NEESR-CR: Full-Scale Structural and Nonstructural Building System Performance during Earthquakes

To date, only a handful of full-scale building experiments have been conducted. Of these, only select experiments in Japan have focused on evaluating the response of nonstructural component and systems (NCSs) during earthquake shaking. This belies the fact that NCSs encompass more than 80% of the total investment in building construction and over the past three decades, the majority of earthquake-induced direct losses in buildings are directly attributed to NCS damage.

To this end, we are proposing to conduct a landmark test of a five-story building built at full-scale and completely furnished with NCSs, including a functioning passenger elevator, partition walls, cladding and glazing systems, piping, HVAC, ceiling, sprinklers, building contents, as well as passive and active fire systems. The NEES-UCSD and NEES-UCLA equipment combine to realize this unique opportunity and hence advance our understanding of the full-scale dynamic response and kinematic interaction of complex structural and nonstructural components and systems. While most NCSs in these experiments will be designed to state-of-the-art recommended seismic provisions; we will also include non-seismic detailed designs widely used in low-seismic regions of the United States. Furthermore, we will investigate the potential for protecting critical NCS systems using, for example, damping and/or isolation methods. A unique fire testing payload project has been developed (**with no funding requested of NSF**) to capitalize on the proposed building test program. This will involve conducting non-thermal and live fire testing to investigate post-earthquake fire and life safety performance of both the structure and NCSs. Finally, data from this unique experiment will be used to compare with earthquake performance predictions using available commercial and research computational modeling platforms.

This research is essential because even though dynamic response of building systems is fairly well understood, the response of NCSs, particularly their dynamic response and kinematic interaction with other components, remains largely unexplored. We admit this project is ambitious, however, planning has been in the works for over two years, including two on-site full-day workshops to solicit interest amongst industry and government agencies. We have developed a strong industry steering committee (ISC) with committed support of over $3.4M, and another $600k pending, demonstrating the community's strong desire to undertake this study.

Transformative Impact and Intellectual Merits: Research at the system level that incorporates the structure, the NCSs and addresses issues like detrimental kinematic and dynamic interaction between systems components, is lacking. This research is transformative in that it will for the first time allow tests of complex systems, which look closely at these multidisciplinary issues, using facilities that are fully equipped to investigate, in a controlled environment, the effects of earthquakes on building system performance. Experimental data will be generated to validate advanced nonlinear simulation platforms used for performance-based seismic design, and will be evaluated in socio-economic terms for ease of interpretation and comparison.

Broader Impacts: Outcomes from this work will have broad and immediate impacts on performance-based design of NCSs, including fire protection systems. Our team includes key industry members leading design development activities such as ATC-58, as well as others on code writing committees, to ensure successful infusion of the project findings into practice. This work will support the doctoral studies of three students in the earthquake engineering area and one master student in each of the construction management and protective systems areas. In addition, the project has developed unique partnerships to attract a diverse student group to earthquake engineering via educational activities that engage faculty and students from Howard University, a historically-black University, as well as high school students from the Construction Tech Academy (an 89% non-white male engineering and construction magnet program in San Diego).

1.0 Project Team Table

The project team is composed of a diverse group of internationally recognized experts in the fields of earthquake engineering, building and nonstructural systems (Table 1a) and includes members of different ethnicity, age and gender from both industry and academia; including a historically black University (Howard University). Note an important component of our team is an Industry Steering Committee (ISC, Table 1b). The ISC is composed of industry leaders that have provided pledges of financial and in-kind (engineering and materials) support to the project. Note that the ISC includes *internal* project team members; in addition, an *external* advisory board will be named following acceptance of the proposal by NSF (as outlined in Section 11.1).

Table 1a – Project Team: Core Members

Name and Title	Affiliation	Expertise	Role in Project	Annual Time
Tara Hutchinson Assoc. Prof.	UC San Diego (UCSD)	Nonstructural components and systems (NCS)	Project PI **NCS Leader**	1 month
José Restrepo Prof.	UCSD	Structural system (SS)	Project Co-PI **SS Leader**	1 month
Joel Conte Prof.	UCSD	Nonlinear Simulations (NLS)	Project Co-PI **NLS Leader**	1 month
Brian Meacham Assoc. Prof.	Worcester Polytechnic University	Fire Engineering	**Payload Project Leader**	None
Ken Walsh Prof.	San Diego State University (SDSU)	Construction management (CM)	Senior Personnel **CM Leader**	1 month
Claudia Marin Asst. Prof.	Howard University	Protective systems (PS)	Senior Personnel **PS Leader**	1 month
Robert Bachman Consultant	Consultant	Nonstructural seismic damage	**Industry / Gov. Liaison Leader**	1 month[a)]
Matthew Hoehler Research Director	Hilti North America	Anchorage	**Industry Liaison Leader**	1 month[a)]

[a)] Time supported by industry funding. No funding of NSF requested.

Table 1b – Project Team: Industry Steering Committee (ISC) Members [a)]

Contact Name	Affiliation	Expertise
Panos Papavizas	Baltimore Aircoil	Heat transfer technology / thermal storage
Konrad Eriksen	Dynamic Isolation Systems	Isolation Systems
Andres Vasquez	CPFilms	Window films
Robert Englekirk	Englekirk Partners/ESEC	Building Design
Praveen Malhotra	FMGlobal	Property loss prevention
Raimund Zaggl	Hilti AG	Anchorage and firestop
Rich Lloyd	Mason Industries	Vibration control and seismic bracing
Johnny Kwok	MMFX	Reinforcement steel
Alberto Franceschet	Permasteelisa	Facades
Gabriel Toro	Risk Engineering	Ground motion hazard and risk analysis
Ian Aiken	Seismic Isolation Engineering, Inc.	Protective systems
Frank Resch	Schindler Elevators	Elevators and escalators
Philip Caldwell	Square D / Schneider Electric	Electrical Equipment
William D. Perry	Tate	Access floors
Stacy Scopano	Tekla	Database technologies

[a)] Role in the project is to provide technical guidance in the area of noted technical expertise. Annual time is described in the Supplemental documents. All time is supported by industry funding.

While our project proposal to NSF focuses on building and nonstructural component and system (NCS) performance under seismic loading, a key element of the project is also post-earthquake fire performance. **However, this proposal to the NSF-NEESR program does not seek in any way support for the fire investigation aspects of the project – we recognize this is not allowed as stated in the solicitation – rather these efforts are entirely funded by outside sources – refer to Section 10.1 (Payload Opportunities) and letter of commitment in the supplementary documents by payload project leader Prof. Meacham**.

2.0 Experimental Facilities Table

This proposal will make use of the NEES-UCSD Large High-Performance Outdoor Shake Table (LHPOST), supplemented by the resources of the mobile NEES-UCLA Linear Inertial Shaker (LIS), sensors, and data acquisition systems, to conduct full-scale seismic testing. We anticipate using all 500 data acquisition channels available at NEES-UCSD, as well as additional sensors and a 96-channel data acquisition system available from the UCLA equipment site. The total duration of time on the LHPOST is approximately 12 months: 7 months for construction, during which instrumentation can overlap for 2 months, 3 months for seismic testing, and 1 month for demolition. Use of the UCLA equipment will be needed for 4 of the 12 months. The proposed schedule for table time is illustrated in Table 2, where "C" indicates building construction, "I" indicates instrumentation, "S" indicates seismic testing, and "D" indicates demolition. Pending the external support for the fire testing payload (Section 10.1), an additional 2.0 months of site usage will be needed.

Table 2 – NEES Equipment Site Usage Time

Site	Jan 2011 – Dec 2011											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UCSD LHPOST	C	C	C	C	C	C+I	C+I	I	S	S	S	D
UCLA LIS/Sensors								I	S	S	S	

3.0 Functional Budget Table

We estimate the total cost of this effort to be \$5.2M, of which we are seeking \$1.2M in support from NSF. The breakdown by area and year of the requested NSF funds is presented in Table 3. The balance of the funding, an estimated \$4.0M, will be provided through a combination of direct financial and indirect (materials and labor) support from industry, government, and non-governmental organizations. Table 4 summarizes the distribution of funds required of other (external) funding sources. At present, we have obtained written letters of commitment totaling nearly \$3.4M, with another \$600k pending from the California Seismic Safety Commission (CSSC), as summarized in Table 5. Letters of support with committed contributions are provided in the Supplemental documents.

Table 3 – NSF Requested Funding (In Thousands)

	Year 1	Year 2	Year 3	Total	% of Total
Research Activities	$320	$320	$320	$960	**80%**
Experimental Activities **(UCSD)**	$64	$258	$258	$580	48%
Experimental Activities **(UCLA)**	$0	$30	$30	$60	5%
Non-Experimental Activities	$256	$32	$32	$320	27%
Specimen Removal / Disposal	$0	$0	$0	$0	0%
Education and Outreach	$40	$40	$40	$120	**10%**
Data Archiving and Sharing	$20	$20	$20	$60	**5%**
Management	$20	$20	$20	$60	**5%**
Total	**$400**	**$400**	**$400**	**$1,200**	**100%**

Table 4 - External Resources Required (Cash, Materials and Services - In Thousands)

	Year 1	Year 2	Year 3	Total	% of Total
Research Activities [a)]	$1077.3	$1077.3	$1077.3	$3,232	**80%**
Education and Outreach	$134.7	$134.7	$134.7	$404	**10%**
Data Archiving and Sharing	$67.3	$67.3	$67.3	$202	**5%**
Management	$67.3	$67.3	$67.3	$202	**5%**
Total	**$1346.6**	**$1346.6**	**$1346.6**	**$4,040**	**100%**

[a)] Includes $220,000 for specimen removal and disposal at the end of Year 3.

Table 5 – External Resources (Pending NSF Award)

Organization	Cash	In-Kind Services	In-Kind Materials	Total
Arup [a), e)]				
Baltimore Aircoil [a)]				
CSSC [b)]				
CP Films [a), c)]				
Dynamic Isolation Systems				
FMGlobal (NCS) [a)]				
Englekirk Partners /C4 [c), d)]				
Hilti [a)]				
Mason Industries [a)]				
MMFX [c)]				
Permasteelisa [a)]				
Risk Engineering [a)]				
Ruskin [a), e)]				
Seismic Isolation Engineering, Inc.				
Schindler Elevators [a)]				
SimplexGrinnell [a), e)]				
Square D / Schneider Electric				
Tate Access Floors [c)]				
Tekla [a)]				
Tyco Building and Fire Products [a), e)]				
Total	**$1,165,000**	**$1,220,800**	**$1,654,100**	**$4,039,900**

[a)] Value of committed service and materials as reflected in letters of support (Supplemental documents).
[b)] Proposal under review with decision pending.
[c)] Estimate of funds distribution (letters provided without monetary value or only partial monetary value).
[d)] Englekirk Partners / C4 (Carpenters/contractors cooperation committee) will lead the efforts to raise these funds, targeted towards support for building construction and demolition costs, as outlined in sponsors support letter
[e)] While these industries are primarily fire-related, their contribution is for use in supporting cost efforts associated with materials and placement of the seismic testing of fire-related products.

4.0 Summary of Proposal Preparation Discussions with NEES Equipment Site Personnel

Schedule, equipment needs, design coordination, execution of the fire (**payload**) experiments, and site concerns have all been discussed with the NEES-UCSD site staff. Co-PI Restrepo is the site director and designer of this facility, with intimate knowledge of its capabilities, site constraints, and other issues needed for conducting an experiment of this scale. We have also discussed this project with Dr. Nigbor at

NEES-UCLA and expressed our interest to use the LIS, Kinemetrics sensors and data acquisition system during our experiments.

5.0 Vision

Our vision is to make breakthrough advances in the understanding of total building systems performance (structural and nonstructural *systems*) under moderate and extreme seismic conditions through full-scale testing. We will obtain data, which are sorely needed to characterize the earthquake performance of building and nonstructural building systems, including nonstructural systems with protective measures. This data will be used to validate nonlinear simulation tools, which in turn can be used for performance-based seismic design of nonstructural and building systems. Such an approach will help address societal building risk and performance expectations, and increase the post-earthquake safety of buildings and its occupants through changes in regulations, responses and technologies. Outcomes from this work will have broad and immediate impacts on seismic design guidelines for NCSs, while also providing guidance regarding protective measures geared towards minimizing damage to NCSs. Our team includes key industry members leading design development activities such as ATC-58 (2007), as well as others on code writing committees, to ensure successful infusion of the project findings into code design documents.

The work proposed directly aligns with the research and outreach program priorities reported by the Earthquake Engineering Research Institute (EERI, 2003) and the National Research Council of the National Academies (NRC, 2004). Furthermore, this proposal responds directly to a call for comprehensive shake table testing of building systems as recommended during an NSF sponsored NEHRP community workshop in September 2007 (ATC-73, 2007; Priority 4, Table 1.)

6.0 Literature Review

6.1 Currently Supported NEESR and other Full-Scale Building Projects

The project team is aware of and has discussed the proposed development with the PIs of two existing NEESR projects, which have an emphasis on performance evaluation of nonstructural systems (NEESR-GC@UNR, Maragakis PI and NEESR-SG@SJSU, McMullin PI). Members of this team (Hutchinson) are also closely linked with the NEESR-GC project. During pre-proposal preparations, Prof. Maragakis presented to our team (including the ISC) the details of the GC project. Within the inventory of NCSs, the GC project focuses on ceiling, piping, and partition subsystems, which represents a limited portion of the NCS inventory. Moreover, system level experiments are limited to a two-story building 'segment' planned for testing at NEES-UNR. In this sense, it is felt that the proposed work will complement (and not overlap) the current GC efforts. The project at SJSU led by Prof. McMullin is focused on drift-sensitive NCSs only (e.g. cladding), and is being conducted absent building interaction, therefore this work is different and complementary to McMullin's efforts as well. These two groups will be represented in a NEESR advising committee to ensure best use of resources among the three projects.

From 2007 through early 2009, E-Defense in Japan has conducted a series of tests on full-scale steel and concrete structures, including seismically isolated and passively damped systems. There is no doubt that the testing conducted by the Japanese on unanchored contents will be valuable to US practice, when the research results are released in a few years. However, the other nonstructural components tested are based on Japanese practice, which is totally different from US practice and therefore has limited value in the United States. Furthermore, none of the testing conducted to date at E-Defense has included a working elevator. While it has been suggested that US nonstructural suppliers cooperate on E-Defense projects, cost negotiations with E-Defense have proven to be prohibitive for most US suppliers. Finally, the design of seismic isolation systems is significantly different between the US and Japan in terms of the design displacement demand specified for isolators (US demand is generally much larger). The proposed project should be considered as complimentary to the E-Defense testing. The project team will continue to follow the Japanese work through its Academic Liaison Group (Section 11.2) to benefit from their lessons.

6.2 Past Research

6.2.1 Nonstructural Components and Systems

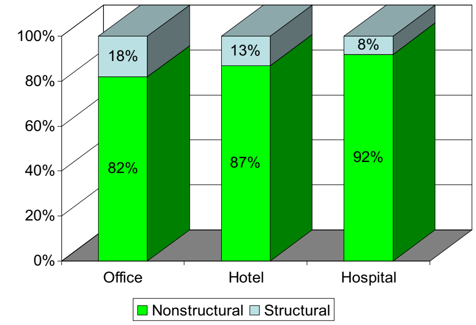


Fig. 1 Typical investments in building construction (after Taghavi and Miranda, 2003).

Nonstructural components and systems (NCSs) are generally categorized as being either an architectural, mechanical, plumbing, or content item or system of items. Architectural includes, for example, nonbearing walls and partitions, veneer and finishes and access floors. Mechanical and plumbing includes items such as HVAC systems, elevators, lighting fixtures, piping systems. In addition, architectural and mechanical/plumbing type NCSs also include fire protection systems, which, as required by code, must be installed in all buildings. Building contents encompass the remaining items, for example, file cabinets, book cases, computers and communication equipment. Least appreciated by building design engineers, NCSs encompass more than 80% of the total building investment (Fig. 1). Unfortunately, these items also come in numerous types (geometries, weights, flexibilities), are placed within various locations in a building, have a variety of attachment conditions (or not), and may be interacting with the building itself. Although they are placed within the dynamic environment of the building, they are not a part of the load-bearing system of the structure. Generally we classify NCSs as either drift- or acceleration-sensitive. However, a number of these elements, depending on their detailing and connections, may be subject to damage due to either excessive drift or acceleration. The complexity of their response is well known and design to limit their damage is difficult, largely due to a lack of experimental data providing insight on the behavior of the numerous types.

6.2.2 Observed and Potential Damage to NCSs due to Earthquake Shaking

Fig. 2 Cartoon depicting observed building interior damage from the 1843 Guadeloupe earthquake. (Source: NISEE, 2009)

Since the 19th century, NCSs have demonstrated their potential to create a dangerous environment for building occupants during earthquake shaking (Fig. 2). Moreover, since these elements generally represent more than 80% of the total investment of a building (Villaverde, 2004; Taghavi and Miranda, 2003), even minor damage can translate to significant financial losses. Loss of function of critical building NCSs (e.g. electrical, plumbing, networking) can cripple businesses, while damage to operations NCSs within a building (e.g. plumbing, gas lines) can be detrimental to a buildings ability to function, potentially resulting in an otherwise structurally sound building being demolished. This occurred for a number of structures subjected to the Nisqually earthquake in Washington 2001 (e.g. Filiatrault et al., 2001). Moreover, it is well recognized that the survival of many NCSs is essential to assuring operative post-earthquake emergency services (via communications, fire and police stations).

Overall, the performance of NCSs in past earthquakes has been poor at best. A number of case studies have observed that dollar values associated with damage to NCSs during earthquake shaking far exceed the costs associated with structural repair (e.g. Steinbrugge and Schader, 1973; Naeim, 2000). Furthermore, since NCSs are damaged at response intensities much lower than those required to produce structural damage, low level, high probability earthquake events have the potential to result in significant economic losses and business disruptions. The recent 2006 Hawaii earthquake for example, with minor damage to structural elements, resulted in widespread nonstructural damage to residential, industrial, and commercial buildings. Initial damage estimates for this event were in excess of $100M, with nearly all costs associated with nonstructural damage (RMS, 2006).

The images shown in Figs. 3 and 4 present examples of observations post-earthquake to select types of NCSs. Absent real case histories or full-scale tests within a building, it is not clear if the images from over 30 years ago would reoccur, should a large trembler occur today. According to the Federal Emergency Management Agency (FEMA), direct losses in the Olive View Memorial Hospital (Fig. 4) were on the order of $6.6 Million or 11 percent of the total replacement cost of the building and were caused mainly due to nonstructural damage (FEMA 2008). The center could not be used in the immediate aftermath of the earthquake, a prime function expected from such a critical facility.

Fig. 3 1971 San Fernando Earthquake: damaged converter in Sylmar. (source: NISEE, 2009)

6.2.3 Combined Building and NCS Tests

In the United States, testing of full-scale building systems has been limited to wood-frame houses (Fisher et al., 2000; Mosalam, 2002; van den Lindt and Liu, 2007) and reinforced concrete wall buildings (Panagiotou et al., 2007a, b). Some of these structures were outfitted with nonstructural components; however, the emphasis was primarily on the building structural performance. It is also noted that in general NCSs have been tested in isolation, not only from the building, but also from other nonstructural components of the system they might otherwise interact with. For example, the testing of partition walls is typically conducted by testing the walls themselves, with rigid top and bottom structural reaction systems (e.g. Rihal, 1982; Serrette and Ogunfunmi, 1996; Bersofsky, 2004; Lang and Restrepo, 2006; McMullin and Merrick, 2007).

Fig. 4 1971 San Fernando Earthquake: damaged to piping at Olive View hospital power plant. (source: NISEE, 2009)

In 2005, Panagiotou et al. used the NEES-UCSD shake table to test a 7-story building slice built at full-scale. This building was tested in two phases. Phase II afforded an opportunity to investigate the earthquake response and anchor loading associated with pipe runs supported on trapeze hangers at three levels of the structure (Hoehler et al., 2009). L-shaped groups of six, 6 in. diameter, cast-iron pipes attached to trapezes were mounted on the 1st, 4th and 7th floors of the building (Fig. 5). This test program showed that total accelerations measured on the pipes exceeded those predicted by ASCE 7 (2005), Section 13.3.1 (equations for nonstructural components). This was despite the fact that the modal frequencies of the pipes did not coincide with any building modal frequencies.

Since the 2005 inauguration of the E-Defense large shake table in Japan, there has been a coordinated research effort to test complete building systems built at full-scale or near full-scale to improve knowledge of system behavior to strong shaking (NEES, 2008). This effort has resulted in the testing in 2006 of a 6-story reinforced concrete building designed to older standards (Yousok et al., 2007). In 2007 a two-story sub-assemblage from a high-rise building was tested on the E-defense shaking table to observe the effects of long duration earthquakes with significant low-frequency content on the response of building contents and nonstructural elements designed to Japanese standards. As noted previously, NCSs are also part of a 5-story steel moment resisting frame building tested by Suita et al. on the E-Defense shake table in 2007. At the time of writing of this proposal in 2009, a 5-story steel frame structure is being tested to investigate the performance of various passive structural damping systems. The test structure will include Japanese style ceiling, partition and façade systems on a portion of the structure. Comprehensive research reports in English of these tests are still under preparation.

7.0 Research Program Justification, Plan, and Expected Outcomes

7.1 Justification

To facilitate performance-based seismic design of buildings and nonstructural *systems*, the *integrated performance* of the system subjected to ground motions must be well understood and quantifiable. This requires: (i) experimental data describing the seismic performance of the structure, the NCSs and if applicable, its protective systems, when subjected to ground motion scenarios - this data can then be used for predicting damage, downtime and life safety impacts, (ii) experimental data describing the post-earthquake reliability and performance of buildings and its NCSs to develop informed evacuation and emergency response plans, (iii) changes to engineering practice, which can be delivered via design guidelines. To obtain these elements, a full-scale building test program, which integrates the building and its NCSs, coupled with a comprehensive implementation plan, is required.

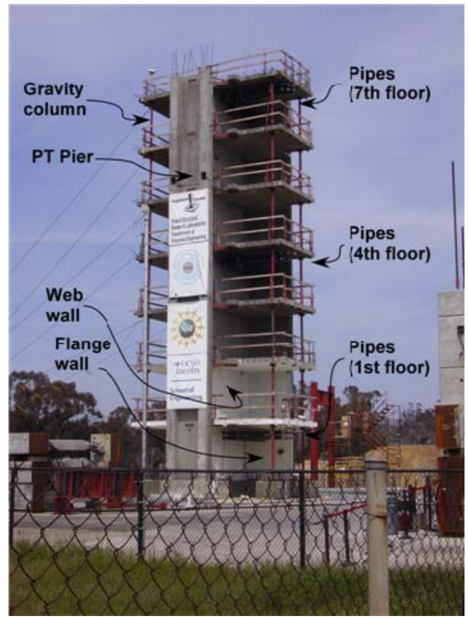


Fig. 5 View of 7-story building slice and location of pipes.

7.2 Scope of Research Program

To assess the building and its nonstructural system performance as envisioned, a key component is the construction of a building, which will be subjected to a range of ground motions. Upon earthquake excitation of the structure, it then provides a test bed for assessing conventional and protected NCS system performance. Five integrated tasks are proposed to undertake this work, as described in the following sections.

7.2.1 Task A – Structural System (SS)

7.2.1.1 Phase 1 – Design: The lateral force resisting system chosen for the building is a five story reinforced concrete moment resisting system, with beams and columns 20 inches in depth and an 8 inch thick slab (Fig. 6). Such a configuration is commonly found in California. Connection details will be selected in consultation with Industry partners supporting the building construction efforts (led by Englekirk Partners/C4–the Carpenters/contractors cooperation committee – refer to supplementary documents). Candidate details include the innovative framing configurations tested in previous years at UCSD (Warcholik and Priestley, 1998; Chang et al., 2008; Englekirk and Wang, 2008). These systems, which included use of high strength concrete, precast assemblies adapting ductile insert concepts and high strength steels, demonstrated superior performance over conventional special moment resisting frame connections.

The number of floors in this building requires a full-height elevator in the prototype building. The plan geometry of the typical floor was conceived to optimize the use of the LHPOST footprint of 40'x25' (Fig. 7). This building will be rather flexible, which is suitable for the testing of displacement-sensitive NCSs. To stiffen the lower floors, it may be feasible to provide supplemental bracing to the building, thereby increasing the potential for large accelerations and supporting investigations of the response of force-sensitive NCSs – this option will be assessed once all NCSs are selected. We note that the diaphragm is discontinuous due to the current implementation of the stair and elevator opening – this is recognized as a realistic configuration in a building structure that one needs to address during design. The staircase, an important element of fire egress, will provide evidence of the interaction with rather flexible structural systems. Stairs will be provided with and without slip joints to accommodate the imposed drift. It is anticipated that stairs at those floors without a joint may attract significant story shear, which will likely damage the stairs and cause torsion in the building response. The building will also include a shaft for an operating elevator, which is described in Section 7.2.2.

The building design lateral forces will be obtained using displacement-based design methodologies that were used in the design of the UCSD 7-story building test (Englekirk, 2007; Panagiotou and Restrepo 2009). Preliminary design indicates an effective first modal mass of 215 Tons at an effective height of 42 ft. from the base of the LHPOST platen. The base-shear seismic coefficient at overstrength for the building, including dynamic effects, has been estimated at 40% of the total building weight. This shear force is much less than the horizontal force capacity of the LHPOST of 1465 kip. Likewise, calculations show that the maximum overturning moment for the building system is well within the limiting overturning moment of 14,800 kip-ft for the bare table.

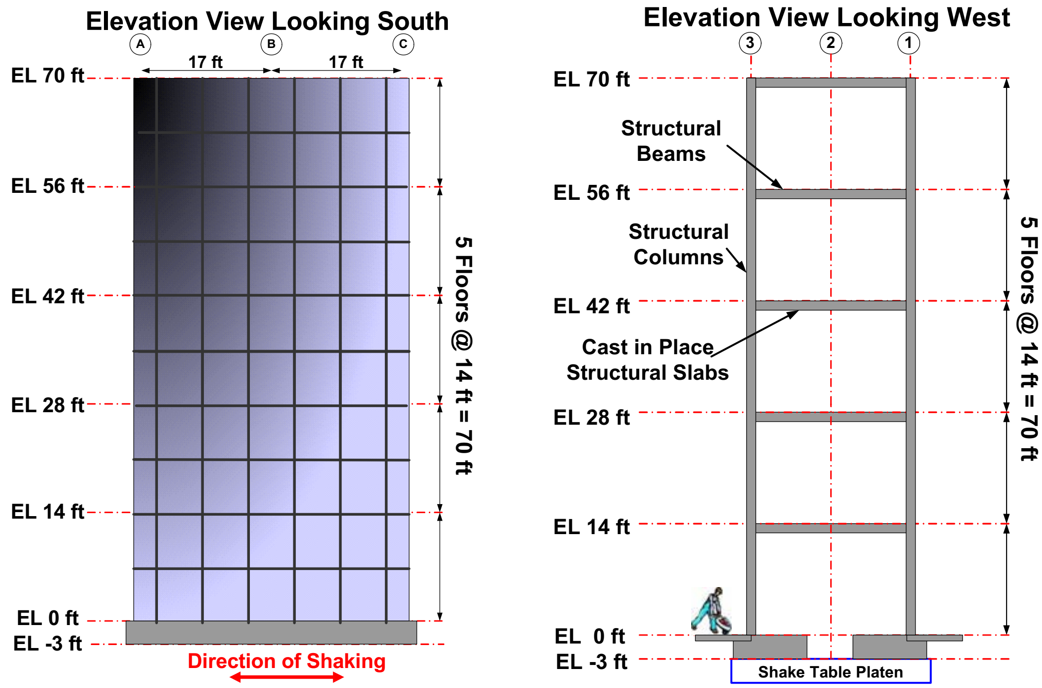


Fig. 6 Schematic elevations of the test building.

7.2.1.2 Phase 2 – Instrumentation and Monitoring: The complete building, including the nonstructural elements will be instrumented with approximately 160 strain gages, 180 displacement sensors (DCDTs) and 180 DC-coupled accelerometers. Total displacements will be monitored at four locations with a 50Hz, 3 mm resolution GPS system recently acquired by NEES-UCSD. Details of the NCS instrumentation are provided in Section 7.2.2.2.

7.2.1.3 Phase 3 – Testing and Data Analysis: The building will be subjected to four earthquake records for a soil site class D in San Bernardino, Southern California. Earthquakes whose predominant period closely matches the fundamental period of the building will be selected. These motions will be associated with four key hazard levels, namely, 50% probability of exceedance in 30 years, 50% in 50 years, NEHRP Design Earthquake (DE) and the NEHRP Maximum Considered Earthquake (MCE) level. We note that the San Bernardino Mountains segment of the San Andreas Fault has not seen a major rupture since 1812. According to Olsen et al. (2006) the average recurrence interval for a surface rupture of this portion of the fault is 146 years. Therefore, for the final earthquake test, we plan to use a record obtained from the hybrid modeling of a M 7.7 South-North rupture of the San Andreas fault, in which the low frequency content and long duration will be obtained from the TeraShake simulation of the Southern California Earthquake Center (SCEC) supplemented by stochastic simulations for the high frequencies (Somerville et al., 2006).

Prior to and between earthquake tests, the building will also be subjected to long-duration ambient vibration tests and to long-duration low-amplitude 0.5-25Hz band clipped white noise (WN) tests with root-mean-square (RMS) amplitudes of 2%, 3% and 5% g. All of these tests, with the exception of the ambient vibration, will be applied in the East-West direction using the single axis LHPOST. In addition, the NEES-UCLA LIS will be mounted on top of the building. A low-magnitude, white noise force vibration will be applied by the LIS in the North-South direction, which is orthogonal to the axis of the LHPOST. During this period, visual inspection will be made of passive and active NCS fire protection systems to assess damage resulting from the ground motions.

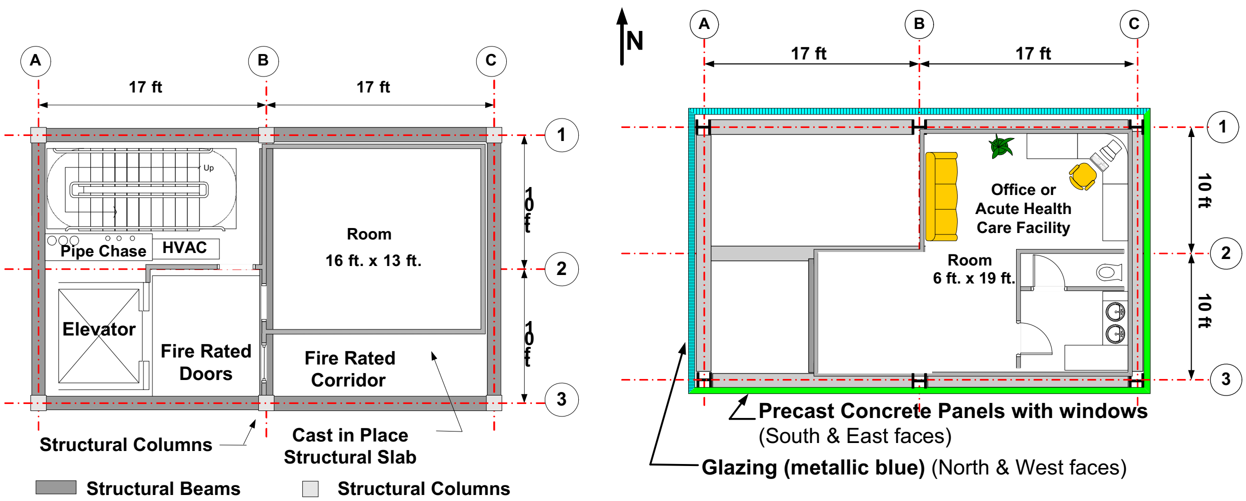
Acceleration time-histories will be used to estimate the modal parameters of the test structure at various damage states using the following system identification methods: (1) Natural Excitation Technique combined with the Eigensystem Realization Algorithm (NExT-ERA), (2) Data-driven Stochastic Subspace Identification (SSI-DATA), and (3) Enhanced Frequency Domain Decomposition (EFDD) (Moaveni et al., 2006).

7.2.2 Task B – Nonstructural Systems and Components (NCSs)

7.2.2.1 Phase 1 – Design: Outfitting the structure with a variety of NCSs results in these systems and components being subjected to the dynamic environment realized in real earthquakes, while simultaneously interacting amongst themselves and with the building. Accordingly, a task within this project is the performance monitoring and evaluation of the NCSs mounted within and on the building. While the types of NCSs and their details will be largely dictated by consultation with our industry partners, thus far we have obtained firm commitment and desire from our project team ISC specializing in all three broad categories of nonstructural systems (architectural, mechanical and electrical, and building contents). Namely, our ISC will be outfitting the structure with and monitoring the performance of: (i) glazing (including laminated glass), (ii) cladding, (iii) an elevator, (iv) fire dampers, (v) access floors, (vi) ceiling subsystems, (vii) HVAC components and subassemblies, (viii) fire sprinkler and riser system, (ix) fire detection, alarm and communications systems, and (x) smoke and fire barriers. Note that during our two pre-proposal workshops held at UCSD (see Section 11.2), we had significant interest by a number of other companies in all three broad NCS categories, and therefore we are quite confident that additional systems will be installed in the building. A number of these NCSs are traditionally anchored to the structural floor or walls, and common details and products used for anchorage will be provided by industry partner Hilti. Using the exact anchorage conditions expected in the field allows us to not only replicate the real boundary conditions, but also measure anchor forces and deformations of the anchors themselves during dynamic shaking. Alternatively, some NCSs will be isolated or otherwise protected from seismic movement. Plans for protecting NCSs are described in Section 7.2.3.

The systems proposed thus far span from drift to acceleration sensitive; mounted on the exterior (exoskeleton) of the building, to within the building; attached and unattached; and each vary in their basic detailing (geometry, flexibility, mass, and dynamic properties). The same NCS may be installed at different floor levels; for example, one installed using modern code-based design, while another installed absent seismic code detailing guidance. We will consult with our industry partners regarding the final selection of the NCS installation details. Some systems will be interacting with the structure, while others not; and some systems (such as the HVAC subsystem) will have interaction amongst its various components. In addition, there will be numerous unanchored contents that are representative of those typically found in a building of this type. Contents with relatively low coefficients of friction, such as those on wheels, appear to be most sensitive to total absolute floor displacements, rather than accelerations. The floors of the building will be designed thematically, and thus accommodate a variety of types of NCSs (Fig. 7). For example, as shown in Fig. 7b, the upper floors (3-5) will be office space, and at least one of these floors will be outfitted as an acute health care facility and an intensive care unit (ICU). The elevator will be installed as per typical field installation, and run from the ground level to the uppermost floor of the structure. Adjacent to the elevator will be an open stairwell (Fig. 7a). Fire-rated and smoke-rated barriers will enclose select floor areas.

7.2.2.2 Phase 2 – Instrumentation and Monitoring: The exact details of the instrumentation will vary significantly depending on the type of NCS, its connection, and its internal details. Depending on the complexity of the NCS, we anticipate that each NCS may need approximately 10-15 sensors to fully characterize its global forces and deformations. Measurements relative to the structure will be needed to assess its drift demands, while absolute accelerations will be needed to determine force amplifications. Displacement transducers, strain gages, and accelerometers will be used, while digital cameras will also be mounted within the various rooms and videos post-processed to track key feature changes in the scene (Nastase et al., 2008; Doerr et al., 2008; Hutchinson et al., 2009). The video tracking will be useful for complex NCSs, where traditional analog sensor measurements are cumbersome. Laser scanning in 3D will also be performed before and after shaking to produce point cloud models in real color, supporting calculation of relative movement/deformation in both structural and nonstructural components. We would like to collect data to not only identify damage onset, but also the characteristics of this damage (such as cracking of concrete or glazing, or failure of bracing or supports) and its implications on the operation of the NCS. Therefore, following the ground motion tests, further visual inspection and documentation of damage, using non-destructive testing such as pressurization (suppression system (water), egress system (smoke)) and imaging, will be used to help identify and catalog damage states of NCSs.



(a) (b)

Fig. 7 Schematic plans of floor layouts at (a) lower floors (1 and 2) and (b) upper floors (3-5).

7.2.2.3 Phase 3 – Testing and Data Analysis: The various NCSs will be subjected to dynamic shaking via input from the building structure and the LIS equipment. The sequencing of testing is therefore also similar to that described in Section 7.2.1.3. In addition to the building-induced shaking, as time allows before and between major shaking events, impulse "hammer" tests will be performed locally on the various NCSs, to characterize their modal properties, without filtration of the input signal through the building. Response data will be processed to determine the acceleration and displacement characteristics of the various NCSs to earthquake shaking. Time history response signals to white noise input will be frequency-domain filtered and used to evaluate changing dynamic properties between earthquake shaking.

7.2.3 Task C – Protective Systems

The implementation of protective systems to mitigate the damaging effects of the earthquake response on both structural and nonstructural components of the test specimen will be investigated in this project. Protective systems are defined herein as any system that is intended to improve the performance of the building components during earthquakes. The possibility of providing overall building response protective devices, such as dampers and isolators, will be considered. Specifically, the implementation of isolators at the base of the building would provide the opportunity to demonstrate the effectiveness of seismic isolation in reducing acceleration response and improving NCS system behavior in earthquakes. The decision regarding the implementation of structural protective systems will be made in close collaboration with our ISC and largely depend on construction feasibility.

A task within this project is to identify those NCSs that are likely candidates for use of protective measures, develop cost and construction feasible measures, and finally, implement, monitor and evaluate the NCS response with the designed protective systems. Measures to be considered may include simple mechanical solutions, such as wire bracing or ductile restraint systems, or slightly more elaborate systems such as visco-elastic dampers, isolators or hybrid damping-isolator systems. The type of protective systems for the NCSs and their details will be defined in consultation with our industry partners. Designed protective systems considered for NCSs may include: (i) a base isolated computer floor, (ii) isolation systems for piping or ducts, (iii) flexible piping connections and (iv) restraints for isolated and non-isolated (mechanical or electrical) equipment.

The implementation of the protected-NCSs into the building test program will be based on the estimated fragility of the NCS and the prediction of demands on the NCSs with and without such measures. Predictive modeling will be undertaken through detailed numerical studies using the OpenSees (PEER, 2009) framework. The analysis will consider the subsystems (protective system-NCSs) subjected to the predicted building floor motions and interstory drifts. If required, OpenSees will be modified to properly include the model of a specific protective system. The instrumentation for the protected-NCSs during testing will vary significantly depending on the type of protective system, NCS, connection and details. Test results will be critical in: (i) identifying the level of performance provided by the selected protective measure, (ii) the characterization of the protective systems; (iii) optimization of the protective systems and (iv) providing experimental data regarding the protective system-NCS behavior during earthquake motions – this data will be needed for subsequent simulation efforts and development of simplified procedures to predict the responses of protective system-NCSs.

7.2.4 Task D –Simulation

Three simulation efforts will be undertaken during this project, namely those related to (i) simulating the buildings performance during earthquake shaking, (ii) simulating the NCSs performance during earthquake shaking, and (iii) simulating the performance of protected NCSs during earthquake shaking.

Simulation of the *building structural performance* and linking this performance to different damage levels will make use of nonlinear time history analyses conducted in the OpenSees framework (PEER, 2009). We will implement a macroscopic flexure-shear strut-and-tie model being developed at UCSD by Panagiotou et al. (2006) into OpenSees to undertake this analysis. This model will account for the interaction between shear, flexure, and axial forces and the corresponding deformations and will borrow concepts from the modified compression field theory for modeling the softening in the compressive stress-strain relationship of concrete caused by transverse strain. Once these material and element models are incorporated into OpenSees, we will perform high-performance simulations on the bare and completed building using the NEESit high-performance computing resources available through the San Diego Super Computer Center.

Simulation of the *NCSs performance* will also use the OpenSees platform, with the expressed goal of evaluating existing modeling tools via comparison with the experimental results. We will perform these analyses in two fashions. First, models of the building structure will be augmented with lumped spring-mass-dashpot models of the larger, heavier NCSs, and those NCSs with fundamental frequencies nearest to that of the building. This may require us to use simplified stick models with generalized linear or nonlinear (depending on the NCS) material behavior. Second, isolated NCS models will be developed and dynamic characterization information data obtained from impulse (hammer) tests will be used for calibrating the numerical models. We will evaluate when uncoupled (so called cascade) analysis is sufficient, and conversely, when it is essential, to adequately estimate the NCS performance. Numerical tools being developed as a part of the NEESR-GC@UNR will be leveraged for these simulations.

A culminating effort of the simulation task will be a two-day multi-disciplinary (structural, and NCS community) *blind prediction workshop* hosted at UCSD during year 3. The objective of this workshop is to bring the various communities together for the purposes of assessing the capabilities of existing modeling methodologies (simplified approaches, numerical (e.g. FEM), and analytical) in predicting the building, NCS, and protective systems response to seismic excitations. The project team has demonstrated success of such an approach (EERI, 2006), and we particularly note the unique value in the context of this project, due to its multi-disciplinary nature. Recent similar endeavors (EERI, 2006, 2008) attracted the active participation of local and overseas researchers, practicing engineers and students, and allowed assessment of the predictive capabilities and shortcomings of existing and new analytical tools.

7.2.5 Task E – Construction Management

The construction portion of this project provides an opportunity for mentoring and education in construction engineering. To this end, we will rely on existing partnerships between SDSU and local industry to recruit an industry mentor to serve as the owner's representative during the construction phase. The mentor will work with SDSU faculty to mentor graduate, undergraduate and high-school students. Due to site restrictions, the small footprint of the building, and donated work content, special attention to coordination, procurement, and constructability will be critical. The construction management team (investigators, mentor, and students) will facilitate by circulating construction documents for both the in-kind work and paid work among the project team. A general contractor will be selected during design, to inform the design with construction process knowledge. At least one constructability review workshop will be held with critical path and high-value trade contractors as the design nears completion.

During construction, detailed observations of construction processes will be made to provide materials for classroom use regarding construction productivity, construction methods, or process capability projects, in furtherance of educational objectives for the project. Furthermore, data will be collected to populate building information modeling (BIM) of the structure for use in college classes and in modules to be deployed at Kearny High School's Construction Technical Academy (CTA) (see Section 8.1). Construction progress tracking will also be conducted at a high level of detail to facilitate research into construction production processes. The production models of Walsh et al. (2007) suggest that a Little's Law-like approach can be applied to construction operations. From this concept, a more fundamental understanding of work sequencing and queuing in construction appears possible. With graduate students involved in the construction management, high levels of detail to support validation and extension of these production models can be captured.

7.3 Expected Outcomes

The experimental data as well as the validated simulation tools generated during this project are natural and expected outcomes of this effort. In addition, one of main deliverables of our work is the implementation of projects findings into design guidelines. The industry/liaison for implementing the findings of this project, Robert Bachman, has been a member of the NEHRP Provisions Update Committee since 1990 and chaired the ASCE 7 committee that developed the current U.S. seismic load requirements between 2000 and 2006. He is currently vice chair of the overall ASCE 7 committee. Under his leadership, the project is well situated for disseminating results to the appropriate committees. In addition, many of the members of the ISC have held key positions on these committees and will aid in disseminating the research findings in a timely manner to the appropriate code committees.

Several other standards used in the United States have supplementary earthquake requirements. These include for example ASTM A17.1 for elevators, ASTM E580 (2008) for suspended ceilings and NFPA 13 (2007) for automated sprinklers. In California, the Office of Statewide Health Planning and Development (OSHPD) and the Department of State Architecture (DSA) develop additional requirements for hospitals and schools, which are beyond those found in ASCE 7. Representatives of the code committees, OSHPD, DSA and others, who develop these nonstructural seismic code requirements, will be invited to participate in a code and regulatory advisory committee and provide input to the project. This group will be used as a primary communication vehicle for transferring research results to the code writing community.

8.0 Education, Outreach, and Technology Transfer Activities

Important aspects of this project are (i) its contribution to our understanding of building and NCS behavior through full-scale system-level tests, (ii) its contributions to our understanding of the use of protective systems in concert with NCSs to minimize seismic-induced damage and (iii) its ability to serve as an attractor to earthquake engineering careers because of the unique nature of the experiment itself. These contributions are only valuable if the results can be widely distributed via EOT activities.

8.1 K-12 Initiatives

Educational efforts on the hazards of earthquake are of course not new, especially at the K-12 instructional level. What is desperately missing at present, however, is a technical perspective of earthquakes and their effects on NCSs. To this end, the proposed educational activities are designed to infuse the research activity into a wide range of educational levels, including secondary curricula where the opportunity to attract new generations of earthquake engineers will be exploited.

A primary K-12 delivery vehicle proposed in this work involves a partnership with the Stanley E. Foster Construction Tech Academy (CTA). The CTA, a unit within the San Diego City Schools, opened in 2002 as a magnet campus for students interested in engineering, architecture, and construction, and is now a Gates Foundation school. CTA's student body is non-traditional for science and engineering, with an 89% non-white-male population. The CTA approach to education relies on a cross-curricular setting in which students work together to solve real-life pre-engineering and engineering problems that are present in both the local and global arenas. An objective of the educational program of this project is to provide a relevant earthquake engineering experience to students at CTA, and develop curriculum modules. Learning objectives will be developed for each module and assessed. At least two cycles of deployment should be possible within the proposed project schedule. Vetted modules will be made available to other high schools via the Project Lead the Way curriculum at SDSU, and via the project web site.

CTA teachers (pre-engineering and visualization) will be engaged in the research to develop the curriculum modules for secondary education, using a request for Research Experience for Teachers (RET) supplemental funding of NSF. Educational modules will be developed with the participation of project researchers and incorporating project results that explain the seismic response of structures, nonstructural and protective systems, and the research process. Completed curriculum modules will include classroom materials, background for laddering student learning via web/handout, scripted in-class exercises, homework assignments/solutions, and an annotated teacher's manual. An existing collaboration between CTA, SDSU, and the Associated General Contractors (AGC) will allow CTA students to participate directly in the research via internships.

8.2 Undergraduate Student Initiatives

This project will provide unique and stimulating theortetical and experimental research experiences in an exciting field to underrepresented undergraduate students from Howard University (a historically-black University). The proposed activities will provide these students opportunities to correlate the mathematical idealization with the real behavior of structures under earthquake loading. This will no doubt have the effect of influencing and encouraging students to participate in research or to pursue graduate studies in structural engineering. We will request Research Experience for Undergraduates (NEES-REU) supplemental funding of NSF for this initiative.

8.3 Technology Transfer Initiatives

As our research program advances, a series of workshops and seminars will be offered to the practicing engineering community on the fundamentals of earthquake resistant design from a performance-based perspective, emphasizing the NCS and protective measures. This will include a summer institute at one of the core universities for current and future engineering faculty to provide them the basic tools for teaching and researching performance-based earthquake design of buildings. Where appropriate, we will engage and partner with professional organizations (ASCE-SEI, SEAOC, etc.) in these outreach activities. Finally, a capstone outreach activity of our work is the multi-disciplinary blind prediction workshop planned during year 3 (see Section 7.2.4).

9.0 Data Archiving and Sharing Plan

The project will utilize NEESit resources including: NEEScentral, WebEx, OpenSees, and various remote participation tools. It is an expressed goal of the Core Team to produce high quality, fully reproducible results and documentation. Documentation deemed by the investigator to be essential for future reproduction of the experiments or simulations, such as, measurements, calibrations, observations, analyses, images, commentary, reports, logs, notes, and electronic notebook entries that relate directly to the experiments, will be stored and archived in an appropriate searchable format on NEEScentral. Investigators will submit Structured Data (as appropriate) to the Permanent Repository of NEEScentral within six months from the end of an experiment. Much of the project data will be made accessible to the public within six months from the time of placement in NEEScentral, i.e., within 12 months from the end of the experiment. Restricted Data, as designated by the PI, will be made accessible to the public within 24 months from the time of placement in NEEScentral.

10.0 Payload Opportunities

There are numerous payload projects that exist for the proposed effort. Three potential payload opportunities are identified here, namely: (i) retrofit of structural components (e.g. using composites), (ii) evaluation of new sensing methods/tools and (iii) pre-qualification tests. Each of these (and others) could be adopted for this building test, with varying degrees of complexity, with the exception of the third opportunity, which might be more suitably considered using the NEES-UB Nonstructural Component Simulator. We have discussed this with the NEES-UB team and it was agreed that this could be a focus of future advertised payload opportunities. While these payload opportunities will be advertised to the community, the team has one well developed payload project, which is already planned during these experiments, as described in Section 10.1.

10.1 Post-Earthquake Fire Performance Investigations – Payload Project

In the 1906 San Francisco earthquake, it has been estimated that post-earthquake fire resulted in more damage than the earthquake itself, with a three-day conflagration spread over an area of more than four square miles (NOAA, 1972; Geschwind, 2001). Although much has changed in terms of building materials, construction technology, design practice and building regulation since 1906, the amount of post-earthquake fire damage in events as recent as Northridge and Kobe indicate that research on post-earthquake fire performance is sorely needed (NIST, 1994; Ohnishi, 1997; Sekizawa et al., 2003; Chen et al., 2004). To this end, the proposed program provides an opportunity to identify those characteristics of either ground motion induced damage, resulting fires, or the combination of seismic damage and fire, that can lead to dangerous situations for escaping occupants and emergency responders – in a full-scale setting. As such, in this project, a payload effort related to post-earthquake fire investigations will be undertaken. **<u>No funding is sought of the NSF-NEESR program for this effort.</u>** Funding is being sought in conjunction with this proposal, from NIST and a variety of industry sponsors. Prof. Brian Meacham of WPI has committed to undertake this payload project, as described in his letter provided in the supplementary documents. Prof. Meacham has already worked with NEESInc and determined shared use status is applicable to the payload effort (see supplementary documents – letter by NEESInc).

11.0 Project Implementation Plan

The planned duration of the project is three years (see project schedule - supplementary documents). During this time, the project team will meet regularly using NEES (Webex) or other remote tools, on a monthly basis. In-person meetings will be held at least twice a year thereafter. To facilitate both project implementation (management and coordination) and dissemination, a project website will be hosted by UCSD. The website will include: (i) concise summaries of the project tasks, (ii) periodic updates on task progress, (iii) links to real-time project information, e.g. cameras showing construction progress, (iv) simulation competition and workshop announcements, and (v) links to project relevant NEES resources.

11.1 Project Organization

Fig. 8 illustrates the roles and responsibilities of the project team. The core project team is composed of five academics (Conte, Hutchinson, Marin, Restrepo, and Walsh), two industry leaders (Bachman and Hoehler), an expert associated with the planned payload effort (Meacham), and graduate and undergraduate students from each of the core Universities. A strong industry consortium is composed of three committees, namely: *Industry Steering Committee (ISC), Engineering and Regulator Advisory Committee (ERAC),* and an *Academic/International Liaison Group (ALG)*. The ISC is composed of industry financial sponsors (Table 1b). The ISC was largely formed during two pre-proposal workshops hosted at UCSD in June and August of 2007. Approximately 30 members from industry, government, and academe participated in each workshop and helped guide the scope of the proposal. The ISC will provide industry input on the research and testing to be performed and be involved in the interpretation of results, particularly with regard to its relevance to code requirements from a supplier perspective. The ERAC is a committee to be named following award of NSF funds (per the NSF solicitation). The ALG is composed of researchers in complementary areas of research in the U.S. and abroad (see Section 6.1). Their purpose is to limit overlap, identify synergies, and communicate best practices identified in related projects.

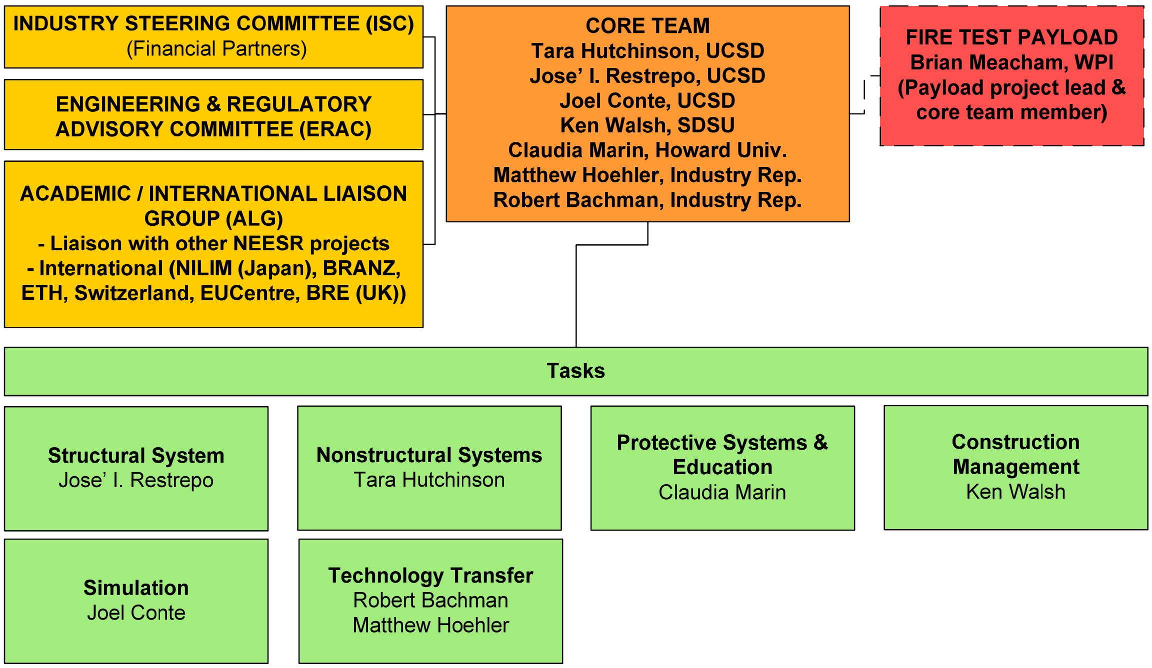


Fig. 8 Project organizational chart.

12.0 Project Risk Mitigation Plan (see Supplemental documents)

13.0 Results from Prior NSF Support

Tara Hutchinson - NSF Grant #EEC-9710568: Performance Characterization of Bench and Shelf-Mounted Equipment, support through PEER, $120,000, (10/01-04/04). **Summary:** The focus of this research was to evaluate the seismic performance of bench and shelf-mounted equipment and contents. **Publications:** [see *References Cited*.] Hutchinson and Ray Chaudhuri, 2003, 2004, 2006; Ray Chaudhuri and Hutchinson 2004a-c, 2005, 2006a-b; Hutchinson et al., 2005.

Kenneth Walsh – NSF Grants #CMMI-0333724: Pervasive Production Space: An Innovative Information Technology Framework for Homebuilding $300,000 (10/03-10/06) and **PFI 0090559**: "AzPATH-A Partnership for Housing Innovation in Arizona," $600,001 (1/01–1/05), with Bashford and Sawhney, Ariz. State Univ. The focus of the research was to conceptualize construction production to drive innovation and improved performance. **Publications:** [see *References Cited*.] Walsh et al., 2004, 2007; Walsh, 2007; Walsh and Sawhney, 2004; Bashford et al. 2003, 2005; Walsh and Miguel, 2003; Sawhney et al., 2009.

José Restrepo (PI) and Joel Conte (Co-PI; with Luco, Seible, and Van Den Einde) - NSF Grant #CMS-0217293: Large High Performance Outdoor Shake Table, $5,890,000 (Oct. 02 – Sept. 04). **Summary:** This cooperative agreement awarded under NEES, established a NEES Large High-Performance Outdoor Shake Table site at UCSD. **Publications:** [see *References Cited*.] Van den Einde et al., 2004; Restrepo et al., 2005; Conte et al., 2004, 2006, 2007; Ozcelik et al., 2006, 2008a, b, c.

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