4th International Conference on Earthquake Engineering
Taipei, Taiwan
October 12-13, 2006

Paper No. 301

# EXPERIMENTAL EVALUATION OF NONSTRUCTURAL COMPONENTS UNDER FULL-SCALE FLOOR MOTIONS

Gilberto Mosqueda[1], Rodrigo Retamales[2], Dave Keller[2], Andre Filiatrault[3] and Andrei Reinhorn[4]

## ABSTRACT

Observations during past earthquakes have demonstrated the seismic vulnerability of nonstructural components and equipment with their expensive recovery and/or replacement costs. With the exception of the nuclear industry, the limited data collected form past earthquakes are not sufficient to fully characterize the seismic behavior of nonstructural components and develop effective mitigation measures. To address these limitations, the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB) has commissioned under the National Science Foundation's George E. Brown Junior Network for Earthquake Engineering Simulation (NEES) program a dedicated Nonstructural Component Simulator (UB-NCS) composed of a two-level testing frame capable of simultaneously subjecting both displacement-sensitive and acceleration-sensitive nonstructural components to realistic full scale floor motions expected in typical multi-story buildings. Both levels of the testing platform can subject nonstructural components to 3g accelerations, 2.5 m/s velocities and +/- 1 m displacements. A series of experiments are currently underway using the UB-NCS consisting of a hospital room constructed of gypsum wallboards on light gage steel studs. The interior of the room will be furnished with self-standing and anchored building contents typical in acute care medical facilities. The experimental data will be used to evaluate the seismic fragility of both acceleration sensitive medical equipment and displacement sensitive partition walls. This paper summarizes the characteristics and unique capabilities of the UB-NCS equipment, the dynamic testing protocol considered for UB-NCS, and the planned experiments to evaluate the seismic fragility of nonstructural partition walls and medical equipment under realistic floor motion demands in multi-story buildings.

Keywords: nonstructural components, seismic fragility, experimental methods

## INTRODUCTION

With the development of performance-based earthquake engineering (Bozorgnia and Bertero 2004), harmonization of the performance levels between structural and nonstructural components becomes vital. Even if the structural components of a building achieve an immediate occupancy performance level after a seismic event, failure of architectural, mechanical, or electrical components of the building can lower the performance level of the entire building system. This reduction in performance caused by the vulnerability of nonstructural components has been observed in several buildings during the recent 2001 Nisqually earthquake in the Seattle-Tacoma area (Filiatrault et al. 2001) and during several other earthquakes that have occurred in the last 40 years. According to Miranda et al. (2003),

[1] Assistant Professor, University at Buffalo, State University of New York, Buffalo, NY, USA, mosqueda@eng.buffalo.edu
[2] Graduate Student Researcher, University at Buffalo, State University of New York, Buffalo, NY, USA
[3] Professor, University at Buffalo, State University of New York, Buffalo, NY, USA
[4] Clifford C. Furnas Professor of Structural Engineering, University at Buffalo, State University of New York, Buffalo, NY, USA

the contents and nonstructural components in office, hotel and hospital buildings compose about 82%, 87% and 92% of the total monetary investment in a building, respectively. Clearly the investment in nonstructural components and building contents is far greater than that of structural components and framing. Therefore, it is not surprising that in many past earthquakes, losses from damage to nonstructural building components exceeded losses from structural damage. Furthermore, the failure of nonstructural building components could become life-safety hazards or could affect the safe movement of occupants evacuating or rescue workers entering buildings.

In comparison to structural components and systems, there is still relatively limited information on the seismic design of nonstructural components. Basic research work in this area has been sparse, and the available codes and guidelines (FEMA 1994, 2000, Canadian Standard Association 2002) are usually, for the most parts, based on past experiences, engineering judgment and intuition, rather than on objective experimental and analytical results. Often, design engineers are forced to start almost from square one after each earthquake event: observe what went wrong and try to prevent repetitions. This is a consequence of the empirical nature of current seismic regulations and guidelines for nonstructural components.

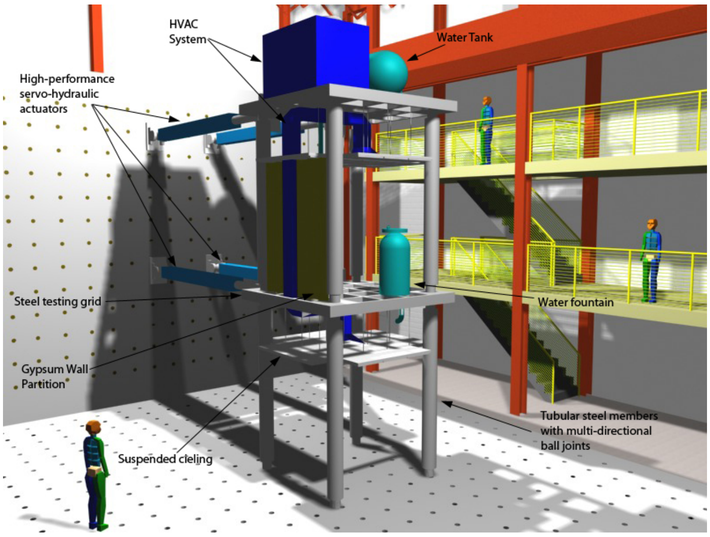



Figure 1. Nonstructural Component Simulator.

In order to reproduce in real-time the full-scale multi-axial seismic floor motions that are required to properly assess the seismic performance of nonstructural components, the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB) has commissioned under the National Science Foundation's George E. Brown Junior Network for Earthquake Engineering Simulation (NEES) program a dedicated Nonstructural Component Simulator (UB-NCS). The UB-NCS illustrated in Figure 1 is a modular and versatile two-level platform for real-time experimental performance evaluation of displacement- and acceleration-sensitive nonstructural components and equipment. The UB-NCS can provide the dynamic stroke, hydraulic flow and force necessary to replicate full-scale displacements, velocities and accelerations at the upper levels of multi-story buildings during earthquake shaking. The input motions can be obtained from recorded floor motions of buildings during past earthquakes or the simulated numerical response of a building to a given earthquake record. In order to more broadly assess the seismic vulnerability of nonstructural components independent of building or earthquake record, a general testing protocol has been proposed by the authors (Retamales et al. 2006). Testing protocols for displacement sensitive (racking protocol) and acceleration sensitive (shake table protocol) nonstructural components have been separately developed (ATC 2005), whereas the NCS has the unique capabilities to simultaneously subject test specimens to absolute floor acceleration and inter-story drifts expected in multi-story buildings.

## NONSTRUCTURAL COMPONENT SIMULATOR

Experimental testing is likely the best mean to fully understand the behaviour of nonstructural components subjected to seismic excitations. Until recently, experimental testing facilities did not have the capability to subject nonstructural components to both the absolute motions and the deformations experienced at upper story levels of multi-story buildings. The story response at these uppers levels is typically much greater than the excitations at the ground level, for which earthquake simulators and other structural testing equipment are typically designed to replicate.

The main requirements for performing real-time seismic testing of nonstructural components resides in the ability of the servo-hydraulic equipment to reproduce the multi-directional absolute floor motions at various levels of building structures excited by earthquake ground motions. In order to assess these equipment requirements, floor motions recorded in four instrumented buildings during major earthquakes in California were considered for the design of the UB-NCS. One of these buildings was shaken by the 1989 Loma Prieta earthquake, while the other three were shaken by the 1994 Northridge earthquake. Table 1 summarizes the peak responses measured and estimated at the roof level of these instrumented buildings.

From Table 1, it can be seen that the envelope of the roof responses of the four instrumented buildings are a peak acceleration of 1.5g, a peak velocity of 2.1 m/s, and a peak-to-peak stroke of 2 m. To meet these peak demand parameters, the UB-NCS testing frame is activated by four identical high performance dynamic actuators capable of subjecting nonstructural components and equipment up to 3g horizontal accelerations, 2.5 m/s (100 in./sec) velocities and ± 1 m (40 in.) displacements for specimens up to 30 kN (6.9 kips) per level. Each actuator has a reversal load capacity of 100 kN (22 kips) and a mid-stroke length of approximately 4.5 m (15 ft). Figure 2 shows the uni-axial and bi-axial testing configurations for the UB-NCS mounted against the strong wall. Vertical accelerations can also be included in an experiment by mounting the testing frame on one of the existing SEESL earthquake simulators.

Table 1. Peak seismic responses at roof level of four instrumented buildings.

| Building | Building Description and Location | Measured Peak Roof Accel. (g) | Estimated Fund. Period *T* (s) | Estimated Peak Roof Velocity (m/sec) | Estimated Peak Roof Displ. (m) |
|---|---|---|---|---|---|
| Pacific Park Plaza | 30-story, 95 m height. Concrete shear walls and moment resisting frames. Emeryville, CA. | 0.37 Loma Prieta | 2.69 | 1.55 | 0.67 |
| Olive View Medical Center | 6-story. Concrete moment resisting frames and steel plate shear walls. Sylmar, CA. | 1.50 Northridge | 0.33 | 0.77 | 0.04 |
| 7-story R/C building | Moment resisting frames in perimeter and flat plates and columns in the interior. Van Nuys, CA. | 0.58 Northridge | 1.98 | 1.79 | 0.57 |
| 13-story R/C building | Non-ductile moment resisting concrete frames with concrete shear walls in basements. Sherman Oaks, CA | 0.45 Northridge | 3.00 | 2.10 | 1.00 |

The testing frame is composed of two square 3.8 m (12.5 ft) platforms with an inter-story height of 4.25 m (14 ft). Beams are constructed from HSS200x150x13 mm hollow tube sections and the columns are made of HSS200x200x13 mm (Figure 3). The platform is a 0.6x0.6 m (2x2 ft) grid with tie-down holes spaced at 0.3 m (1 ft). Additionally, four centrally located cruciform shapes are removable to provide four 1x1 m square (3.5x3.5 ft) openings, which can accommodate tall equipment that may span more than one level. Three-dimensional swivels are used at the column-platform connections to allow for the bi-directional motion of the frame. The frame can be braced in one direction for unidirectional testing. Figure 4 show the deformed shape of the NCS. A comparison between the nominal and the experimentally obtained performance curves from 2 of the 4 actuators is shown in Figure 5, which verifies the capabilities of the equipment to achieve velocities of 2.5 m/s.

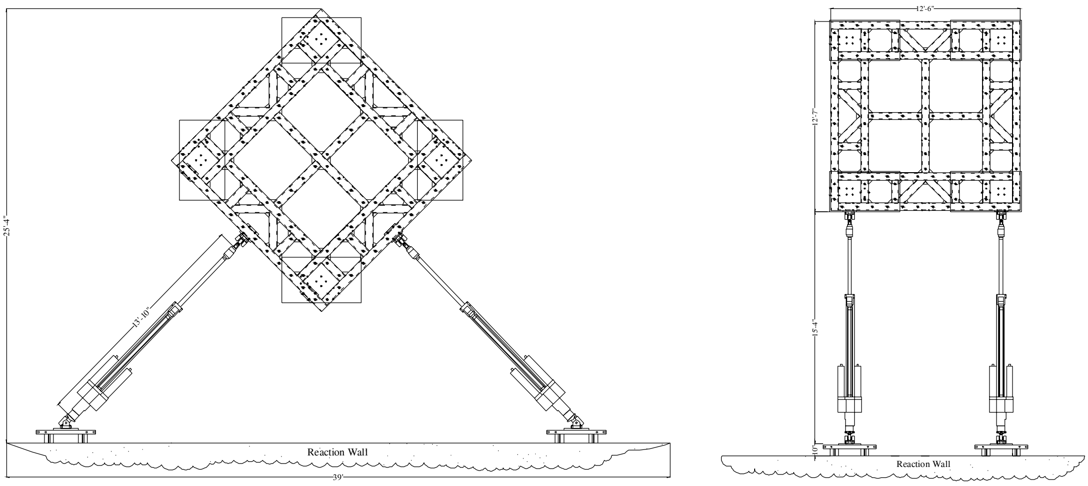



Figure 2. Plan view of bi-axial and uni-axial testing configurations (1’=0.3048 m).

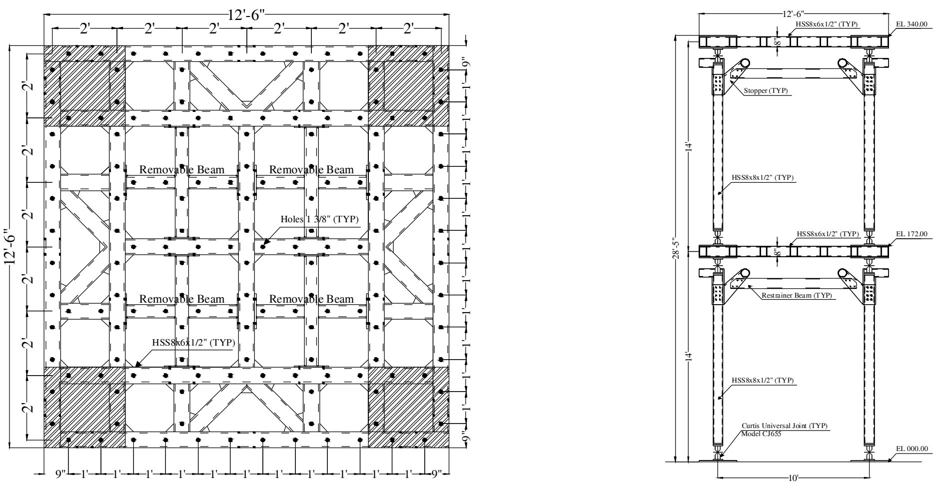



Figure 3. Plan view and elevation UB-NCS (1’=0.3048 m).

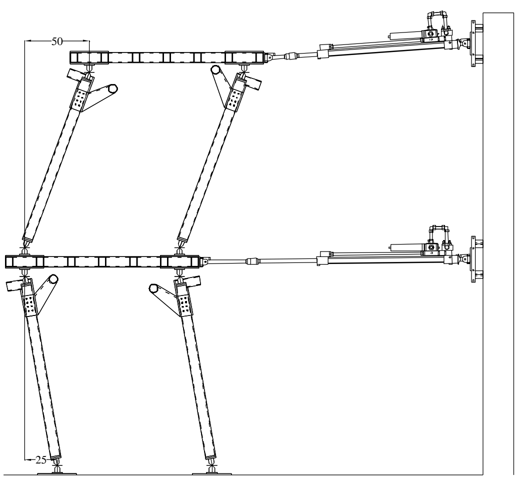



Figure 4. Deformed shape of UB-NCS
32% inter-story drift at top level. (1”=25.4 mm).

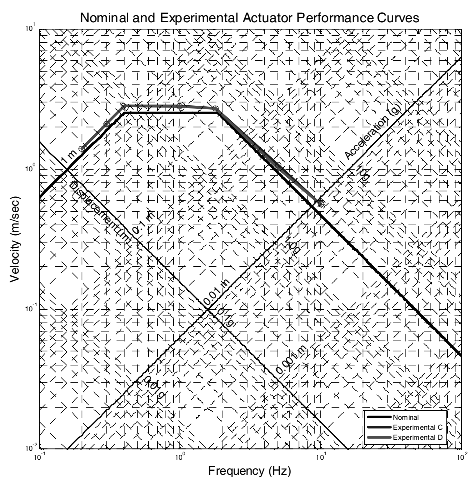



Figure 5. Actuator performance curves.

## EXPERIMENTAL PROGRAM

An experimental program is currently underway to evaluate the seismic performance of nonstructural components under full-scale floor motions. In the planned experiments, a mock hospital room enclosed by gypsum wallboards with steel stud framing will be evaluated. The room will be furnished with medical equipment critical for the operation of health care facilities following a seismic event. The nonstructural partition walls are drift sensitive and the medical equipment selected for these experiments will be primarily acceleration sensitive. The partition walls will be constructed between the lower and upper levels of the UB-NCS and will be loaded with a cyclic loading protocol that will simultaneously subject the test specimens to the expected drifts and accelerations in two continuous levels of a multi-story building. Prior to conducting these experiments, the NCS is undergoing extensive evaluations to tune the hydraulic actuators and characterize its performance under typical payloads. The experimental setup to characterize the performance of the first level of the UB-NCS is shown in Figure 6.

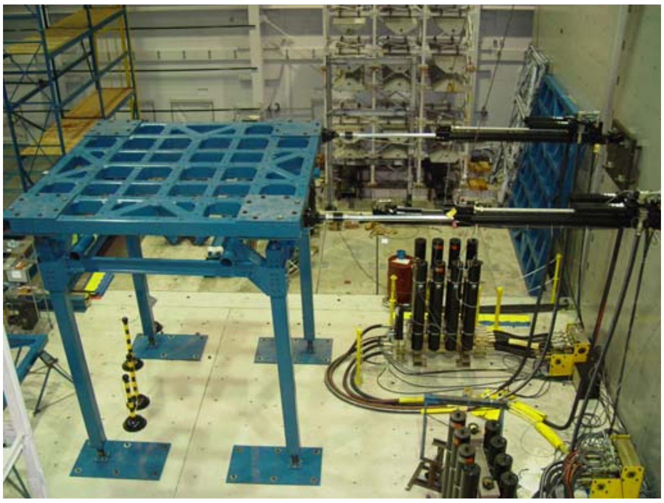
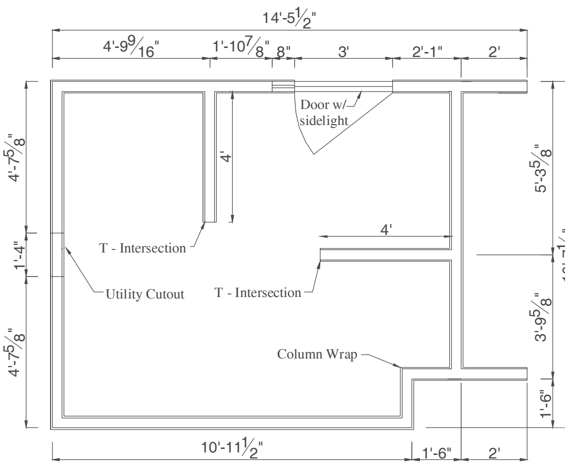


Figure 6. UB-NCS configured for single level testing.

### Displacement Sensitive Nonstructural Components

The nonstructural partition wall model is based on a similar specimen tested by Restrepo and Lang (2005) at the University of California-San Diego, using the pseudo-static loading protocol developed by Krawinkler et al. (2002). The specimen is intended to simulate a typical space which can be found in a modern office, hotel or hospital building. The walls are composed of gypsum wallboard mounted to steel studs. Concrete slabs will be attached to the top and bottom of the UB-NCS second level to simulate the boundary conditions imposed by Restrepo and Lang (2005). The walls of the specimen will be connected to the upper and lower concrete slabs through steel tracks, which are rigidly attached to the slabs. The design details will be selected to conform to standard construction practices. Slight modifications were made to the original design in order to fit the specimen within the UB-NCS. The final layout and dimensions of the specimen are shown in Figure 7. The footprint of the specimen over the concrete slab and NCS platform are demonstrated in Figure 8.

The specific goals of this project are to: (1) evaluate the seismic performance of a gypsum wallboard partition specimen under dynamic loading including simultaneous floor acceleration and inter-story drifts; (2) compare the progression of damage observed in partition walls with the specimens tested by Restrepo and Lang (2005) using a different loading protocol; (3) assess the actual construction practices (framing, wall geometry, boundary and support conditions, etc.); and finally (4) evaluate capabilities and practical limitations of UB-NCS.



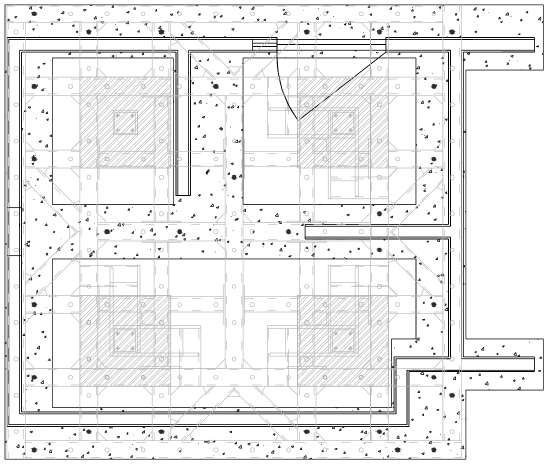



Figure 7. Geometry of specimen for the UB-NCS demonstration project (1"=25.4 mm, 1'=0.3048 m).

Figure 8. Layout of the specimen mounted on the UB-NCS.

**Acceleration Sensitive Nonstructural Components**

An extensive series of tests to evaluate the seismic fragility of acceleration sensitive medical equipment will also be performed. Both self-standing and anchored medical equipment is being considered for these experiments. The selection of equipment will be based on items available to the researchers through collaborations with the World Health Organization Collaborating Center for Disaster Mitigation in Health Facilities headquartered at the University of Chile, the World Health Organization and the Pan-American Health Organization. Testing priority will be given to equipment most critical for continued operation of essential services in a hospital following a seismic event. Table 2 summarizes, in order of importance, the services qualified as the most essential for the functionality of health facilities immediately following an earthquake, during the stabilization period, during the recovery and cleanup period, and during the transition period back to normal operation.

The ranking of the medical services shown in Table 2 is based on surveys completed by health-sector professionals following the Kocaeli and Chi-Chi earthquakes (Myrtle et al 2005). Based on the information collected, equipment essential for continuity of trauma services was also prioritized and is shown in Table 3. Note that Table 3 does not necessarily show the equipment that is most vulnerable to damage during strong ground motions which is the focus of the proposed experiments.

Table 2. Services to be prioritized (after Myrtle et al. 2005)

| Service |
|---|
| Trauma |
| Communication central |
| Pharmacy |
| Blood bank |

Table 3. Medical equipment critical for operation (after Myrtle et al. 2005)

| Medical equipment |
|---|
| Monitors |
| Ventilators |
| X-rays (portable) |
| Defibrillators |
| Anesthesia machines |
| Sterilizing equipment |

**Loading protocol**

In order to evaluate the seismic performance and fragility of partition walls and medical equipment, a bi-axial dynamic testing protocol will be considered. The protocol proposed by Retamales et al (2006) will be scaled to seismic demands associated to seismic hazard levels with probabilities of exceedance ranging between 50% in 50 years and 2% in 50 years. The excitations will be applied simultaneously in two perpendicular directions in increasing order of amplitudes. The amplitudes for each seismic hazard level are scaled using the approach suggested in FEMA 356 (2000) and given by Equations (1) and (2):

$$P_R = \frac{-Y}{Ln\left(1 - P_{EY}\right)} \tag{1}$$

$$S_i = S_{i_{10/50}} \left(\frac{P_R}{475}\right)^n \tag{2}$$

where $P_R$ is the mean return period, $P_{EY}$ is the probability of exceedance in time *Y*, $S_{i_{10/50}}$ is the spectral acceleration parameter at a 10%/50 year exceedance rate, $S_i$ is the spectral acceleration parameter at the desired probability of exceedance, and *n* is a factor which depends on the region where the seismic hazard is evaluated.

Table 4 summarizes the multipliers applied to the proposed displacement protocols (both top and bottom levels) in order to scale the input motions for other seismic hazard levels. Figure 9 shows a comparison of the scaled displacement protocols being considered for the planned experiments.

Table 4. Multiplier factors required to estimate protocols associated to different seismic hazard levels.

| Probability of exceedance | Max. Protocol Acceleration (g) | Scale Factor |
|---|---|---|
| 2%/50yr | 1.51 | 1.00 |
| 5%/50yr | 1.15 | 0.76 |
| 10%/50yr | 0.94 | 0.62 |
| 50%/50yr | 0.54 | 0.36 |

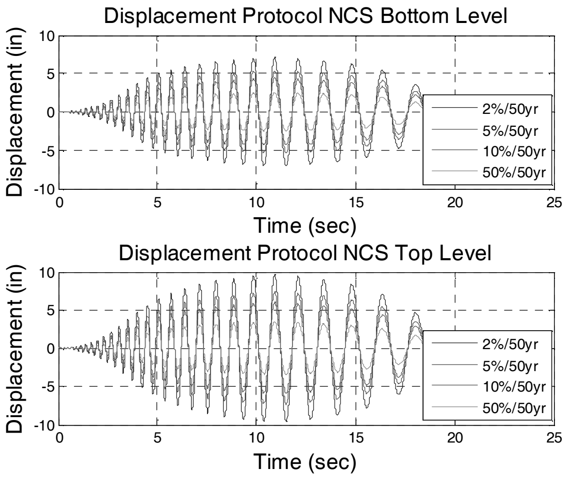



Figure 9. Displacement protocols for several seismic hazard levels.

## CONCLUSIONS

At the present, experimental testing facilities do not have sufficient capability for investigating the performance of nonstructural components under realistic seismic loading. This deficiency is serious considering that the investment in nonstructural components and building contents is far greater compared to structural components and framing. Not surprisingly, losses from damage to nonstructural building components exceeded losses from structural damage in several recent earthquakes. In order to better understand the seismic behaviour of nonstructural components, the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (UB) has commissioned under the National Science Foundation's George E. Brown Junior Network for Earthquake Engineering Simulation (NEES) program a dedicated Nonstructural Component Simulator (UB-NCS) which can subject non-structural components to realistic full-scale horizontal and/or vertical floor motions.

Experiments under preparations will demonstrate the potential of the UB-NCS in subjecting nonstructural components to realistic full scale floor motions. The first experiments will focus on acute care facilities, particularly medical equipment that is critical to maintain continuous operation following a seismic event. The experiments will simultaneously subject partition walls and medical equipment to expected floor accelerations and displacements in multi-story buildings.

## ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation under award number CMS-0429331 and award EEC-9701471 through the Multidisciplinary Center for Earthquake Engineering Research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

## REFERENCES

ASTM (1997). *ASTM 1049-R97: Standard Practices for Cycle Counting in Fatigue Analysis*. American Society of Testing Materials.

ATC (2003). *ATC-58-2: Preliminary Evaluation of Methods for Defining Performance*, Applied Technology Council.

ATC (2004). *ATC-58: Engineering Demand Parameters for Nonstructural Components, Project Task Report, Phase 2*, Applied Technology Council.

ATC (2005). *ATC-58: Interim Protocols for Seismic Performance Testing of Architectural, Mechanical and Electrical Components, Third Draft*, Applied Technology Council.

Bozorgnia, Y. and Bertero, V.V., Editors (2004). *Earthquake Engineering, From Engineering Seismology to Performance-Based Engineering*. CRC Press, Boca Raton, FL.

Canadian Standard Association 2002, Guideline for seismic risk reduction of operational and functional components (OFCs) of buildings, *Standard CSA S832-01*, Mississauga, Ontario.

FEMA (1994). Reducing the risks of nonstructural earthquake damage, a practical guide, Federal Emergency Management Agency (FEMA), *Report No. FEMA 74*, Washington, DC.

FEMA (2000). Prestandard and commentary for the seismic rehabilitation of buildings, Federal Emergency Management Agency (FEMA), *Report No. FEMA 356*, Washington, DC.

Filiatrault, A., Christopoulos, C., Stearns, C. (2001). "Guidelines, Specifications, and Seismic Performance Characterization of Nonstructural Building Components and Equipment." *PEER Report 2002/05*, University of California, Berkeley.

Halldorsson, B. (2004). "The Specific Barrier Model: Its Calibration to Earthquakes of Different Tectonic Regions and the Synthesis of Strong Ground Motions for Earthquake Engineering Applications." *PhD Dissertation*, Department of Civil, Structural and Earthquake Engineering, University at Buffalo.

Krawinkler, H., Parisi, F., Ibarra, L., Ayoub, A., Medina, R. (2002). *Development of a Testing Protocol for Wood frame Structures*, Consortium of Universities for Research in Earthquake Engineering (CUREE).

Myrtle, R.C., Masri, S.F., Nigbor, R.L., Caffrey, J.P. (2005). "Classification and Prioritization of Essential Systems in Hospitals under Extreme Events." *Earthquake Spectra*, **21**(3): 779-802.

Restrepo, J., Lang, A. (2005). *Interim Report to PEER Advisory Board. Year 7: Performance Evaluation of Gypsum Wallboard Partitions, Results of Test 1*, Pacific Earthquake Engineering Research Center (PEER).

Retamales, R., Mosqueda, G., Filiatrault, A., Reinhorn, A.M. (2006). "Experimental study on the seismic behavior of nonstructural components subjected to full-scale floor motions." *Proceedings, 8th US National Conference on Earthquake Engineering. April 18-21,* 2006*, San Francisco, California*.

Taghavi, S., Miranda, E. (2003). Response Assessment of Nonstructural Building Elements, *PEER Report 2003/05*, University of California Berkeley.