Issue No. 41 Winter 2005

The John A. Blume Earthquake Engineering Center

Department of Civil & Environmental Engineering, Stanford University

Director: Professor Gregory G. Deierlein
Administrative Associate/Editor: Racquel Hagen

Telephone: (650) 723-4150, Fax (650) 725-9755 Website: blume.stanford.edu E-mail: racquelh@stanford.edu

## Allin Cornell Named 2005 Joyner Lecturer

**Professor Allin Cornell** has been named the 2005 William B. Joyner Memorial Lecturer. The lecture, entitled "On Quantifying the Seismology-Engineering Interface" will be given at the EERI Annual Meeting in Ixtapa, Mexico in February and the SSA Annual Meeting in Incline Village, Nevada in April. The Joyner Lecturer is chosen on the basis of outstanding Earth science contributions to the theory/practice of earthquake engineering or outstanding earthquake engineering contributions to the direction and focus of Earth Science research, together with demonstrated skills of communication at the earthquake-science/earthquake-engineering interface. Bill Joyner was a USGS seismologist who worked closely with the engineering community, including many of us at the Blume Center until his death in 2001.

## Alumni News

**Blaise Duvernay** (MS '01), wife Liza and son Julien welcomed their new family addition, Anna, on November 27 in Neuchâtel, Switzerland.

**Luis Ibarra** (PhD '2004) and his wife Cristina welcomed their third child and first daughter, Isabel, on December 28. Luis' hopes for an all-male Ibarra baseball team were dashed, but Cristina was thrilled to finally have a little girl.

## 2005 Blume Distinguished Lecture to be Given by Jeremy Isenberg

The 2005 John A. Blume Distinguished Lecture will be presented on April 7, 2005 by Jeremy Isenberg of Weidlinger Associates. Isenberg's lecture will be on "Civil Engineering Aspects of Homeland Security." Please see the Blume Center website for more information and location or send an email to majordomo@lists.stanford.edu with "subscribe blume_center_seminar" in the body of the email (leave the subject line blank).

## Proceedings Available

An International Workshop on *Performance-Based Design - Concepts and Implementation* was held in Bled, Slovenia, from June 28 to July 1, 2004. The workshop, co-organized by **Peter Fajfar** and **Helmut Krawinkler** and sponsored by the PEER Center and Slovenian organizations, brought together more than forty of the leading researchers and engineers from fourteen countries to assess the state of knowledge and discuss future directions for research and design practice on issues important for the development and implementation of performance-based earthquake engineering concepts.

The forty-three papers prepared for the workshop are compiled in the proceedings, which are available from PEER for $45 (plus postage for overseas orders). Please address requests to PEER Reports Orders, PEER, 1301 South 46th Street, Richmond, CA 94804.

## Blume Center News

In October 2004, **Dr. Renate Fruchter** was invited to give a series of guest lectures on AEC Global Teamwork at Bauhaus University. During the same trip, she also visited Royal Technical University (KTH) and Skanska Corporation in Stockholm in October 2004 to strengthen the cooperation and engagement in the AEC Global Teamwork course CEE222/122 offered every year in Winter and Spring Quarter at Stanford in collaboration with universities worldwide.

On October 7 and 8, **Professor Anne Kiremidjian** attended the 2nd International Workshop on Remote Sensing for Post-Disaster Response. PhD Candidate **Pooya Sarabandi** presented a joint paper with Professor Kiremidjian and Beverly Adams of ImageCat on "Methodological Approach for Extracting Building Inventory Data from Stereo Satellite Images".

On Oct. 16, **Professor Greg Deierlein** presented a lecture on "Role of Nonlinear Simulation in Performance Based Earthquake Engineering" at the J.F. Abel Symposium, Cornell University. Professor Deierlein also participated in the AISC Specification Committee, where the next 2005 edition of the AISC Specification for Steel Buildings was formally approved (Chicago, Nov. 19), and represented the PEER Center at the NSF Annual ERC Meeting in Washington, DC (Nov. 17-18).

**Professor Helmut Krawinkler** gave a presentation of "Exercising Performance-Based Earthquake Engineering" at the Third International Conference on Earthquake Engineering, in Nanjing, China, October 19-20.

**Professor Greg Deierlein** made a presentation on research advancements towards performance based earthquake engineering at the Oct. 24 meeting of ACI Committee 374 in San Francisco. PhD Candidates **Won Lee** and **Kyle Douglas** also gave presentations at the Conference.

In November, **Professor Sarah Billington** attended the Annual Convention of the American Segmental Bridge Institute held in Tampa, Florida. She presented experimental research in a talk titled "Cyclic Response of Unbonded Post-tensioned Segmental Precast Concrete Bridge Piers."

**Professor Anne Kiremidjian** was invited to give one of four commemorative lectures at the University of Kobe in Kobe Japan for the 10th anniversary of the January 17, 1995 earthquake on December 9 and 10.

In December, **Professor Sarah Billington** gave a presentation titled "Biodegradable Composites for the Building Industry" at the annual meeting of the United States Business Council on Sustainable Development hosted by Stanford's Graduate School of Business.

**Dr. Renate Fruchter** established cooperation relations with two new partner universities - University of Winsconsin Madison, US, and Manchester University, UK - towards worldwide dissemination efforts of the AEC Global Teamwork education model and collaboration technology infrastructure.

# RESEARCH SPOTLIGHT

## Rate-Dependence in High-Performance Fiber-Reinforced Cement-Based Composites for Seismic Applications

**Kyle S. Douglas and Sarah L. Billington**

### INTRODUCTION

In light of the lessons learned from past earthquakes and the advances in earthquake engineering, critical facilities such as hospitals are in need of conforming to current earthquake-resistant design specifications. Additionally, it is desirable for critical facilities to be operable immediately or very soon after a seismic event. For many such facilities, retrofitting the structure poses a considerable problem in that the facility should be allowed to function while the retrofit strategy is being installed. The need for both continuing functionality during and after an earthquake necessitates a flexible and portable retrofit strategy that can be put in place and repaired with minimal disturbance to the facility.

We are currently investigating a retrofit strategy for steel framed structures that can accommodate floor plans and secondary system layouts of the existing facility and provide minimal disturbance to the function of the building during installation and repair. The proposed retrofit system, which is shown for a single bay in Figure 1, consists of a series of precast, high-performance fiber-reinforced cement-based composite (HPFRCC) panels that act as deep beams when resisting lateral load. The panels are connected to each other using steel tabs and pretensioned bolts. Each pair of panels is then connected to the steel frame with angles and pretensioned bolts. Depending on the layout of the facility, the individual panels may be moved into place and installed into specified bays with minimal disturbance to the function of the facility. Furthermore, damaged panels can be easily replaced by simply unbolting them from the frame and installing a new panel. Because the infill consists of a series of panels instead of a full wall, the system can accommodate floor plans and secondary systems that may require access through the bay by adjusting the location of each pair of panels. Details of proposed panel reinforcement and connections are given in [1].

Pilot experiments have been conducted on single panels [2]. Simulation methods are needed to predict the impact of such a system in a large structure. For such simulations, a material model for the fiber-reinforced concrete is needed. However, the load rate-dependence of the material is not yet known and is therefore being investigated experimentally to provide information for developing an accurate material model. Highlights of the rate-dependent experiments are presented here.

### HPFRCC MATERIALS

The infill panels for the retrofit system are composed of HPFRCC and reinforced with welded wire mesh and traditional steel reinforcement. The HPFRCC material used in this retrofit system is referred to as an Engineered Cementitious Composite (ECC), which is designed to exhibit steady-state cracking in uniaxial tension [3, 4], resulting in the formation of multiple, very fine cracks. The multiple cracking leads to a strain hardening-like response in direct tension (Figure 2). During the strain-hardening phase of loading, the fibers in ECC are debonding from the matrix. The strain hardening response, ductility in tension, and fine multiple-cracking distinguish ECC from traditional fiber-reinforced concrete (FRC), which typically softens after initial cracking.

The ECC investigated here is comprised of a Portland cement-based mortar matrix that is reinforced with a 2% volume fraction of short, randomly distributed, high-modulus polymeric fibers. The mortar consists of fine silica sand (less than 0.2 mm in diameter), which represents the only aggregate in the composite. Other HPFRCC materials under investigation use different matrix mix designs with steel fibers or a combination of steel and polymeric fibers.

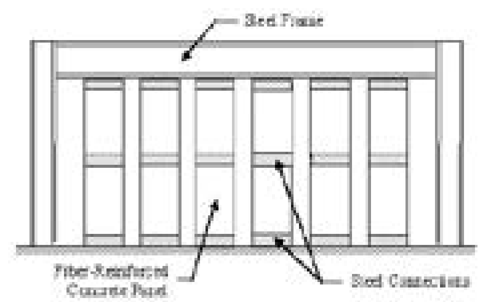



*Figure 1: Proposed retrofit system*

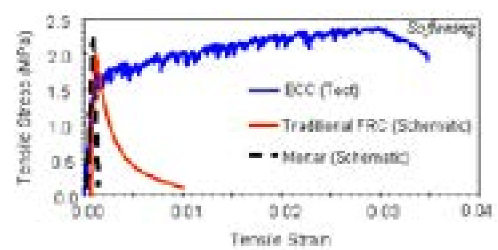



*Figure 2: Uniaxial tensile response of cement-based materials.*

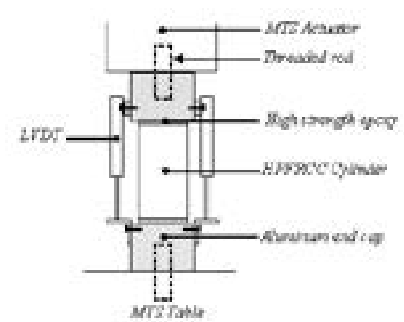



*Figure 3: Test setup*

### STRAIN RATE EXPERIMENTS

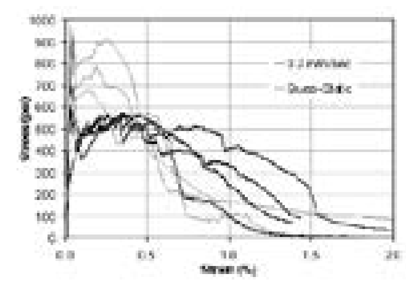
Currently, experiments are underway to examine the effect of strain rate on the tensile, compressive, and cyclic properties of different types of HPFRCC. The results of these experiments are of particular importance to simulating the material behavior of HPFRCC in structures (such as the proposed retrofit system) subjected to cyclic or seismic loads. Specifically, these results will be used to create a rate-dependent model for the material in finite element analyses, if necessary.

In general, strain rates in reinforced concrete structures may be as high as 0.05 – 0.1 $sec^{-1}$ during an earthquake [5, 6]. Therefore, to be consistent with these rates and other studies in the literature [7], four strain rates are being considered for this test series: a quasi-static rate of $2 \times 10^{-5}$ $sec^{-1}$, a transitional rate of $2 \times 10^{-4}$ $sec^{-1}$, and "seismic" rates of 0.02 and 0.2 $sec^{-1}$. The results from the quasi-static rate will serve as a base for the test series, while the two largest strain rates are intended to bracket the rates that the HPFRCC might experience in an earthquake.

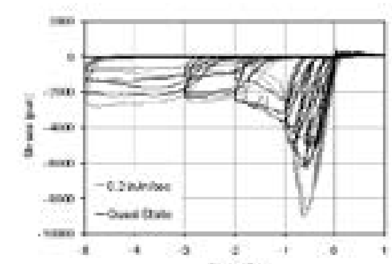
For each strain rate, the HPFRCC specimens are subjected to monotonic compression, monotonic tension, and reversed-cyclic tension and compression. The specimens are loaded as shown in Figure 3. Aluminum end caps are attached to the specimens with high strength epoxy. These end caps are then connected to the 55-kip MTS machine with threaded rods. Three LVDTs are attached to the end caps to measure the displacement of the cylinders.

### PRELIMINARY RESULTS

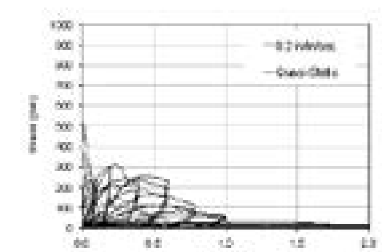
Early results from the strain rate experiments are presented in Figure 4 for two sets of ECC. Since the retrofit system intends to make use of the ductility of these materials, changes in ductility with strain rate are important to note. In tension, the effect of strain rate can be seen in Figure 4(a). At the highest strain rate, the ultimate tensile strength can increase by 50%, while ductility is halved. These trends are also observed in the cyclic behavior shown in Figures 4(b) and 4(c), with the effect seemingly less dramatic in compression but amplified in tension.



*(a)*



*(b)*



*(c)*

*Figure 4: The effect of load rate on the (a) monotonic tensile properties of ECC 1, (b) cyclic properties of ECC 2, and (c) a close up of the cyclic tension response for ECC 2*

The effect of strain rate on the ductility of ECC may impact the structural performance of reinforced ECC elements such as the panels in the infill panel retrofit system. Cyclic lateral load tests on reinforced ECC panels [2] have demonstrated that the structural strength of these panels can increase as much as 35% relative to similarly reinforced panels made of concrete. The increase in structural strength is attributed to the ductility of the ECC (also demonstrated in [8]), since the concrete was 25% stronger than the ECC in compression. At increasing drift levels, the ECC panels maintained their integrity, leading to a higher structural strength and more hysteretic energy dissipation. Consequently, decreases in the ductility of ECC with increased strain rate will likely limit this potential increase in strength and hysteretic energy dissipation.

Future analyses of the strain rate test results will identify any variations in when softening in tension occurs during cyclic loading relative to compressive failure. It has been shown that as long as the compressive strength has not been reached, cyclic loading does not limit the tensile strain capacity of these HPFRCCs [9].

### SUMMARY & FUTURE WORK

Results from strain rate experiments on HPFRCC materials used in a proposed retrofit system were presented. Preliminary analysis of ongoing experimental work has shown that seismic strain rates can have a significant effect on the strength and ductility of HPFRCC materials. The loss of tensile strain capacity is of particular importance since this can limit the ability of the material in combination with reinforcement to increase strength and to dissipate significantly more hysteretic energy than traditional reinforced concrete during an earthquake.

Additional HPFRCC materials will be tested and results will be used to develop a rate-dependent material model for finite element analysis of HPFRCC materials in the infill panel applications. Future work will also include creating a reliable beam-element model to simulate the cyclic behavior of an individual panel of the retrofit system. The models will be calibrated to the pilot studies of single panel behavior performed earlier [1], and will provide an efficient way to simulate larger structures with the retrofit system in place.

### REFERENCES

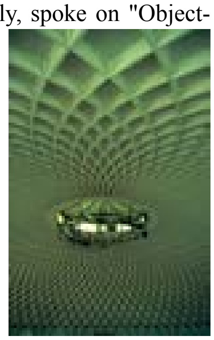
1. Kesner, K.E. "Development of seismic strengthening and retrofit strategies for critical facilities using engineered cementitious composite materials." PhD Thesis. Cornell University, Ithaca, NY, 2003.
2. Kesner, K.E. and Billington, S.L., "Investigation of Infill Panels made from Engineered Cemetitious Composites for Seismic Strengthening and Retrofit" ASCE J. Structural Engineering, accepted for publication (2004).
3. Marshall, D.B. and Cox, B.N. "A J-integral method for calculating steady-state matrix cracking stresses in composites." Mechanics of Materials 1988; 7: 127-133.
4. Li, V.C. and Leung, C. "Steady-state and multiple cracking of short random fiber composites." Journal of Engineering Mechanics 1992; 118(11): 2246-2264.
5. Scott, B.D., Park, R., and Priestley, M.J.N., "Stress-Strain Behavior of Concrete Confined by Overlapping Hoops at Low and High Strain Rates," ACI Journal, 1982; 79(1): 13-27.
6. Mahin, S.A., and Bertero, V.V., "Rate of Loading Effects on Uncracked and Repaired Reinforced Concrete Members." Report No. UBC/EERC-72/9, Earthquake Engineering Research Center, University of California, Berkeley, Dec. 1972, 148 pp.
7. Maalej, M., Zhang, J., Quek, S.T., and Lee, S.C., "High-Velocity Impact Resistance of Hybrid-Fiber Engineered Cementitious Composites." *Fracture Mechanics of Concrete Structures*, Li et al (eds), 2004, pp. 1051-1058.
8. Fischer, G. and Li, V.C., "Influence of matrix ductility on the tension-stiffening behavior of steel reinforced engineered cementitious composites (ECC)." ACI Structures Journal, 2002; 99(1): 104-111.
9. Kesner, K.E., Billington, S.L., Douglas, K.S. "Cyclic response of highly ductile fiber-reinforced cement-based composites." ACI Materials Journal, 2003; 100(5): 381-390.

## Blume Website Redesigned

The Blume Center website has been redesigned with more information and easier to use navigation. Please visit the new site at http://blume.stanford.edu.

## Fall StrGeo Seminars

The Blume Center had the privilege of hosting several special seminars in the Fall Quarter. On November 10, Visiting Professor C.H. Loh spoke on "Structural Health Monitoring : An element of hazard mitigation"; Luca Gusella from the University of Bologna, Italy, spoke on "Object-oriented Image Understanding and Postearthquake Damage Assessment" on November 29; and Ashraf Habibullah of Computers & Structures, Inc. gave a seminar on "What can ETABS, SAP, and other CSI programs do for me?" on December 1.



On October 26, we were honored to host a lecture by Professor David Billington of Princeton University. His lecture, "The Art of Structural Design: From Scholarship to Teaching to Practice", discussed a new type of scholarship devoted to the greatest work of modern structural engineering that promises to inspire students to see the future of practice as holding the potential for innovation and for new forms of elegance within the central engineering diciplines of efficiency and economy. Professor Billington's expertise is in thin shell concrete structures, bridge design and the history and aesthetics of structures. He was recently honored with the NSF Director's Distinguished Teaching Scholar's Award.

## Newly Published Blume Technical Reports

TR146 - **D. Pachakis** and **A.S. Kiremidjian**, *Estimation of Downtime Related Revenue Losses in Maritime Ports due to Earthquakes*

TR147 - **C. Li** and **R.I. Borja**, *Finite Element Formulation of Poro-Elasticity Suitable for Large Deformation Dynamic Analysis*

TR148 - **S.A. King**, **A.S. Kiremidjian**, **P. Sarabandi**, and **D. Pachakis**, *Correlation of Observed Building Performance with Measured Ground Motion*

Blume Center Technical Reports are available for free as downloads at http://blume.stanford.edu/Blume/TechnicalReports.htm.

## Winter 2004 Graduates

The following students graduated with a Masters Degree in Structural Engineering and Geomechanics in December 2004: **Tayakorn Chandrangsu**, **Sushil Chauhan** *(Thornton-Tomasetti)*, **Kaustubh Khanvilkar** *(Thorton-Tomasetti)*, **Seung Bum Kim**, **Doo Hyun Kwon**, **Jungwoo Lee** *(Bureau Veritas)*, **Carlos Machado**, **Meris Ota**, **Byoung Sok Shin** *(Middlebrook & Louie)*, and **Dorian Sulc**; **Tony Gonzalez** received his Masters Degree in the Design-Construction Integration Program. **Jorge Ruiz-Garcia** *(Universidad Michoacana)*, **Jinxing Cheng** and **Victor Calo** received their Doctorates in Structural Engineering and Geomechanics.

The John A. Blume Earthquake Engineering Center
Department of Civil & Environmental Engineering
Stanford University
Building 540, MC: 4020
Stanford CA 94305-4020