Seismic Performance of a Two-Story Two-Bay Reinforced Concrete Building

Rachel Howser[1], Manan Bhalja[2], Chris Caruso[3], Y.L. Mo[4], and K.C. Tsai[5]
[1]*University of Houston, Houston, TX 77204, USA . E-mail: rnhowser@uh.edu*
[2]*University of Houston, Houston, TX 77204, USA . E-mail: mjbhalja@uh.edu*
[3]*University of California, Berkeley, Berkeley, CA 94707, USA. E-mail: ccaruso1@berkeley.edu*
[4]*University of Houston, Houston, TX 77204, USA. E-mail: yilungmo@egr.uh.edu*
[5]*National Center for Research in Earthquake Engineering, Taipei, 106, Taiwan. E-mail: kctsai@ncree.org.tw*

Abstract: The National Science Foundation awarded the Department of Civil and Environmental Engineering at the University of Houston in Houston, Texas with the funding to complete research on a reinforced concrete building at the National Center for Research on Earthquake Engineering in Taipei, Taiwan. The educational goals of this grant were to test the seismic performance of a complex structure under combined flexural, shear, and torsional loading. This paper focuses on completing a lateral load test on the specimen, collecting data from the test using a system of smart aggregates, and seismic simulation of the building. The project consisted of a biaxial pseudo-static lateral load test of a three-dimensional two-story two-bay reinforced concrete frame structure. The test specimen contained two low-rise shear walls and a mid-rise shear wall arranged to create an asymmetric floor plan. This specimen would then be subject to cyclic lateral loads so as to generate torsion, allowing its effects on specimen behavior to be studied and modeled. During the test, research on the applicability of smart aggregates to assess the seismic impacts and damages that lead to catastrophic consequences. A network of actuator-sensor smart aggregates was used to assess the severity of the damage on the structure. The assessment is based on sensor damage indices and damage matrices that relate the damaged state to the healthy state of the structure. Additionally, seismic simulation of the building was completed through the use of "Simulation of Reinforced Concrete Structures," a nonlinear finite element computer program that runs within OpenSees. Because of the complexity of the structure, the results of the test will provide researchers around the world with unique test data.

INTRODUCTION

The National Science Foundation (NSF) awarded the Department of Civil and Environmental Engineering at the University of Houston (UH) in Houston, Texas with the funding to complete research on a walled, three-dimensional, two-bay, two-story, asymmetric, reinforced concrete (RC) building. There were three objectives associated with the project, including : a.) developing an innovative piezoceramic-based multi-dimensional and multi-functional smart aggregate network for the seismic performance evaluation of RC structures, b.) conducting a reversed cyclic loading test on a RC structure with smart aggregates and correlate the smart aggregate-based damage index and damage matrices with results from conventional methods such as visual inspection, measurements from load cells, accelerometers, and displacement sensors, and c.) simulating a walled, three-dimensional, two-bay, two-story, asymmetric RC frame using "Simulation of Reinforced Concrete Structures" (SRCS), a nonlinear finite element computer program that runs within OpenSees.

The laboratory chosen for the project was the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. The project investigator, Dr. Y.L. Mo from UH, was a Division Head of NCREE from 1997 to 2000 and has been an advisor since 2003. Taiwanese researchers planned to conduct a full scale tests on a two-story, two-bay, RC building under reverse cyclic loading during the summer of 2008. Researchers at UH attended a workshop at NCREE in April 2007 to discuss research details of cooperation in smart aggregate research associated with this project. Over the next year, UH contributed to NCREE's design and analysis of the building in addition to the development of the smart aggregates to be used in the project.

The knowledge gained from this international collaboration is significant because it will result in a multi-hazard first responder system for civil infrastructures and a reliable model for three dimensional RC structures. Since RC structures comprise 50% of all the superstructures in the United States, the proposed research will positively impact a part of infrastructure that amounts to tens of billions of dollars. The proposed international collaboration will initialize the development of advanced sensing technologies to produce smart RC structures while enhancing innovations and productivity of the research and education efforts. Increasing economic globalization is making it essential that the education experience of engineering students include a global perspective and an appreciation of the societal implication of their work. This project will greatly improve the academic exchanges among the two institutions. Such exchanges ensure long term cooperation in the fields of structural modeling and smart materials and structures.

Three recently graduated American students, Rachel Howser, Manan Bhalja, and Chris Caruso, traveled to Taipei during the summer of 2008. UH hoped to recruit students from universities that offered limited research opportunities, students that represented underrepresented minorities, and females. Bhalja focused on Objective A while Caruso concentrated on Objective B and Howser attended to Objective C. The three students traveled on different days but where in Taiwan from late May 2008 until late August 2008. The anticipated outcomes of the research included gathering test data from a complex structure, monitoring the health of the building, simulating the frame response to seismic excitation, and comparing the simulated results to the actual test data.

Manan Bhalja was chosen to work with the smart aggregates (SA) placed in the structure. Bhalja had previous experience using SA. Since a major aspect of this research was to develop SA based sensing techniques and collect important data using data acquisition systems, the project investigator selected him to be the student to assist with the data collection and sensor network development. At the time of the research, he held a bachelors degree in Civil Engineering and was set to start a masters program in Civil Engineering at UH.

Chris Caruso was chosen as part of this grant because of his prior research experience at UH. The project investigator works on many research projects, both domestic and foreign. His involvement in the 3D RC building experiment necessitated American involvement in the project on-site because of the large amount of American funding in the project. Caruso started his first year as a graduate student at the University of California at Berkeley in the Fall of 2008 as a candidate for the Master of Science degree in Civil Engineering.

Rachel Howser was chosen to complete the seismic simulation of the RC frame. Howser earned her Bachelor of Science in Civil Engineering from Rose-Hulman Institute of Technology in May 2008 and began her graduate work at UH in the fall of 2008. Howser had significant knowledge of the OpenSees framework prior to beginning the project. She spent the summer of 2007 modeling hollow reinforced concrete columns in a nonlinear finite element computer program, "Simulation for Reinforced Concrete Structures" (SRCS) (Zhong 2005) which runs within the OpenSees framework.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The research program carried out consisted of experimental specimen preparation and completion of the experiment itself. The first task involved sensor preparation, organization, and installation. In addition, theoretical predictions of building properties and behaviors were necessary for a better formulation of the load history and testing procedure. Concrete cylinder tests for compressive strength were performed to this end, in addition to calculations of the specimen's theoretical stiffness center and creation of a simple elastic model for validation purposes.

Due to the specimen's size and complexity (see Figure 1 for a picture of the specimen), a total of 225 different sensors were used to collect data about the structure's behavior during testing. Each of these sensors needed to be properly installed and catalogued to ensure acceptable data collection and post-test processing. It was especially important that sensor locations be correctly matched with data-logger outputs because the project's final data will be made available to many research institutions throughout the world.

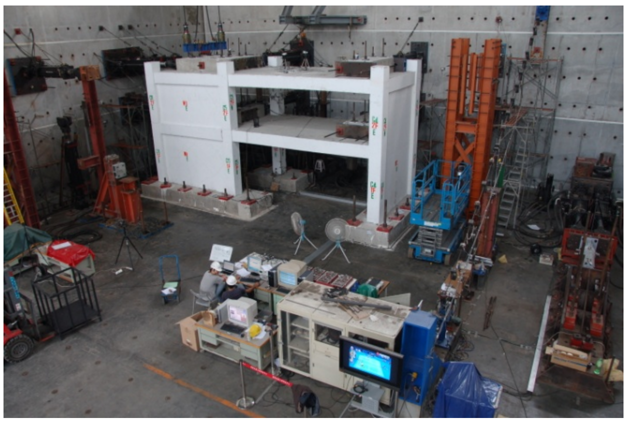

Figure 1: Picture of RC Building

Some of the work performed on-site was intended to allow accessibility of the work being performed at NCREE to outside researchers, particularly those in English-speaking countries. Although the lab personnel were familiar with English, their speaking and writing skills were insufficient to perform the tasks Caruso performed with relative ease. Therefore, Caruso's work allowed lab workers and researchers to focus on other tasks more specific to the specimen fabrication and preparation, which often required individuals fluent in Mandarin Chinese to communicate with construction workers or lab employees.

Caruso's interaction with the host laboratory was both professional and personal. NCREE's researchers have enough familiarity with English to roughly compensate for the IREE awardee's inexperience with Mandarin Chinese; however, many tasks would have been performed more efficiently if communication with NCREE researchers were easier. Regular meetings were held for the researchers and lab workers involved in the project to assess progress and solve current problems. In these meetings, a combination of English and Mandarin Chinese were used where appropriate and NCREE researchers were eager to ask our assistance in project-related matters despite the obvious language barrier.

Caruso's accomplishments in the program consist mainly of contributions to help complete the biaxial test on schedule. This included completion of the sensor catalogue for ease of sensor installation and data analysis. Considering the relatively large amount of data streams coming from different sources, particular care was necessary to ensure that data signals were not mislabeled, leading possibly to false conclusions about the structure's behavior. Since many people were involved in the test preparation, it was also necessary that channel assignments and corresponding sensor locations be publicly known and fully understood.

Additionally, analytical work was performed to determine the theoretical location of the building's stiffness center. This information was needed in order to fashion an appropriate load history for the biaxial test. Since the effects of torsion on building systems is of particular interest to this project, the researchers intended for the load history to move the building in such a way as to maximize this torsional effect. A systems-oriented approach was used to model the two-story structure as a lumped parameter mass and spring system. Combined with calculated stiffness for each column and wall stiffness values obtained from an OpenSees finite element model, the stiffness center could then be found using simple equilibrium equations.

Bhalja's focus in the project was on the development of smart aggregates (SA) and their application in structural health monitoring of the RC building. He worked under Dr. Wen I Liao, a researcher at NCREE, and a professor at National Taipei University of Technology (NTUT). During the first month of his stay, he and Dr Liao's students prepared smart aggregates. They embedded the SA into the RC building and decided the actuator-sensor network to be used for data acquisition.

After the early age strength monitoring test, a bending test was performed on the RC beams. The purpose of the test was to perform health monitoring of the beams subjected to flexural loads. Since the cracks act as stress relief, the transmission energy and amplitude of the signal decreases with increasing crack width. However, the results revelead that the drop in amplitude is not significant. This led to the conclusion that a power amplifier should be used to generate stronger signals and a better data acquistion board was necessary to read reliable signals. This test helped identify a few problems that could be encountered with the RC building test. Soon after, Dr. Liao made a request to NCREE for two new data acquistion boards. Within a week, NCREE purchased the boards.

Before the week of the RC building test, the Bhalja worked with Dr. Liao's students to check the sensor signals using the new data acquisition boards and power amplifier. For the entire building, 32 SA were designated as sensors and 9 SA embedded in the building foundation at various locations were designated as actuators. Since the critical locations of high bending moments are at the column and shearwall base, this actuator-sensor network can reveal the relative damage at these and other critical locations. Each actuator was excited with single frequency sine wave of 10 Hz, 100 Hz, 1 KHz, 5 KHz and with a sweep sine ranging from 0.5 KHz to 5 KHz. The excitation covered these range of frequencies because small cracks attenuate signals of lower frequencies and larger cracks attenuate signals of high frequencies. The data was collected at the initial positive and negative peaks of each loading steps, and at the 0 point after the third loading cycle. The data was collected until a drift ratio of 3% after which two columns failed under shear and buckling modes. The analysis of an actuator sensor pair below shows the damage index of the sensor located on the low rise shear wall. Seen below the sensor are few shear cracks which would reduce the transmission energy of the signal. Figure 2 shows the damage index at seven points.

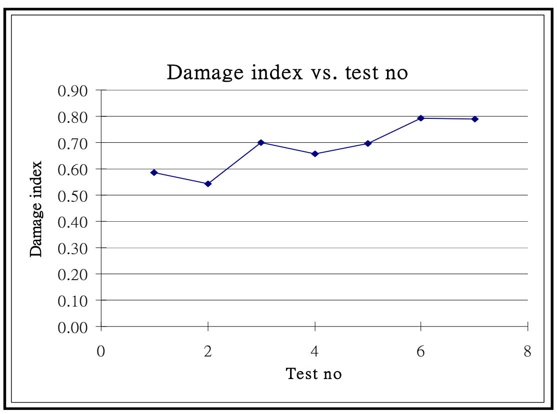

Figure 2: Damage Index

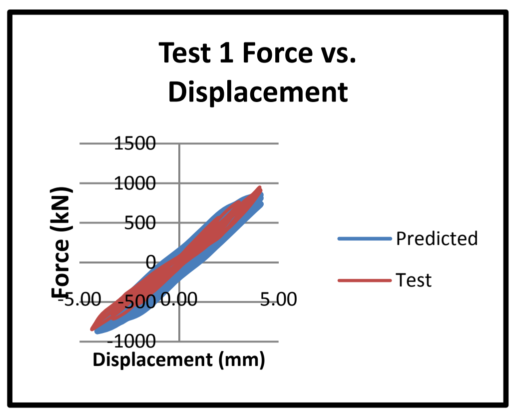

Figure 3: Test 1 Force vs. Displacement Relationship

The results appear to be as expected. As is shown in Figure 2, as the drift ratio increases with each test number, the positive cycle puts one side of the wall in tension which results in the crack width getting larger and the damage index getting larger. Bhalja had the most interaction with the lab personnel during the test of the RC building. The interaction was limited to halting the test after each cycle to collect the data. He also worked with the lab personnel to route the PZT cables with other data collection cables as LVDT and rotation gauges to the data acquisition boards.

Howser's research consisted of learning "Simulation of Reinforced Concrete Structures" (SRCS) and using it to simulate an asymmetric, three-dimensional, walled, RC frame's response to seismic excitation. SRCS is based on the Cyclic Softened Membrane Model (CSMM) (Mansour and Hsu 2005a, 2005b), a constitutive model that predicts shear behavior of reinforced concrete structures. SRCS's accuracy was confirmed by testing three full-scale reinforced concrete rectangular hollow bridge pears at NCREE (Mo et al. 2006). Howser's chief challenge was to implement SRCS in a three-dimensional application. It had never been done. The previously successful simulations included two-dimensional columns and walls. The key to the highly successful SRCS was its innovative plane stress element. However, this element can only be implemented within a two-dimensional model. Howser was required to develop creative solutions to simulate the frame response accurately.

Other researchers at NCREE were also focusing on simulating the frames response to seismic excitation. All of the researchers had problems simulating the shear walls in the structure and the unique loading conditions. Although no other researchers were using SRCS, Howser greatly benefited from being able to discuss ideas with these individuals face-to-face on a regular basis. These benefits included being able to communicate with her colleagues without the obstacles of a 13 hour time difference or the technological difficulties that often occur during teleconferences. It was also much easier to communicate with someone directly when the other individual is not speaking his or her native tongue.

Howser's simulation of the frame was quite unique. The walls in the structure were rather difficult to accurately simulate. SRCS has been proven to simulate walls quite accurately; however, it is only capable of testing them as two-dimensional elements. To simulate the walls, Howser modeled each wall separately in two-dimensions using SRCS. She then measured the various elastic and plastic material properties of the RC walls using this simulation. After that, she inputted these properties into n-dimensional plastic materials available in OpenSees and simulated the entire system. This provided excellent results when torsion was not introduced into the system (Tests 1 and 2), but did not perform as well when torsion was present (Tests 3 and 4). Howser was not able to accurately predict Test 5. She ran into divergence problems associated with the finite element analysis. See Figures 3 for plots of the actual versus predicted force versus displacement curves for the entire frame.

In addition to her simulation, Howser also helped to document the response of the frame during the test. Experiencing the frame's response first-hand allowed Howser to gain a better understanding of how her model should behave and allowed her to see flaws within her simulation. For example, when she simulated the wall response in two dimensions, she was unable to apply a force in the third dimension; therefore, she neglected the flexural capacity of the wall. This did not seem to cause major problems during the uniaxial tests, but may explain some of the discrepancy in the biaxial tests. Her future work will focus on accurately modeling the biaxial tests.

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

This award promoted diversity in many different ways. The three students, Howser, Caruso, and Bhalja were already quite diverse. They came from dramatically different cultural, social, and educational backgrounds. Howser grew up in a poorly educated all Caucasian community in the Midwest where very few people have a bachelor's degree. She went to school at a highly respected private engineering college that focuses on engineering design. The school rarely completes any research in civil engineering that does not focus on civil engineering education. In contrast, Caruso is from a part of the northeast where nearly everyone is highly educated. For his undergraduate degree, he chose to go to a school that focuses on liberal arts but offers a general engineering degree with a focus in civil engineering. He also did not have the opportunity to do research at his undergraduate institution. Bhalja is originally from India, but moved to the United States when he was 16. He lived on the west coast until moving to UH to complete his undergraduate degree. UH, or course, prides itself on completing a significant amount of research activities.

This already diverse group of students joined researchers from NCREE and National Taiwan University (NTU). NCREE is situated on NTU's campus and many of the NTU faculty members and students work at the lab. Between the American students and their Taiwanese co-researchers, the group was extremely diverse. It allowed for very effective brainstorming sessions where the diversity greatly enhanced the number and variety of ideas the group created. It also allowed each individual to not only make contacts but friends all over the world with different skills and from different cultural, social, and educational situations.

This award fostered a much greater tie between UH and NCREE. Since Dr. Mo had formerly served as a Division Head and currently serves as an advisor for NCREE, there was already a small connection between UH and NCREE; however, this project allowed many researchers from both institutions to work together on a large scale project. This created a much stronger tie between the two institutions by connecting many students and faculty members from both UH and NCREE. The resulting relationship was very positive and the researchers are sure to want to work together again if given the opportunity.

The award also greatly enhanced the international perspective of the U.S. researchers. By being immersed in a foreign culture, they were forced to learn about nearly every aspect of it. None of the U.S. students knew Mandarin Chinese before they traveled to the country. All three of the students taught themselves some of the language out of books while they were there, but the communication barrier was quite large. The researchers at NCREE all spoke English; however, the students often had difficulty operating outside the laboratory without a basic knowledge of the language. The students also learned a lot about Taiwanese culture which was quite different than U.S. culture. Research practices in Taiwan were not unique to the culture, but there were many cultural differences regarding things like eating, gift giving, and social interaction that had to be observed outside of the laboratory.

The broader impacts of the international cooperation affected not only the researchers themselves, but also UH, NCREE, and the world. The U.S. students gained an invaluable cultural experience through the program. UH and NCREE found that through their cooperative efforts they are able to accomplish groundbreaking research, and this proves to the world the benefits of international cooperation.

DISCUSSION AND SUMMARY

There were many significant accomplishments associated with this project. The structure tested was quite complex. The results of the test will provide researchers around the world with unique test data. In addition to the test data, other aspects of the project including the use of the smart aggregate sensors and the use of SRCS to simulate the structure will benefit the profession by providing alternative seismic performance evaluations and seismic simulations. Furthermore, the international cooperation associated with the project was a priceless accomplishment associated with the project.

A best practice that should be included in future operations of the IREE Program is a language class. It would greatly aid students who were traveling to another country to complete research if they could at least communicate basic needs in the country's native language. It would be very nice if IREE could provide funding or partial funding for such a class. It would be very helpful if this class was taken before the students left the U.S., but would also be of use if the students took the class once they reached the foreign country.

ACKNOWLEDGEMENTS

This project was made possible through NSF grant number EEC-0649163. The program managers for this project were NSF Research Experience for Undergraduates Program Manager Esther Bolding and NSF International Research and Education in Engineering Program Manager Win Aunt.

REFERENCES

1. Howser, R., Laskar, A., and Mo, Y.L., (2007), "Seismic Interaction of Flexural Ductility and Shear Capacity," REU Report, Department of Civil and Environmental Engineering, University of Houston, Houston, TX.

2. Mansour, M. and Hsu, T. T. C., (2005), "Behavior of Reinforced Concrete Elements under Cyclic Shear: Part I—Experiments," *Journal of Structural Engineering*, ASCE, Vol. 131, No. 1, January, pp. 44-53.

3. Mansour, M. and Hsu, T. T. C., (2005), "Behavior of Reinforced Concrete Elements under Cyclic Shear: Part 2—Theoretical Model," *Journal of Structural Engineering*, ASCE, Vol. 131, No. 1, January, pp. 54-65.

4. Mo, Y.L., Y.K. Yeh, J. Zhong and T.T.C. Hsu, (2006). "Seismic Behavior of Shear-Critical Hollow Bridge Columns," ASCE Structures Congress, St. Louis, MO, May 18-21.

5. Zhong, J. X. (2005), "Model-Based Simulation of Reinforced Concrete Plane Stress Structures," *PhD dissertation*, Dept. of Civil and Environmental Engineering, University of Houston, Houston, TX.

BRIEF BIOGRAPHIES OF RESEARCHERS

Manan Bhalja received his B.S. degree in Civil Engineering at the University of Houston. He also enrolled in graduate school at the University of Houston in Fall 2008 on a part time basis to pursue a thesis based Masters degree in Structural Engineering.

Christopher Caruso received the B.S. degree in Engineering from Swarthmore College in 2008. He is currently completing his M.S. degree in Civil Engineering from the University of California at Berkeley, to be completed in 2009.

Rachel Howser received the B.S. degree in Civil Engineering from Rose-Hulman Institute of Technology in 2008. She is currently working on her M.S. degree in Civil Engineering at the University of Houston.

Y.L. Mo earned his Ph.D. in Structural Engineering in 1982 from the University of Hanover in Germany. Dr. Mo currently serves as a professor at the University of Houston in Houston, Texas as well as the director of the Thomas T.C. Hsu Structural Research Laboratory at the University of Houston.

K.C. Tsai earned his Ph.D. in Structural Engineering from the University of California, Berkeley. Dr. Tsai currently serves as a professor at the National Taiwan University in Taipei, Taiwan as well as the director of the National Center for Research on Earthquake Engineering in Taipei, Taiwan.