern structural testing equipment includes:

- Two single-ended, servo-hydraulic MTS actuators with 365 kN (82 kip) compression and 240 kN (54 kip) tension capacity; one with 760 mm (30 in. stroke) and one with 300 mm (12 in.) stroke. Both have 57 lpm (15 gpm) servovalves.
- Two single-ended, servo-hydraulic MTS actuators with 650 (146 kip) compression and 450 kN (100 kip) tension capacity; both have 760 mm (30 in.) stroke, and 57 lpm (15 gpm) servovalves. Recently a 350 lpm (90 gpm) servovalve has been fitted to one of these actuators.
- One single-ended, servo-hydraulic MTS actuator with 1460 kN (328 kip) compression and 960 kN (216 kip) tension capacity; with 510 mm (20 in. stroke) and a 57 lpm (15 gpm) servovalve.
- One double-ended, servo-hydraulic MTS actuator with 960 kN (216 kip) tension and compression capacity; with 150 mm (20 in. stroke) and a 57 lpm (15 gpm) servovalve.
- One four-channel TestStar digital controller, and associated hardware and software, including pseudo-dynamic testing capabilities.
- One two-channel TestStar digital controller, and associated hardware and software, including pseudo-dynamic testing capabilities.

- In addition to the computer-controlled MTS actuators, the laboratory has numerous manually-controlled ones, including several new Power Team and older ENERPAC ones. The new Power Team equipment includes two270 kN (60 kip), 250 mm (10 in.) actuators and two 450 kN (100 kip), 250 mm (10 in.) ones that can be used in combination with the MTS system to provide constant loading or displacement to test specimens.
- A broad variety of universal test machines (UTM), including (1) a Riehle 1800 kN (400 kips) screw-type UTM with a testing opening 6.6 m (15 ft.) high and a 1.2 m (4 ft.) wide, and (2) a modern MTS 810 245 kN (55 kip) capacity UTM controlled by a Teststar system, and including hydraulic grips and environmental chamber. The latter is ideal for mechanical and environmental testing of advanced materials. Several other older testing machines, with capacities ranging from 20 kips to 450 kips are also available.

Environmental Chamber: Another key element in this laboratory is a unique, large environmental chamber suitable for studying full size structural components under various combinations of loading and environmental conditions. This chamber is 19 ft long, 13 ft wide and 12 ft high with cyclic temperature range from -40^{o}F to 180^{o}F, relative humidity range from 20% to 95%, fresh and salt water spray, and UV exposure. The laboratory also has a 400 ft^2 room having the ability to maintain constant temperature and humidity level for long-term material and structural component evaluation, a 1400 ft^2 concrete mixing and preparation facility with full ASTM test apparatus, plus a fog room, and polymer composites preparation room, and other material and testing areas.

MICROSTRUCTURAL CHARACTERIZATION FACILITIES (Material Science & Engineering)

Image Analysis Laboratory - This laboratory facility includes both automatic and semi-automatic image analysis instrumentation. The Zeiss Videoplan System, coupled with a Zeiss ICM 405 inverted light microscope, handles all functions of quantitative microscopy on a semi-automated basis. The Videoplan performs routine data acquisition, storage and manipulations. There is also an interface to our main-frame Cyber computer which allows more sophisticated data manipulation. Measurements of area, diameter, angle, length, centroid, and form factor can be made, as well as the digitizing of irregular curves such as fracture profiles. This instrument significantly reduces the level of effort necessary to quantitatively analyze micrographs or curves, and plays a central role in our analyses for quantitative fractography.

X-Ray Diffraction Laboratory -The available instrumentation includes the following: 1 Philips automated powder diffractometer (PW 1800) with Micro-Vax II, high resolution graphics, JCPDS Powder Diffraction File, and analysis software 1 Huber, computer controlled Seenan-Bohlin thin film diffractometer and analysis software 4 general purpose x-ray generators 3 Philips vertical diffractometers (two equipped with diffracted beam monochromators and the third with a high temperature specimen stage), 1 General Electric horizontal diffractometer, 2 high resolution double crystal diffractometers (one with computer control), assorted cameras for powder and single crystal studies, and 1 Kratky small angle x-ray scattering apparatus. The x-ray diffractometers are used to collect data for qualitative and quantitative polycrystalline phase analysis. Bulk specimens as well as crystalline thin films and surface layers are currently being studied. Diffraction profile analysis is used for crystallite size and strain measurements and for texture analysis of plastically deformed poly-crystalline solids. X-ray Computed Tomography facilities include two dedicated workstations with 8-mm tape drives and a total of 1.8-Gbytes of dedicated hard disk space. Two other workstations are also used extensively used to process the tomography data. Several copies of IDL and clones (PV Wave), advanced imaging languages, and a number of high-resolution imaging monitors are in use analyzing the tomography data.

Nondestructive Evaluation/Optics: The large testing facilities described above are complemented by a nondestructive evaluation/optics laboratory located in the main CEE building. This facility is housed in a secure room that includes a Melles Griot optical table. This nondestructive evaluation laboratory is one of only a very small number of facilities that can investigate both the optical generation and detection of elastic waves in solids. The existing dual probe laser interferometer (that uses a 2 watt argon-ion laser) has the sensitivity and robustness necessary to make structural measurements. Generation of ultrasound is accomplished with either a 10 or a 450 mJ Nd:YAG laser.

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Computer Facilities and Equipment

Funding has been requested for one PC computer for conducting the some of the analyses and synthesizing all computational and experimental results that are to be done at the University of Illinois. Any required large-scale analyses will be conducted at the National Center for Supercomputing Applications (NCSA). NCSA continues to support user communities by offering the resources that are the foundations of advanced cyberinfrastructure. The total computational resources exceed 43 TF supported by over 1 PB of disk storage as part of the infrastructure. The systems are on an internal 10 GbE network. Below is a summary of those resources.

NCSA Compute Resources

Copper (Cu)
Power4 IBM p690 systems
384 processors, 8 with 64 GB/system, 4 with 256 GB/system
Peak performance: 2 TF
35 TB SAN GPFS filesystem

Tungsten (W)
Xeon 3.2 GHz Dell cluster
2,560 processors, 3 GB memory/node, Myrinet
Peak performance: 16.4 TF
140 TB Lustre Filesystem

Mercury, Phase 1 (Hg 1)
Itanium 2 1.3 GHz IBM Linux cluster
512 processors, 4 GB and 12 GB memory/node, Myrinet
Peak performance: 2.662 TF
230 TB SAN GPFS filesystem
--*Mercury 1 and 2 comprise the largest computational resource for the TeraGrid*

Mercury, Phase 2 (Hg 2)
Itanium 2 1.5 GHz IBM Linux cluster
1334 processors, 4 GB memory/node, Myrinet
Peak performance: 8 TF
50 TB NSD GPFS filesystem
--*Mercury 1 and 2 comprise the largest computational resource for the TeraGrid*

Cobalt (Co)
SGI Altix systems, 2x512 processors Itanium 2 1.6 GHz systems, Linux
1,024 processors, 3 TB total memory
Peak performance: 6.5 TF
370 TB SAN storage with SGI CxFS filesystem
8 x 8p SGI Prism visualization systems with Infiniband interconnects to the 512p SMPs
30 TB SGI-based Oracle server

Tungsten 2 (T2)
Intel EM64T 3.6 GHz Dell Linux cluster
1024 processors, 6GB of memory per node, Infiniband interconnect
Peak Performance 7.4 TF
4 TB IBRIX filesystem
Primarily used by NCSA Industrial Partners

Mass Storage
The environment currently consists of 2 SGI Origin 3900 servers running EMC/Legato DiskExtender (UniTree) with 35 TB of SAN disk cache, 38 LTO2 tape drives, 6 IBM3590 tape drives, and 2 ADIC libraries. The total archival storage capacity of this environment is 3 PB.

Infrastructure SAN
284 TB of SAN connected storage for infrastructure and special projects.

High-Performance Network
All computing platforms are interconnected to a multi-10 gigabit network core. The NCSA high-performance computing environment has access to the Abilene high-performance network through a shared 10-gigabit-per-second connection. NCSA also is one of the leading sites for I-WIRE, an optical networking project funded by the state of Illinois. I-WIRE provides lambda services for several projects, including NCSA's 30-gigabit-per-second connection to the TeraGrid network.

Display Systems
Tiled Display Wall: This environment consists of 40 NEC VT540 projectors, arranged in a matrix 5 high and 8 across. The output of the NEC VT540s is rear-projected towards a single screen, creating a large-format, high-resolution image space that is 8192 x 3840 pixels. A 40-node PC Linux cluster is used to drive the display wall. The machines are dual-processor Intel Xeons, running at 2.4 GHz, with Nvidia FX 5800 Ultra graphics accelerator cards, and communicating over Myrinet.

High Definition Passive Stereo Theater: The NCSA High Definition Passive Stereo Theater is a 1920x1080 display on an 6' x 3'5" screen. The projectors used are JVCD-1LA. The display is driven by a dual AMD Opteron 242 processor running at 1.6 GHZ. Graphics hardware consists of a Nvidia Quadro FX3000.

Applications Software
NCSA offers a variety of third-party applications and community codes that are installed on the high-performance systems at NCSA, including ABAQUS, which will be used for this research. These applications cover a wide range of science and engineering domains, data analytics and visualization, mathematics and statistics. Complete information on the packages available and detailed descriptions of them are available at: http://hpcsoftware.ncsa.uiuc.edu/Software/user/index.php?view=NCSA.

Experimental Facilities and Equipment

MUST-SIM FACILITY
Teleparticipation in all tests conducted at the University of Minnesota will be conducted within the NEES MUST-SIM Facility at the University of Illinois.

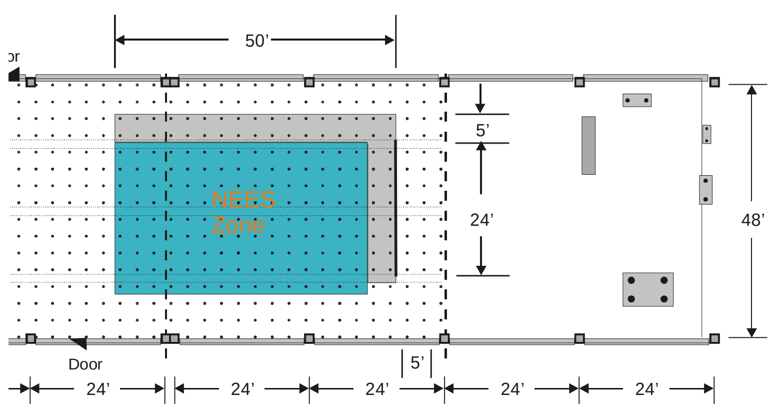

Figure 1. MUST-SIM Reaction Wall

The primary objective of the "Multi-Axial Full-Scale Sub-Structured Testing and Simulation" facility (MUST-SIM) is to develop a physical-analytical simulation environment whereby full scale structure-foundation-soil systems are subjected to complex loading and boundary conditions representing earthquake ground motion effects and the ensuing actions and deformations, captured by state-of-the-art sensors, are processed and visualized by local and remote users. The major components of the MUST-SIM facility are described below:

Reaction Structure

The MUST-SIM facility is located in the Newmark Structure Laboratory. The reaction structure consists of a 5-foot thick and 28-foot high L-Shaped strong wall that is post-tensioned to a 17-foot thick box girder strong floor as shown in Figure 1.

Loading and Boundary Condition Boxes

The three loading and boundary condition boxes (LBCBs) each consist of a 6' x 8' loading platform that is connected by six actuators to a three-sided blue reaction box as shown below in Figure 2. Each LBCB can be post-tensioned to any location on the strong floor or strong wall on any of the three sides of its reaction box and then used to apply all six possible actions (3 translations and 3 rotations) from the loading platform onto a test structure. The loading and displacement capacities of the LBCBs are:

X-Direction: 660/440 kips comp/tens; stroke of ± 10"
Y-Direction: 330/220 kips comp/tens; stroke of ± 5"
Z-Direction: 990/660 kips comp/tens; stroke of ± 5"
θx: 880 kip.ft with pitch of plus/minus 12 degrees
θy: 1063 kip.ft with roll of plus/minus 10 degrees
θz: 880 kip.ft with yaw of plus/minus 12 degrees

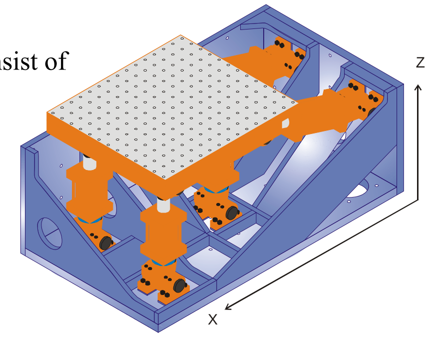

Figure 2: Loading and Boundary Condition Box (LBCB)

Instrumentation

Five video cameras are available in the MUST-SIM facility and are available for this research. These video cameras are remotely controllable. Three advanced non-contact measurement systems are also available in the MUST-SIM facility to provide an unprecedented level of detailed experimental test data. The Krypton system is able to measure the coordinates in 3-dimensional space of up to 256 light-emitting-diodes to an accuracy of better than one-thousandth of an inch at a sampling rate of up to 3000 individual readings per second. The Stress Photonics system is able to measure two-thirds of the Mohr's circle of strain at every pixel location in a 480 x 640 pixel image of an epoxy coating that is applied to the surface of the test specimen. The close-range digital photogrammetric system uses several high-definition digital cameras in conjunction with a developed software tool to provide the coordinates of an unlimited number of high-contrast targets.

Teleparticipation Facilities

A state-of-the-art video-teleconferencing facility is available that includes a Polycom Viewstation as well as two large Smart Boards that enable projection of computing desktops into a large viewing format. These will be used to display all NEES telepresence client interfaces during the experiments conducted at the MAST Facility.

Office Facilities and Living Arrangements for Visitors

Ample office space is available for the University of Illinois personnel for this project within the Newmark Civil Engineering Laboratory of the Department of Civil and Environmental Engineering. In addition, the Department of Civil and Environmental Engineering as well as the MUST-SIM Laboratory (which is housed within the Newmark Civil Engineering Laboratory) have office space available for all visitors from the University of Minnesota who may come to participate in the research at the University of Illinois.