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THE JOHN A. BLUME EARTHQUAKE ENGINEERING CENTER

DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING, STANFORD UNIVERSITY

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HARESH SHAH DELIVERS 2004 BLUME DISTINGUISHED LECTURE

On January 15, the Blume Center welcomed Professor Emeritus Haresh Shah back to campus to present the fourth John A. Blume Distinguished Lecture. Professor Shah's lecture, "THE LAST MILE - Earthquake Risk Mitigation Assistance in Developing Countries," drew on his knowledge of seismic risk management and his dedicated service to government agencies and non-profit organizations throughout the world, including UNESCO, GeoHazards International, and the World Seismic Safety Initiative. Questioning whether earthquake risk-management needs in developing countries have been achieved, he explained the utility industry's concept of "the last mile" and the importance of bridging the gap between those who need help and those who can offer help.

While recognizing that much has been accomplished technologically on methods to characterize and mitigate risks, Professor Shah cited data to suggest that the global risk of earthquakes is increasing rather than decreasing, due in large part to dense urbanization in seismic prone regions throughout the world. Measures to mitigate risks are not keeping pace with the growing threat – particularly in developing countries. Professor Shah questioned whether resources to study and mitigate earthquake risks are being used effectively, and he discussed the challenges and steps necessary to make a measurable change in the growing seismic threat.

What actions should be taken to mitigate earthquake risks in developing countries? Professor Shah suggested five: (1) development and strict implementation of earthquake codes for engineered structures, (2) dissemination and training on "How to" type of instructions to build safe non-engineered and rural structures, (3) local help to communities to build safer homes, safer schools, safer hospitals, and safer community infrastructures, (4) build awareness at the individual, family, and community level of earthquakes and what to do before, during, and immediately after an earthquake, and (5) increase social and political preparedness for the next catastrophic event at all levels of private and public enterprises.

Beyond these specific steps, he cited the overriding need for all of us in the earthquake engineering community to reassess our own priorities in research and practice and to recognize the critical importance of devoting appropriate resources to bridge "the last mile".

Copies of Professor Shah's paper can be downloaded at *http://blume.stanford.edu.*

BLUME CENTER NEWS

Professor Sarah Billington delivered an invited lecture, "Cyclic Response of Precast Bridge Piers with Unbonded Post-Tensioning and Ductile Fiber-Reinforced Concrete", for the Structural Engineering Distinguished Speaker Series at the University of California at San Diego, on December 10.

Graduate students **José Andrade** and **Sara Casciati** presented papers with co-author **Professor Ronnie Borja** at the 11th International Conference on Soil Dynamics and Earthquake Engineering and the 3rd International Conference on Earthquake Geotechnical Engineering held at the University of California, Berkeley, January 7-9.

Thirty seven graduate students accompanied **Professors Anne Kiremidjian**, **Greg Deierlein** and **Eduardo Miranda** to the Stanford Student Night at the February 3 dinner meeting of SEAoNC. Prior to the dinner, SEAoNC organized a tour of the San Francisco office of KPFF.

Rupa Garai, a Masters student in the Structural Engineering and Geomechanics Program, and her husband, Anjan, welcomed a baby girl, Antara, on February 11.

On February 20 and 21, **Professors Sarah Billington**, **Allin Cornell**, **Greg Deierlein**, **Chuck Menun**, **Anne Kiremidjian**, **Helmut Krawinkler**, **Kincho Law** and **Eduardo Miranda**, as well as several of their graduate students attended the PEER Annual Meeting in Palm Springs. Professors Krawinkler, Cornell and Miranda reported on research concerning the Van Nuys testbed assessment of the bay area highway network, and Professor Deierlein made several presentations on research coordination within the context of the performance-based engineering framework.

On February 24, **Professor Sarah Billington** made a presentation for a Stanford Alumni Event. The topic of the presentation was "Engineering for Sustainability: the Built Environment Perspective."

Professor Sarah Billington attended the ACI Spring Convention in Washington D.C. on March 14-15.

Professor Greg Deierlein presented a study entitled "Simulating Collapse under Earthquake Ground Motions" at the North American Steel Construction Conference in Long Beach on March 25.

Professor Anne Kiremidjian presented two papers on wireless structural sensors at the SPIE 11th Annual International Symposium on Smart Structures and Materials held in San Diego in March. The papers were prepared jointly with graduate students **Lykomidis Mastroleon** and **Krishnan Nair Kesavan**.

RESEARCH SPOTLIGHT

Validating Seismic Performance of Composite Moment Frames through Full-Scale Testing

Paul Cordova, Gregory G. Deierlein and Keh-Chyuan Tsai

Composite moment frame systems, consisting of reinforced concrete columns integrated with steel beams, have been around in some form for nearly twenty-five years as a cost effective variation of traditional moment frames. These composite systems resemble conventional steel frame construction except that the steel columns are replaced by high strength reinforced concrete – the primary incentive being reduced material cost. In the US, they are particularly attractive for mid- to high-rise buildings due to several unique construction staging techniques that decreases the construction time of these systems. On the other hand, Japan prefers to employ this system for low-rise office and retail buildings in order to utilize the long-span capabilities of the steel beams. Research and building code development over the past fifteen years have helped establish composite frames as viable alternatives to conventional steel or reinforced concrete construction.

From the standpoint of seismic design, composite frames provide the opportunity for detailing tough and reliable beam-column connections. Shown in Fig. 1 is a typical connection where the steel beam passes continuous through the column, thereby eliminating the need for welding or bolting the beam at the point of maximum bending moment. Compared to conventional steel frame construction, this detail avoids fracture problems encountered in welded frames during the 1994 Northridge earthquake; and with respect to conventional reinforced concrete construction, the composite connection avoids problems associated with reinforcing bar anchorage and congestion. Extensive testing and research over the past fifteen years have demonstrated that composite connection details can provide excellent strength and deformation capacity. This research, particularly work by the second author, has served as the basis for design recommendations developed through the ASCE committee on composite construction (ASCE 1994).

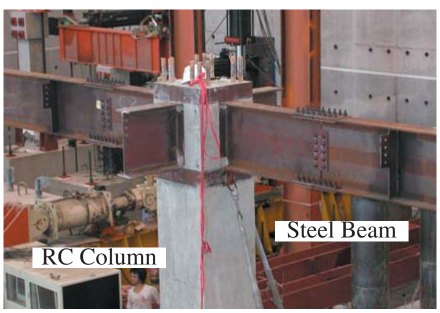

Figure 1 - Typical Composite Joint

Full-Scale Validation Frame Test

Despite past research that has shown the composite moment frame system to be a viable alternative to conventional moment frames and their development into recent seismic codes (Deierlein 2000), engineers have been hesitant to use this system in high seismic zones such as California. The most recent of this research has culminated into a full-scale frame test to validate the performance of composite frames for seismic design and ultimately serve as a proof of concept for this system. A three-bay three-story composite frame, shown in Fig. 2, was tested at the National Center for Research on Earthquake Engineering (NCREE) in Taipei through cooperation of researchers in Stanford University and Taiwan. Measuring 12-meters tall and 21-meters long, the frame is among the largest test frames of its type ever conducted.

Frame Design: The frame was designed according to current design provisions as a perimeter ductile moment frame for a three-story office building located in a high seismic region. The frame was intentionally designed to the minimum limits of the current building codes so as to represent the minimum expected performance and to interrogate system design parameters. As Taiwan's seismic design codes adopt similar requirements to those in the United States, the frame is equally representative of design standards in both countries. The designs of the 650-mm square reinforced concrete columns were controlled by the strong-column weak-beam (SCWB) criterion, in which an unconservative approach was taken such that the strength of the beams neglected the composite action of the slab. The composite beams range from 400-600mm deep and were designed based on strength requirements in negative bending. With the beams and columns sized for minimum strength requirements, the code-specified drift criterion was satisfied without requiring any further changes in the member sizes.

Figure 2 - Global View of NCREE Test

The frame was detailed and built using the precast method of construction in conformance with standard industry practice. Single story precast column assemblies were integrally cast with the steel beam stubs in a precasting plant, and then shipped and erected on site in the NCREE lab. Beams were connected with bolted moment splices about 1.2 meters out from the column face. Columns were spliced with standard grouted sleeve connectors to develop the full tension strength of the longitudinal reinforcement. Recognizing the large plastic hinge rotations that typically develop at the column base, the column base splices were located one meter above the top of footing. The second and third story column splices were located directly above the steel beams, which is common practice in Taiwan and Japan.

Loading: Lateral loads were applied pseudo-dynamically by three 2940 kN actuators at each floor to simulate earthquake loadings. Two recorded ground motions were used to in the loading protocol; one was from the 1999 Chi-Chi earthquake and the second from the 1989 Loma Prieta earthquake. The records were scaled based on spectral acceleration at the first-mode period of the building to represent earthquake hazards with a 50%, 10% and 2% chance of exceedance in 50 years. The first mode period (1 second) spectral accelerations for three earthquake levels are 0.4g, 0.7g and 1.0g, including site amplification effects. Pseudo-dynamic earthquake loads for each of these three hazard levels were applied sequentially to the frame, followed by another 10%in50year event to represent an aftershock. The test was concluded with a simulated static "pushover" test, which incrementally applied a triangular loading pattern up to a maximum roof drift ratio of 8%.

Frame Test Results: The NCREE RCS frame test was in October

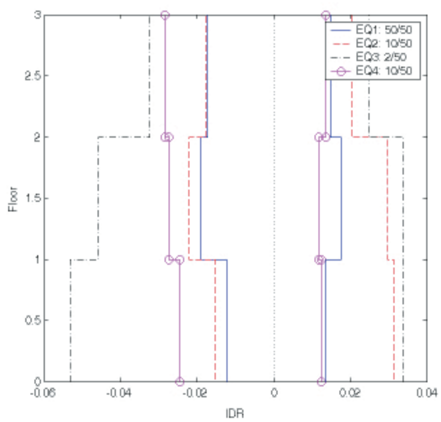

Figure 3 - Max/Min Drifts during EQ

2002 and witnessed by about thirty researchers from the US, Taiwan, and Japan. Testing was broadcasted live via the Internet (see *http://rcs.ncree.gov.tw*), including real-time data plots and live video. The response was monitored and documented with over 300 data channels, visual inspections, and photographic images.

Figure 3 shows the maximum peak story drifts measured during the four pseudo-dynamic time histories. The 50/50 event produced fairly uniform drift demand on the frame, with damage limited to minimal cracking in the RC columns and slight yielding in the lower flanges of the steel beams. Researchers present agreed that the amount of damage generated by this event is consistent with the performance target of "immediate occupancy", where the structural stability was not compromised and the frame required very little if any repair.

The design-level event (10/50) produced maximum drifts ratios up to about 3%, with residual interstory drifts of about 0.5% (20 mm). The RC columns base hinges experienced crack widths of up to 2 mm and were accompanied by some minor spalling of the cover concrete (Fig. 4a). The steel beams in all floors yielded, although the 2nd floor beams experienced much less yielding due to a large material overstrength (40% increase in Fy). Local buckles measuring up to 15-25 mm were found in the hinge regions of the 1st and 3rd floor beams (Fig. 4b). The slab and composite joints were still very much intact, each experiencing only minor cracking at this point. Repairs to the structure would likely involve epoxy injection of cracks, patching of spalled concrete, heat straightening of local flange buckles, and plumbing to reduce residual interstory drift.

Under the maximum considered earthquake, deformations began to concentrate in the first two stories, with maximum interstory drifts of up to 5.5% (220 mm) in the first story. The base of the 1st floor columns had distributed cracks up to 5 mm in width and significant spalling of the cover concrete. As a result of the overstrength of the 2nd floor beams, hinging began to concentrate within the upper region of the 2nd floor columns, with crack widths of 4 mm accompanied by minor spalling just below the beam-column joint. The 1st and 3rd floor beams experienced extensive yielding and large local buckles of the bottom flange and web, with flange tip distortions up to 70 mm. The 1st and 2nd floor slab experienced some local crushing on the interface of the slab and the column as well as cracking on all three floors. The composite joint regions were relatively undamaged, experiencing only minor cracking. With significant local damage and a residual interstory drift of 3.5% (140 mm) in the first story, the consensus of participants at the test was that the frame had reached its "collapse prevention" performance level, implying that the structure would need significant repairs to restore its strength and stiffness.

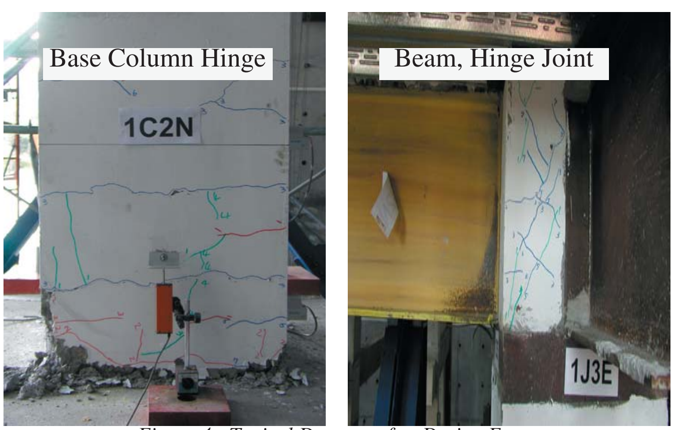

Figure 4 - Typical Damage after Design Event

Analytical Simulations and Performance-Based Design

Detailed inelastic analyses were conducted both prior to the test (blind predictions) and in follow up studies, using the OpenSees software (*http://opensees.berkeley.edu*) developed by the Pacific Earthquake Engineering Research (PEER) Center. Force-based elements that utilize fiber sections to model distributed plasticity are used to represent the RC columns and composite beams. Joint elements are employed to model the joint size and kinematics as well as the failure mechanisms of composite joints. The OpenSees analytical model has proven to simulate the response of the test frame fairly well up to about 3% interstory drift. Beyond this drift level, the model is unable to pick up some of the larger excursions of the test frame since it assumes the steel beams act in pure yielding and does not model the local buckles that begin to control the response of the beams at this level. Studies are also underway to correlate the engineering demand parameters from the results of the OpenSees model with the physical damage witnessed in the frame test. Damage indices, which are calibrated to numerous subassembly experiments, are used to process the computed plastic deformations and then related to the damage found within the elements of the test frame. For more information on the design, results, and planning of the test frame, please see the reference by Cordova et al. (2004).

Conclusions

This recent full-scale frame test, as well as the extensive amount of research that has previously been conducted, has validated the robustness and reliability of the composite frame systems. The test frame performed very well under all earthquake loading scenarios and a final static pushover test that ultimately imposed interstory drifts ratios of about 10%. Composite beam-column joints designed with standard details exhibited excellent behavior, as did the precast column splices. Overall, the test frame clearly demonstrates the capabilities of composite moment frames to meet and exceed the seismic performance expectations implied by modern building codes. Analytical studies have also shown the capabilities to model the performance of these frames up to approximately 3% drift, beyond which the analysis fails to pick up buckling of the steel beam flanges. These models combined with damage indices have shown some promise in correlating damage with analytical results and should prove to be a valuable component in the current shift to performance-based engineering.

References

ASCE (1994), "Guidelines for design of joints between steel beams and reinforced concrete columns," JSE, ASCE, 120(8), 2330-2357.

Deierlein, G.G. (2000), "New Provisions for the Seismic Design of Composite Structures," Earthquake Spectra, EERI, 16(1), pgs. 163-178.

Cordova, P., Chen, C.H., Lai, W.C., Deierlein, G.G., and K.C. Tsai (2004), "Pseudo-Dynamic Test of Full-Scale RCS Frame: Part I & II," Proceedings, ASCE Structures Congress and Exposition, Nashville, Tennessee, May 22-26, 2004, (in press)

Alumni News

Abhijit Kakhandiki (Ph.D. '99) and his wife, Bimba, are pleased to announce the birth of their daughter, Shreya. Born on March 11, she weighed 7lbs, 10oz and was 20" long. Big brother, Pranav, "seems to have taken well to (her)."

Published Papers

Han, T.S., **Feenstra, P.F.**, and **Billington, S.L.**, "Simulation of Highly Ductile Fiber-Reinforced Cement-Based Composites under Cyclic Loading", *ACI Structures Journal*, 100(6): 749-757, 2003.

About fifty students and faculty enjoyed the annual Blume Center Ski Trip to Tahoe over Martin Luther King weekend. The weather was beautiful and the skiing was great!

Alumni, Affiliates and Friends of the Blume Center are encouraged to send news items about yourselves to racqueh@stanford.edu for inclusion in the next newsletter.

Students in **Professor Sarah Billington's** CEE205 Class (Structural Materials Testing & Simulation) watch concrete cylinders undergoing compression and tension testing. The

class competed on designing, fabricating and testing a FRP-wrapped concrete column. The competitive aspects included reaching the highest strength for the least cost, fabrication quality, and accuracy of predicted strength. The students also did compression and tension testing of normal weight, lightweight and high strength concrete, flexural and compression testing of high-performance fiber-reinforced cement-based composites, and fracture testing of aluminum and Plexiglas. Simulation labs included stress analysis of concrete in compression and fiber-reinforced concrete in tension as well as determination of stress intensity factors in fracture specimens.

Winter 2004 Graduates

The following students graduated in the Winter quarter with a Master's Degree in Civil and Environmental Engineering from the Structural Engineering and Geomechanics Program: **Shirin Aalami**, **Matt Breidenthal** (Thornton Tomasetti), **Romaldo De Leon**, **Bhavna Krishan**, **Hui Liu**, and **Shobhna Upadhyaya** (URS). **Amit Kanvinde** received his Ph.D. and is now an Assistant Professor at University of California, Davis.

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