MCEER RESEARCH TASK STATEMENT

<table>
<thead>
<tr>
<th>Thrust Area: 2</th>
<th>Budget:</th>
<th>Yr 9 Assigned Project Number: 9.2.3</th>
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<tr>
<td>Task Title: Integrated Design of Acute Care Facilities with Self-Centering Systems</td>
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<tr>
<td>Investigator/ Andre Filiatrault*, Andrei Reinhorn, Michel Bruneau</td>
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<tr>
<td>Institution: University at Buffalo</td>
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<tr>
<td>*indicates task leader</td>
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Statement of Project Goals: (Conceptually describe what the work is intended to accomplish, in 100 words or less. Do not provide detailed description here.)

The main objective of this year 9 research task is to investigate numerically and experimentally the application of structural systems exhibiting strong self-centering characteristics for the integrated design of new hospital buildings in order to achieve a target resilience level for both structural and nonstructural components and systems. Although the knowledge gained in this research applies to a wide range of self-centering systems, the study focuses on the Post-Tensioned Energy Dissipating (PTED) steel frame concept developed under the leadership of the task leader. This system, unlike traditional welded steel frames, incorporates high strength post-tensioned bars along with sacrificial yielding elements in each beam-to-column connection and is particularly appealing for hospital buildings from an initial cost standpoint. This year 9 research focusing on the response of multi-degrees of freedom structures will build on the work completed in year 8 on single-degree-of-freedom structures. The specific objectives of this year 9 research are to conduct numerical studies of the MCEER west-coast demonstration hospital re-designed using the PTED concept and to conduct, for the first time ever, shake table testing of a large-scale PTED steel model.

Problem Description and Research Approach of Proposed Work for Year 9: (Detailed description of research to be conducted and methodology to be used.)

This year 9 research task aimed at controlling both the transient and residual seismic responses of structural and non-structural components and systems in acute care facilities using the Post-Tensioned Energy Dissipating (PTED) steel frame concept developed under the leadership of the task leader. In this system, the beams and columns are not welded together. Instead, Post-tensioning (PT) self-centering bars along with energy-dissipating (ED) bars are included at each connection, as illustrated in Fig. 1. PTED connections can undergo large transient inelastic deformations with minimal damage to the main structural elements with near zero residual deformations.

Fig. 1 PTED Steel Frame Concept.
This proposed year 9 research task will build on the work completed in year 8 on single-degree-of-freedom (SDOF) PTED structures by focusing on the response of multi-degrees of freedom (MDOF) PTED structures. Specifically, the seismic response of the MCEER west coast demonstration hospital will be re-designed to incorporate a self-centering PTED system. The re-designed building will be first investigated numerically when subjected to the MCEER ground motion ensembles that have been developed at MCEER under the leadership of the task leader in an associated year 8 research task. For this study, it will be assumed that each beam-to-column connection of the seismic steel frames of the demonstration hospital will be designed with a PTED connection of the type shown in Fig. 1. For this purpose, design charts developed from an extensive parametric study on the seismic response of single-degree-of-freedom (SDOF) systems incorporating flag-shaped hysteretic structural behavior, with self-centering capability, conducted in year 8 will be used. The responses of the hospital structure equipped with PTED connections will then be compared to the responses of the original structure incorporating conventional welded beam-to-column connections. Floor acceleration time-histories obtained from the two different framing systems will then be compared to evaluate the differences in the demands to nonstructural components.

The PTED concept will then be evaluated experimentally by conducting shake table tests on a 3-story, 2-bay, steel plane frame model incorporating PTED connections. Because of physical limitations, a complete model of the demonstration hospital could not be considered. In order to increase the scale of the specimen as much as possible, the plane test frame will be sandwiched between existing gravity supported masses. This will allow the test of a three-story structure incorporating exterior and interior PTED connections over three stories. This test configuration was used successfully for the testing of a “zipper frame” concept by the co-task leader (http://nees.buffalo.edu/projects/zipperframes/anouncement.aspx). The test model will be subjected to various ground motions of increasing intensities taken from the MCEER ground motion ensembles. This shake table testing will represent the first dynamic testing ever of a structure incorporating self-centering systems and will provide a unique opportunity to advance the knowledge on these systems.

The shake table tests will be conducted in collaboration with Professor Constantin Christopoulos from the University of Toronto, Canada. Professor Christopoulos has recently developed a modified version of the PTED connections in which the ED bars are replaced by friction connections at the interface between the shear tabs and the beam webs. It is planned to use both types of connections in the test structure (one type in each direction) in order to compare their behavior.

**Assessment of State-of-the-Art:** (Describe other relevant work being conducted within and outside of MCEER, and how this project is different.)

Although the behavior of self-centering systems using shape memory alloys, or fluids constraint in specially build containers have been investigated analytically and experimentally, no study has assessed the demands that self-centering systems imposed on non-structural components in a building. This project will contribute to this assessment through a rigorous numerical study of the MCEER demonstration hospital re-designed with PTED connections. Furthermore, the proposed shake table tests will be the first ones on any kind of self-centering systems.
Progress to date: (If applicable, a short description of achievements in previous years. Clearly distinguish progress achieved in the past year, i.e., accomplishments from April 1, 2004, to March 31, 2005.)

The integrated design of hospital buildings incorporating self-centering systems is a relative new MCEER initiative begun in year 8. At the time of writing, a numerical parametric study on the seismic response of single-degree-of-freedom (SDOF) self-centering systems incorporating flag-shaped hysteretic structural behavior, with self-centering capability, has been completed. For a SDOF system with a given initial period and strength level, the flag-shaped hysteretic behavior was fully defined by a post-yielding stiffness parameter ($\alpha$) and an energy-dissipation parameter ($\beta$), as shown in Fig. 2. A comprehensive parametric study was conducted to determine the influence of these parameters on SDOF structural response, in terms of relative displacement and absolute acceleration, which are also demand parameters for non-structural components. This parametric study was conducted using the MCEER ensembles of synthetic earthquake records that correspond to various probability of exceedence at the locations of the MCEER west coast demonstration hospital. The responses of the flag-shaped hysteretic SDOF systems were compared against the responses of similar bilinear elasto-plastic hysteretic SDOF systems, representative of traditional yielding structural systems. Building structures with initial periods ranging from 0.1 to 2.0s and having various strength levels were considered. Design envelopes for the post-yielding stiffness parameter ($\alpha$) and energy-dissipation parameters ($\beta$) were determined as a function of a given strength ratio between the self-centering and elasto-plastic systems in order to limit the demands on non-structural components to pre-determined levels (see Fig. 3). The results of the study were given in terms of a Relative Performance Index (RPI) defined as:

$$RPI = W_1 \bar{d}_{FS} + W_2 \bar{a}_{FS}$$

$$\bar{d}_{EP} \bar{a}_{EP}$$

$$W_1 + W_2 = 1; \ W_1, W_2 \geq 0$$

where $\bar{d}_{FS}$ and $\bar{d}_{EP}$ are the mean maximum displacement across the earthquake ensemble for the flag-shaped and elasto-plastic systems, respectively and $\bar{a}_{FS}$ and $\bar{a}_{EP}$ are the mean maximum acceleration across the earthquake ensemble for the flag-shaped and elasto-plastic systems, respectively. If $RPI < 1$, the response of the self-centering system is improved compared to the response of the original yielding system. The weighting factors $W_1, W_2$ in the definition of the RPI are introduced to allow some flexibility in the integrated design process. If unrestrained acceleration-sensitive nonstructural components inside the building are of primary importance, the selection of the optimum self-centering system would be based on an RPI obtained for $W_2 \geq W_1$. On the other hand, if significant investment has gone towards securing nonstructural components, the selection of the optimum self-centering system would be based on an RPI obtained for $W_2 \leq W_1$. 

Fig. 2 Parameters of Flag-Shaped System.
Role of Proposed Task in Support of Strategic Plan: *(Describe how the effort will make a unique, useable contribution to the MCEER strategic plan.)*

The strategic plan of MCEER is to develop integrated decision-making tools and processes for the improved seismic resilience of communities. Since acute-care facilities are critical for the successful and rapid recovery of a community in the aftermath of a seismic event, the harmonization of the seismic performance of structural and non-structural components in these facilities is required. This proposed year 9 research task strongly supports the MCEER strategic plan, particularly with regard to the achievement of the seismic resilience objectives by the control of the transient and residual response of both structural and nonstructural systems using innovative self-centering systems. For this purpose, it is proposed to quantify the resilience of PTED steel structures using the concept and quantitative procedure defined by Bruneau and Reinhorn in their MCEER overarching task. This formulation evaluates the resilience in terms of loss of function and time to recovery, which are limited here to the structural and nonstructural components and basic building functions.

Task Integration: *(Describe how the work performed interfaces with other tasks and researchers funded by MCEER.)*

The proposed year 9 research describe herein on self-centering systems is designed to integrate and interface with several research projects conducted in Thrust Area 2 and with the Center Wide Overarching resilience formulation project.
The Specific Barrier Model for Eastern and Western United states ground motions developed at MCEER under the leadership of Papageorgiou are being utilized to generate the ensembles of synthetic strong ground motions to be used in the numerical and experimental studies.

The structural model of the MCEER west coast demonstration hospital developed by Whittaker et al. in their Thrust Area 2 project will be utilized to re-design the structural system with PTED connections. The floor acceleration time-histories obtained from the proposed numerical and experimental studies will be integrated in the floor acceleration database being developed at MCEER in an associated Thrust Area 2 project under the leadership of the task leader.

The plane test frame model configuration proposed for the shake table tests can be re-used for the verification of model of rocking elements with pre-stressing (or external axial loads) developed in an associated Thrust Area 2 task of weakened structures by the co-task leader (Reinhorn). It is proposed to intersect the efforts and complement the work in both tasks. Therefore, the meaning of the PTED solution investigated in this task can be interpreted in a broader perspective.

The experimental seismic fragility curves developed for the acceleration-sensitive non-structural components investigated by the PI in another Thrust Area 2 project will be used to develop design envelopes for self-centering system parameters.

The formulation developed by Bruneau and Reinhorn in their MCEER overarching task will be used to evaluate the resilience of self-centering structures in terms of loss of function and time to recovery.

**Possible Technical Challenges:**

The main technical challenge perceived at the time of writing is related to the tight budget available for the construction of the shake table test model. Collaboration with large steel fabricators will be sought in order to have the test model fabricated free of charge.

**Anticipated Outcomes and deliverables: (Also indicate those of particular benefit to IAB members and other end users.)**

- Set of design criteria for self-centering systems in order to limit demands on non-structural components to pre-determined levels.
- Experimental evaluation of the dynamic behavior of self-centering structural systems.

**Potential end-users beyond academic community: (IAB members and others.)**

- Owners and administrators of acute-care facilities and other facilities that can incorporate self-centering systems in their structural systems.
- Consulting structural engineers.
- MCEER strategic industry partners (e.g. OSHPD)

**Educational outcomes and deliverables, and intended audience:**

Information/deliverables to be included in the UB graduate classes in *Earthquake Engineering* (CIE 619) and *Structural Control* (CIE626). Intended academic audience is graduate students.
Other groups impacted by the research results will include a) the design professional community, b) members of the ATC-58 project team, and c) MCEER strategic industry partners.

It is planned to webcast the shake table tests using the tele-presence capabilities of the NEES grid available at the University at Buffalo so that MCEER strategic industry partners as well as steel fabricators that have donated test specimens can participate remotely in the testing program.

The task leader is very active in educational activities aimed at disseminating the research conducted in Thrust Area 2 at MCEER. On February 24, 2005, a one day Hospital Research & Retrofit Seminar was organized at OSHPD by the task leader. For this occasion, all Thrust Area 2 investigators shared their research results with more than 40 OSHPD engineers. The task leader made a presentation on self-centering systems at this OSHPD seminar.

Furthermore, the task leader conducted the following educational activities in the last year.

<table>
<thead>
<tr>
<th>Date</th>
<th>Audience/Location</th>
<th>Type of Activity</th>
<th>Title of Presentation</th>
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<tr>
<td>02/03/04</td>
<td>York International Management York, PA</td>
<td>Presentation</td>
<td>MCEER Vision, Mission, and Overview of Systems Integrated Research Activities</td>
</tr>
<tr>
<td>03/13/04</td>
<td>High School Students Buffalo, NY</td>
<td>Engineering Seminar &amp; Exhibition for High School Students</td>
<td>Earthquake Engineering Hazards and Mitigation</td>
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<tr>
<td>04/16/04</td>
<td>Holland Elementary School Library Holland, NY</td>
<td>Continuing Education</td>
<td>Earthquakes!</td>
</tr>
<tr>
<td>05/19/04</td>
<td>UJNR Wind and Seismic Effects Panel, Washington DC.</td>
<td>Presentation</td>
<td>MCEER Research Activities in Seismic Retrofit of Acute Care Facilities</td>
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<tr>
<td>10/29/04</td>
<td>Student Leadership Council Members Buffalo, NY</td>
<td>Presentation and Webcast</td>
<td>Welcoming Remarks to New MCEER Graduate and Undergraduate Students</td>
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<tr>
<td>11/11/04</td>
<td>Sheet Metal and Air Conditioning Contractors' National Association Buffalo, NY</td>
<td>Seminar</td>
<td>MCEER Research to Protect Nonstructural Components During Earthquakes</td>
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<tr>
<td>12/08/04</td>
<td>International Seismic Application Technology Buena Park, CA</td>
<td>Presentation</td>
<td>MCEER Vision, Mission, and Research Activities</td>
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<tr>
<td>12/09/04</td>
<td>Southern California Edison Los Angeles, CA</td>
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<td>MCEER Vision, Mission, and Research Activities</td>
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<td>01/21/05</td>
<td>Sheridan Hill Elementary School Clarence, NY</td>
<td>Presentation for “2005 Quake and Shake” activity</td>
<td><a href="http://mceer.buffalo.edu/education/k-12/05QuakeandShake/default.asp">http://mceer.buffalo.edu/education/k-12/05QuakeandShake/default.asp</a></td>
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**Project Schedule and Expected Milestones for the Project:** (Milestones and estimated time of achievement; e.g., Fall, Spring, Summer)

During MCEER year-9, the seismic response of MCEER west coast demonstration hospital re-designed with self-centering systems will be evaluated numerically. Also, shake table testing of a self-centering steel frame model will be conducted.

**Team Members:** (If known, provide names of team members associated with project including project leader, other faculty and their departments, undergraduate students, graduate students, postdoctoral students, industrial participants.)

Andre Filiatrault, Task Leader, Professor
Andrei Reinhorn, Professor
Michel Bruneau, Professor
Dong Wang, Ph.D. Student

All from the Department of Civil, Environmental and Structural Engineering, University at Buffalo.

**Possible Direction of Work in Subsequent Years:**

Evaluation of the behavior of self-centering structures to multi-hazard extreme loading.

**Multi-Hazard Statement:**

a) (Conceptually describe in 200 words or less how some of the work you are conducting as part of your MCEER Year 9 research task can be exported/applied to other natural or man-made hazards including multi-hazard research.)

This task deals with the development of innovative structural lateral load-resisting systems that possess self-centering characteristics that are economically viable alternatives to current conventional lateral-load resisting systems. Self-centering systems have demonstrated through large-scale experimental studies potential for very large inelastic deformations, without any damage to their main connecting structural elements and with the intrinsic properties of returning at, or near, their undeformed position once the solicitation is released. These types of structural systems could be exported to other types of extreme loading arising from sources other than earthquake shaking. PTED steel frames can be viewed as a structural system incorporating a tri-phase behavior with (i) high stiffness before gaps open in the PTED connections that can provide good protection for high rates of loading (e.g. near fault earthquakes, shocks, explosions, blasts, strong sea waves), (ii) energy dissipation capabilities that can provide protection against large amplitude vibrations (e.g. earthquakes, explosions, blasts), and (iii) strong re-centering characteristics that minimize permanent deformations such as resulting from earthquakes, windstorms / wind gusts, traffic, etc.
It can be argued also that the development of lateral load-resisting systems specific to a given type of hazard may not be the best economical solution for multi-hazard mitigation. The use of a lateral load-resisting system that can mitigate several hazards simultaneously would require the development of innovative systems. Self-centering systems have the potential to fulfill this promise.

b) *If you are seeking supplemental multi-hazard funding, describe the multi-hazard milestones that you plan to complete as part of your Year 9 research.*

It is proposed in year 9 to explore the expansion of this task to blast loading. For this purpose, the numerical model of the MCEER west coast demonstration hospital incorporating self-centering systems will be modified in order to perform a series of dynamic analyses under simulated transient blast loading. Dynamic transient forces on the external nodes of the structural model will be generated to represent the sequence of positive and negative pressure gradients on the structural elements of the building arisen from a blast of a given size near the site. Strength degradation models will be included in the analysis in order to simulate the complete failure of structural elements (e.g. beams and columns) during the dynamic response. Because self-centering systems can undergo very large inelastic deformations without structural damage to the main structural elements, it is possible that this system will reduce significantly the potential for progressive collapse by limiting the collapse to the structural elements directly hit by the blast pressure. The complete failure of a lower level column in a PTED frame, for example, may not trigger a progressive collapse since the upper level connections would be able to deform with minimal damage to the structural elements, thereby limiting the collapse propagation, and return to their original position if the column is propped back into position. This work will provide a unique opportunity to evaluate the influence that self-centering systems may have in reducing the progressive collapse of mission-control structures, such as acute-care facilities, under blast loading. Note that the objective of this numerical study is not achieve a reliable model of the blast propagation on the building envelope but to obtain an order of magnitude of the deformations induced in structural elements of PTED frames as a result of blast loading on buildings incorporating cladding systems designed to resist blast pressures.