ISSUE NO. 40 AUTUMN 2004

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

BLUME CENTER STUDENTS AND FACULTY ATTEND 13WCEE

The Blume Center was well represented at the 13th World Conference on Earthquake Engineering in Vancouver Canada, August 1-6. Over 20 faculty and students attended the conference. **Profs. Anne Kiremidjian, Greg Deierlein, Chuck Menun, Allin Cornell, Helmut Krawinkler, Kincho Law, Ronnie Borja** and **Eduardo Miranda**, and Ph.D. Candidates **Jose Andrade, Hesaam Aslani, Kerri Tokoro** and **Paul Cordova** all presented papers. Ph.D. Candidates **Gee Liek Yeo, Kyle Douglas, Won Lee, Pooya Sarabandi, Hesaam Aslani** and **Qiang Fu** had poster presentations. Many Blume Center alumni, affiliates and friends were also at the conference and over 70 attended a Blume Center Reunion dinner at Aqua Riva on August 4. Participants were overheard saying that is was "the best reunion dinner yet."

COLLABORATIONS IN MATHEMATICAL GEOSCIENCES (CMG RESEARCH)

A new research project begins this summer under the direction of **Profs. Dave Pollard** (Geological and Environmental Sciences), **Rafe Mazzeo** (Mathematics), and **Ronnie Borja** (Civil and Environmental Engineering) entitled “Mathematical modeling of the dynamics of multi-scale phenomena during folding and fracturing of sedimentary rocks” funded by National Science Foundation. The project aims at characterizing the geometric shapes of the sedimentary layers within two well-exposed folds using Global Positioning Systems (GPS) and Light Detection and Ranging (LiDAR) data sets, and the principles of differential geometry. The dynamics of folding and fracturing will then be analyzed using continuum mechanics principles and the finite element method to investigate the physical interactions between kilometer-scale folds and the meter-scale fractures observed in the Sheep Mountain Anticline in Wyoming and the Raplee Ridge Monocline in Utah.

Structural Engineering & Geomechanics and DCI students stand "inside" the new Bay Bridge during a field trip to the Caltrans-KFM precast yard in Stockton where major sections of the skyway segment are being fabricated.

BLUME CENTER NEWS

Ph.D. Candidate **Kerri Tokoro** has won ASCE's 2004 O.H. Ammann Research Fellowship in Structural Engineering. The fellowship was endowed in 1963 to foster advances in structural design and construction. Tokoro's research is on developing a technique to predict response interactions in steel frame structures.

Dr. Renate Fruchter, in collaboration with Dr. Ichioka and Mr. Date from Obayashi Corporation, Japan, worked with Stanford OTL to license and deploy at Obayashi the ThinkTank web-based collaboration technology developed by Dr. Fruchter's team in the PBL Lab at Stanford.

Ph.D. Candidate **Jack Baker** was awarded a fellowship to participate in the East Asia Summer Institutes in Japan program, sponsored by NSF, and the Japan Society for the Promotion of Science. He visited several major research centers as part of the National Hazards Mitigation in Japan program, and then spent two months as a visiting researcher at Nagoya University and Kyoto University.

Dr. Renate Fruchter gave three presentations at the 10th International Conference on Computing in Civil and Building Engineering (ICCCBE-X), in Weimer, Germany this June. Dr. Fruchter also gave an invited lecture on *"AEC Global Teamwork"* at the Technical University Bochum in Germany.

Prof. Ronnie Borja edited a special edition of the *International Journal of Computer Methods in Applied Mechanics and Engineering* on "Computational Failure Mechanics for Geomaterials," volume 193, issues 27-29, July 9, 2004. The special edition contains 20 fully refereed articles (over 500 pages) by some of the most active researchers in the area of computational failure mechanics.

Profs. Allin Cornell, Greg Deierlein, Helmut Krawinkler, and **Eduardo Miranda** presented papers at the International Workshop on Performance-Based Seismic Design - Concepts and Implementation, held in Bled, Slovenia, from June 28 to July 1. This workshop, organized by Profs. Fajfar (U. of Ljubljana, former Shimizu Visiting Professor at Stanford) and Krawinkler, brought together 44 of the leading researchers and engineers from 14 countries to assess the state of knowledge and practice related to performance-based earthquake engineering. The PEER Center was the main sponsor of the workshop.

Prof. Ronnie Borja presented a keynote lecture at the 4th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2004) held in Jyväskylä, Finland, on July 24-28, entitled *"Deformation Bands in Multiphase Porous Materials"*.

In July, **Prof. Sarah Billington** led a half-day hands-on session for the Stanford Summer Engineering Academy introducing incoming freshmen to civil engineering. Students participated in a web-based activity where they worked as teams of civil engineers to decide if a certain dam should be repaired or decommissioned based on running fracture analyses and risk analyses as well as evaluating environmental impacts.

Prof. Sarah Billington attended the Planet-X Symposium titled

Blume Center News continued on page 3

RESEARCH SPOTLIGHT

The Role of Epsilon in a Vector-valued Intensity Measure

Jack W. Baker and C. Allin Cornell

Introduction

As nonlinear dynamic analysis becomes a more frequently used procedure for evaluating the demand on a structure due to earthquakes, it is increasingly important to understand which properties of a recorded ground motion are most strongly related to the response caused in the structure. A value that quantifies the effect of a record on a structure is often called an Intensity Measure (*IM*). Spectral acceleration at the first-mode period of vibration, $S_a(T_1)$, has commonly been used as an *IM*. But among records with the same value of $S_a(T_1)$, there is still significant variability in response of a multi-degree-of-freedom, nonlinear structural model. Here we consider a two-parameter (i.e., vector-valued) intensity measure consisting of $S_a(T_1)$ as before, and a second parameter termed ε ("epsilon"). It is found that this *IM* is significantly superior to the *IM* consisting of $S_a(T_1)$ alone. See [1, 2] for additional details and references.

The Definition of Epsilon

Epsilon is defined by engineering seismologists studying ground motion as the number of standard deviations by which an observed logarithmic spectral acceleration (at a specified period) differs from the mean logarithmic spectral acceleration predicted from an attenuation relationship. Because of the normalization by the mean and standard deviation of the attenuation, ε is a random variable with an expected value of zero, and a unit standard deviation. The importance of this parameter will be discussed later.

Calculation of the Drift Hazard Curve using a Vector-Valued IM

To evaluate the effect of ε on structural response, we present a method for predicting the demand on a structure using a vector-valued *IM*.

Structural response assessment can be combined with PSHA results to calculate the mean annual rate of exceeding a given structural response level. This result is referred to as a drift hazard curve, and is used for performance-based engineering as proposed by the Pacific Earthquake Engineering Research (PEER) Center [3]. PEER refers to the structural response parameter as an Engineering Demand Parameter, or *EDP*. In the example below, the *EDP* used is the maximum interstory drift ratio. The typical drift hazard calculation can be adopted for use with a vector *IM* as follows:

$$\lambda_{EDP}(z) = \sum_{\text{all } x_{1,i}} \sum_{\text{all } x_{2,j}} P(EDP > z \mid S_a(T_1) - x_{1,i}, \varepsilon = x_{2,j}) \bullet \Delta\lambda_{IM}(x_{1,i}, x_{2,j}) \quad (1)$$

The term $P(EDP>z|S_a(T_1)=x_1,\varepsilon=x_2)$ is the probability that *EDP* exceeds z, given $S_a(T_1)$ and ε. We will present a method for evaluating this below. Defining $\Delta\lambda_{IM}(x_{1,i}, x_{2,j})$ as $\lambda_{Sa\epsilon[x_{1,i},x_{1,i+1}],\varepsilon\epsilon[x_{2,i},x_{2,i+1}]}$, we take advantage of the fact that we could also express this as the product of the marginal rate density of $S_a(T_1)$, and the conditional probability distribution of ε given $S_a(T_1)$: $\Delta\lambda_{IM}(x_{1,i}, x_{2,j}) = P(x_{2,j} < \varepsilon < x_{2,j+1}|Sa(T1) = x_{1,i}) \bullet \Delta\lambda_{S_a(T_1)}(x_{1,i})$. This form is useful because we obtain the distributions in this way from PSHA: $\Delta\lambda S_{a(T_1)}(X_{1,i})$ comes from the ordinary hazard curve, $\lambda S_{a(T_1)}(X_{1,i})$, and $P(x_{2,j} < \varepsilon < x_{2,j+1}|S_a(T_1) = x_{1,i})$ is a standard PSHA disaggregation result.

Prediction of Building Response Using a Vector-Valued IM

When evaluating Equation 1, we must estimate $P(EDP>z|S_a(T_1) = x_1, \varepsilon = x_2)$. The method we adopt is to scale records to each of several levels, run dynamic analyses and then apply regression analysis to estimate *EDP* as a function of ε for each $S_a(T_1)$ level. In doing this, we must note that some records cause a collapse in the structure, and thus must be treated separately.

The probability of collapse as a function of ε is first estimated using logistic regression, which is a commonly used tool for analyzing binary data. Among a suite of records scaled to $S_a(T_1) = x_1$, we designate C as an indicator variable for records that cause collapse and use the ε value of each record as our predictor. The logistic regression prediction is then:

$$\hat{P}(C \mid S_a(T_1) = x_1, \varepsilon = x_2) = \frac{\exp(\hat{\beta}_0 + \hat{\beta}_1 x_2)}{1 + \exp(\hat{\beta}_0 + \hat{\beta}_1 x_2)} \quad (2)$$

where $\hat{\beta}_0$ and $\hat{\beta}_1$ are coefficients to be estimated from regression on a dataset that has been scaled to $S_a(T_1) = x_1$. By performing this regression for a range of $S_a(T_1)$ levels, one can obtain the probability of collapse as a function of both $S_a(T_1)$ and ε, as seen in Figure 1.

Among the remaining non-collapsing records, there tends to be a relationship between ε and *EDP* of the form $\ln EDP = \beta_2 + \beta_3\varepsilon + e$, where β_2 and β_3 are constant coefficients, and e is the prediction error ("residual"). We can use linear least-squares regression to obtain estimates of the coefficients (denoted $\hat{\beta}_2$ and $\hat{\beta}_3$) and the variance of the residuals (denoted $\hat{Var}[e] \equiv \hat{\sigma}_e^2$). We have verified that the residuals are well represented by a Gaussian distribution, so the probability of exceeding an *EDP* level z given $S_a(T_1) = x_1$, $\varepsilon = x_2$, and no collapse can be expressed as:

$$P(EDP > z \mid S_a(T_1) = x_1, \varepsilon = x_2, \text{no collapse}) = 1 - \Phi\left(\frac{\ln z - (\hat{\beta}_2 + \hat{\beta}_3 x_2)}{\hat{\sigma}_e}\right) \quad (3)$$

where Φ(•) denotes the standard Gaussian cumulative distribution function.

The possibilities of collapse or no collapse are combined using the Total Probability Theorem and Equations 2 and 3 to compute the conditional probability that *EDP* exceeds z:

$$P\left(EDP > z \,\middle|\, \begin{matrix} S_a(T_1) = x_1, \\ \varepsilon = x_2 \end{matrix}\right) = \frac{e^{\hat{\beta}_0 + \hat{\beta}_1 x_2}}{1 + e^{\hat{\beta}_0 + \hat{\beta}_1 x_2}} + \left(1 - \frac{e^{\hat{\beta}_0 + \hat{\beta}_1 x_2}}{1 + e^{\hat{\beta}_0 + \hat{\beta}_1 x_2}}\right) \left(1 - \Phi\left(\frac{\ln z - (\hat{\beta}_2 + \hat{\beta}_3 x_2)}{\hat{\sigma}_e}\right)\right) \quad (4)$$

Although x_1 does not appear in Equation 4, our estimate is implicitly a function of x_1, because records are scaled to $S_a(T_1) = x_1$ before generating the response data to estimate $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$, $\hat{\beta}_3$ and $\hat{\sigma}_e$.

When performing the logistic and linear regressions needed for Equation 4, it has been found that ε is a statistically significant predictor of structural response for a range of structures and spectral acceleration levels considered. The important conclusion is that records with larger epsilon values tend to have a lower probability of causing collapse, and cause lower levels of structural response among records that do not cause collapse.

Why Does Epsilon Affect Structural Response?

When considering why ε could affect structural response, we consider current knowledge about nonlinear response of multiple-degree-of-freedom (MDOF) structures. For a given $S_a(T_1)$ level, values of S_a at periods other than T_1 are known to affect the response of a nonlinear MDOF structure. This is because S_a at shorter periods affect the response of higher modes, and S_a at longer periods affect nonlinear structures because of the effective lengthening of the first mode. Thus, given two records with the same $S_a(T_1)$ value, the record with higher S_a values at periods other than T_1 will tend to cause larger responses in a nonlinear MDOF system.

A record with a positive ε value is one that has a larger-than-expected S_a at the specified period. But what does it tell us about the spectral acceleration at other periods? $S_a(T_1)$ is positively correlated with S_a at other periods, but not perfectly correlated. Thus if ε at T_1 is positive, then the expected values of ε at other periods are *positive but less than* the ε at T_1. The result is that a positive ε value at T_1 tends to indicate a "peak" in the response spectrum at T_1, and a negative ε value tends to indicate a "valley." Consider scaling a record with a peak and a record with a valley to the same $S_a(T_1)$ level. At T_1, the two records will have the same spectral acceleration by construction, but at other periods the valley record will tend to have larger spectral accelerations, which induce larger MDOF responses, than the peak record, as seen in Figure 2. Therefore, ε is an indicator of spectral shape, and this is why it is effective in predicting the response of nonlinear MDOF models. Using a second-moment model for logarithmic response spectra, it is shown by Baker and Cornell [1] that ε is a consistent estimator of peaks and valleys: the effect seen in Figure 2 is not unique to these two records.

Epsilon and Drift Hazard

The drift hazard methodology outlined above is now applied to a sample structure, to demonstrate the effect of adding ε to the *IM*.

Description of the structure: The structure analyzed is a reinforced-concrete moment-frame building located in Van Nuys, CA, which is serving as a test-bed for PEER research. The model has a first-mode period of 0.8 seconds, and contains nonlinear elements that degrade in strength and stiffness, in both shear and bending. Forty historical earthquake ground motions from California are used to analyze structural response. Epsilon values were not considered as a criterion for selection of records, so that the ε values of the record set are random.

Ground motion hazard: We consider the ground motion hazard at the site of the test structure. As the annual rate of exceedance decreases (and the $S_a(T_1)$ level increases) the epsilons contributing to the hazard shift to larger values. In general, for any hazard environment, it can be shown that the ground motion hazard at low mean annual frequencies of exceedance will be dominated by positive ε events [1]. Because positive ε records cause lower response levels on average, it is expected that neglecting to account for ε will result in conservative estimates of the drift hazard, and this is verified for the sample structure.

Drift hazard results: The structural response calculations were combined with the ground motion hazard for the Van Nuys site to compute drift hazard curves as shown in Figure 3. The vector *IM* $\{S_a(T_1), \varepsilon\}$ is evaluated using Equation , and the scalar *IM* $S_a(T_1)$ is evaluated using an analogous procedure. We see that inclusion of ε in the *IM* results in lower mean annual frequencies exceedance at high levels of drift. Analysis was also performed using a vector-valued *IM* $\{S_a(T_1)$, magnitude$\}$ using the same procedure, and replacing ε with magnitude. While the use of magnitude lowers the drift hazard, the effect is much less pronounced than when ε is used, because magnitude's impact on spectral shape is comparatively mild. (Using distance as a second parameter results in a negligible change in drift hazard.)

Conclusions

It is seen that ε has a significant ability to predict structural response, because it tends to indicate whether S_a at a specified period is in a peak or a valley of the spectrum. For a fixed $S_a(T_1)$, records with positive ε values cause systematically smaller demands in structures than records with negative ε values. In addition, by examining disaggregation of the ground motion hazard, it is seen that at low mean annual frequency of exceedance the ground motions are all positive-epsilon motions. Therefore, the practice of scaling up zero-epsilon (on average) records to represent records with positive epsilons is likely to result in overestimation of the demand on the structure at a given hazard level.

A vector-valued *IM* consisting of $S_a(T_1)$ and ε has been proposed. This *IM* will account for the effect of ε on structural response, correcting the bias seen when using $S_a(T_1)$ alone as an *IM*. Alternatively, one could correct for the effect of ε on structural response by intelligently selecting records that have the proper ε value (based on disaggregation results), and then using $S_a(T_1)$ as a scalar *IM*. In either case, it is important to consider the possible effect of ε when estimating structural response.

Acknowledgements

This work was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation, under Award Number EEC-9701568 through the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of NSF.

References

1. J.W. Baker, C.A. Cornell (2004). A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon. Submitted to *Earthquake Engineering & Structural Dynamics*.
2. J.W. Baker, C.A. Cornell (2004). Choice of a Vector of Ground Motion Intensity Measures for Seismic Demand Hazard Analysis. *Proceedings, 13th World Conference on Earthquake Engineering*. Vancouver, Canada. 15p.
3. C.A. Cornell, H.K. Krawinkler (2000). Progress and Challenges in Seismic Performance Assessment. *PEER Center News* 2000; **3**. http://peer.berkeley.edu/news/2000spring/performance.html

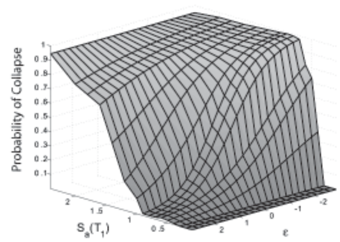

Figure 1. Prediction of the probability of collapse as a function of both $S_a(T_1)$ and ε.

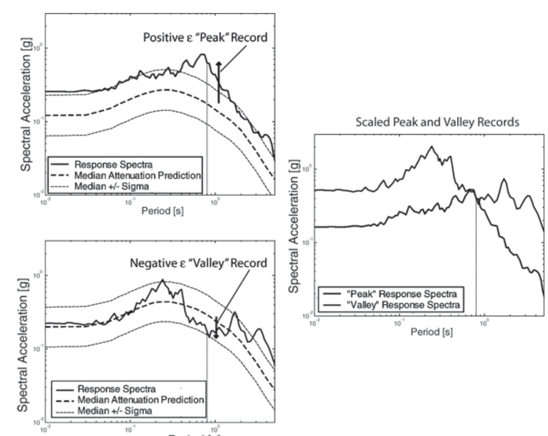

Figure 2. Scaling a negative ε record and a positive ε record to the same $S_a(0.8s)$: an illustration of the peak and valley effect.

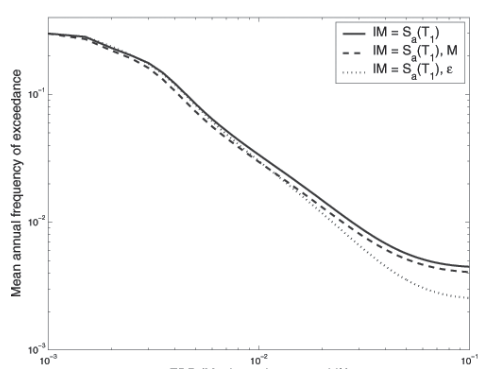

Figure 3. Mean annual frequency of exceedance versus maximum interstory drift using scalar and vector-valued IMs.

Blume Center News continued from page 1

"Technology Innovations Toward a Sustainable Planet" held on the Stanford Campus in July. Ph.D. Student **Molly Morse** presented a poster at the symposium on the research she is conducting with Prof. Billington regarding bio-degradable composites for the building industry.

Prof. Krawinkler gave a presentation on "Sidesway Collapse of Frames with Deteriorating Properties" at the SEAOC Convention held in Monterey from August 25 to 28.

NSF NEES-R Awards

The Blume Center is represented well in the first round of NEES research grants, with Stanford faculty and alumni involved with five of the ten projects that were awarded by the NSF. **Prof. Helmut Krawinkler** is leading a project to investigate the sideway collapse of deteriorating structural systems. **Prof. Anne Kiremidjian** will be working with the research team at the University of Nevada Reno dealing with seismic performance of bridge systems with conventional and innovative materials. **Prof. Amit Kanvinde** (PhD '94), who recently joined the faculty at U.C. Davis, is leading a project on testing and simulation of ultra-low-cycle fatigue cracking in steel structures. Amit will be collaborating with his former adviser, **Prof. Greg Deierlein**, and a Stanford graduate student on this project. **Prof. Luciana Barroso** (PhD '99) is co-PI on a project at Texas A & M concerning the in situ determination of soil modulus and damping as a function of induced strain. **Prof. Jerome Lynch** (PhD '03) is co-PI on a project at the University of Michigan dealing with damage tolerant and intelligent slab-column frame systems, which combine advanced materials and embedded wireless sensors. Look for more developments on these and other projects in upcoming newsletters.

Spring 2004 Graduates

Arash Altoontash and **Gloria Ting Ting Lau** received their Ph.D. degrees in Structural and Geotechnical Engineering during the Summer quarter. Arash is now working at Walter P. Moore and Assoc., in Los Angeles, and Gloria is with FindLaw, Inc. in Mountain View.

Published Papers

Han, T.S. and **Billington, S.L.**, "Seismic Analysis of Structural Concrete Frame Buildings using Interface Modeling," ASCE Journal of Structural Engineering, 130(8): 1157-1168 (2004).

Billington, S.L. and **Yoon, J.K.**, "Cyclic Response of Precast Bridge Columns with Ductile Fiber-reinforced Concrete," ASCE Journal of Bridge Engineering, 9(4): 353-363 (2004).

Alumni News

Pablo Sanz (MS '02) and his wife, Alejandra, welcomed their first child, a daughter, on June 30. Emma weighed in at 6 lbs., 10 oz., and was 20" long. Proud papa returned to Stanford this Fall to study for his Ph.D.

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.

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