The 2010 Progress Report to the Southern California Earthquake Center (SCEC)
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The strong support from the Center continues to help undertake important studies by my research group and produce significant results. The successes this year include the acceptance of our ShakeOut paper to be published in the ShakeOut Special Issue of the Spectra Journal. Two other papers submitted to the Journal of Structural Engineering are in different stages of review. Abstracts of all three papers follow. PDF pre-prints of the accepted papers are available online at http://krishnan.caltech.edu (click on "publications"). Abbreviated versions of the ShakeOut paper and the JSE paper have been accepted for presentation at the 9th National Conference on Earthquake Engineering, organized by EERI to be held in Toronto later this year.

In terms of on-going research, we have been actively pursuing the question, "How would tall steel moment frame buildings collapse under seismic loading". The distribution of moments in a steel moment frame subjected to lateral loads is such that it produces double curvature in all the columns and beams resulting in shear-racking of the frame. Thus, shear deformation and not flexural deformation dominates moment-frame response. This allows the drawing of an analogy between steel moment frames excited by earthquake ground motion and a shear wave traveling through a shear beam. However, moment frame buildings differ from uniform shear beams in three important ways - first, the buildings are not uniform, there is typically stiffness gradation and mass variation over the height of the structure; second, gravity is not present in the shear beam wave propagation problem, whereas, it plays a dominant role in the response of moment frame buildings. Not only do building columns carry axial loads, but gravity also causes second-order overturning moments associated with the self-weight of the structure acting through its deformed configuration under lateral loading, the so-called $P-\Delta$ effect; third, steel-frame buildings do exhibit low levels of damping. Damping has the effect of attenuating the response (which impacts the response to multi-pulse excitation more than single-pulse excitation) and lengthening the apparent period. But the low level of damping inherent in steel structures means that it plays a relatively minor role in the damage localization phenomenon. Despite these differences in nature we find that a 18-story moment frame building responds very similar to a linear shear beam when subjected to a moderate pulse of 1s. More specifically, strain doubling occurs due to constructive interference of the reverse phase of the incident wave with the forward phase that is reflected off the free end similar to the behavior of an ideal beam. Such strain doubling can lead to damage localization which can result in the formation of a shear-compliant block collapse mechanism, consisting of column yielding at floors corresponding to the top and bottom of the shear-compliant block, with significant yielding of the beams or columns or panel zones at each joint in each of the intermediate floors. For moderate loading (motions that are not strong enough to cause structural collapse), the Confines of the Most Pronounced Localization of Yielding (CoMPLY) is controlled by the period of the input ground motion relative to the fundamental period of the structures, with behavior that is very similar to that of an idealized shear beam. However, the response to "collapsogenic" input motions shows a "convergence" of the CoMPLY to the same few stories, rendering it invariant with respect to various measures of the ground motion. This implies that there is a characteristic mechanism of collapse for a given building regardless of the frequency-duration characteristics of the incident ground motion (see Figure 1). This characteristic collapse mechanism happens to be a function of the structural system alone and can be predicted using its basic properties. The ability of being able to predict these characteristics encourages exploration of possible local retrofitting measures to reduce the collapse potential of these structures. Arnar Bjorn Bjornsson, who is a graduate student at Caltech, has been exploring simple retrofitting measures using steel braces. He has successfully demonstrated the increased the collapse resistance of a model of an existing 18-story steel moment frame building using such a retrofit measure

(Figure 2). He presented a poster at the PEER annual meeting held last year in San Francisco which was very well received. In fact, he was one of a handful of students selected by PEER for sponsorship to attend the 7th Center for Urban Earthquake Engineering (CUEE) conference, held this year in Tokyo. This conference was held jointly with the 5th International Conference on Earthquake Engineering (5ICEE). Unfortunately, the dates coincided with his exams, and he could not avail of this wonderful opportunity.

Last year, I also had a chance to work with Phil Maechling and a USC computer science graduate student Jing-Qiao Fu. We started a collaboration toward the visualization of a digital city under the event of an earthquake. Jing-Qiao developed very interesting animations of structures hypothetically located in a city block. We hope to continue collaborating on this front. The idea is to develop an automated workflow for the integrated visualization of seismic wave propagation and the response of a city block.

Finally, NSF has funded a 3-year end-to-end simulation project titled, "Quantifying the Risk Posed to Tall Steel Frame Buildings in Southern California from Earthquakes on the San Andreas Fault". The recently released Uniform California Earthquake Rupture Forecast by the Working Group on California Earthquake Probabilities concludes that there is a high probability that an earthquake of magnitude 6 or larger will occur on the southern section of the San Andreas fault in the next 30 years. The research objective of this award is to do a region-wide quantitative risk analysis of six steel buildings in the 20-story class for the hazard posed by the San Andreas fault. For this, end-to-end computer simulations of ground motion from 36 earthquakes and damage to the six buildings will be carried out. The earthquakes vary in magnitudes from 6.0 to 8.0 and originate at three hypocenter locations on the fault. Two rupture propagation directions will be considered. The Los Angeles metropolitan region will be divided into 636 analysis sites on a uniform grid of about 3.5km spacing. Three steel moment frame and three steel braced frame building models will be analyzed at each site for damage caused by the 3-component motion of the 36 scenario earthquakes. The results will be probabilistically analyzed to quantify the expected annualized economic loss for each building at each of the sites. Remedial measures that prevent collapse of the buildings will be investigated. The study will resolve long-standing questions related to failure modes, degradation characteristics, and collapse mechanisms of steel moment frame and braced frame buildings. This will also provide a quantitative measure of the economic risk due to the seismic activity on the San Andreas fault to the hundreds of high-rise buildings that exist in Southern California.

Abstracts of Submitted and Accepted Publications in the Preceding Year

(a) **Muto, M. and Krishnan, S., 2011. "Hope for the Best, Prepare for the Worst: Response of Tall Steel Buildings to the ShakeOut Scenario Earthquake", vol. 27(2), May 2011, ShakeOut Special Issue, Earthquake Spectra.**

ABSTRACT: The USGS ShakeOut scenario was conceived as part of an effort to increase public awareness and readiness for the next big earthquake on the San Andreas fault through a large-scale emergency drill. To understand the effects of such an event, a source model for a M7.8 scenario earthquake was created and used in conjunction with a velocity model for southern California to generate simulated ground motions for the event throughout the region. This work represents an effort to develop one plausible realization of the effects of the scenario event on tall steel moment-frame buildings. We have used the simulated ground motions with three-dimensional non-linear finite element models of three buildings in the 20-story class to simulate structural responses at 784 analysis sites spaced at approximately 4 km throughout the San Fernando Valley, the San Gabriel Valley and the Los Angeles Basin. Based on the simulation results and available information on the number and distribution of steel buildings, the recommended damage scenario for the ShakeOut drill was 5% of the estimated 150 steel moment frame structures in the 10-30 story range collapsing, 10% red-tagged, 15% with damage serious enough to cause loss of life, and 20% with visible damage requiring building closure.

(b) Krishnan, S. (in revision). "The Modified Elastofiber Element for Steel Slender Column and Brace Modeling", Journal of Structural Engineering.

ABSTRACT: An efficient beam element, the modified elastofiber (MEF) element, has been developed to capture the overall features of the elastic and inelastic response of slender columns and braces under axial cyclic loading without unduly heavy discretization. It consists of three fiber segments, two at the member ends and one at mid-span, with two elastic segments sandwiched in between. The segments are demarcated by two exterior nodes and four interior nodes. The fiber segments are divided into 20 fibers in the cross-section that run the length of the segment. The fibers exhibit nonlinear axial stress-strain behavior akin to that observed in a standard tension test of a rod in the laboratory, with a linear elastic portion, a yield plateau, and a strain hardening portion consisting of a segment of an ellipse. All the control points on the stress-strain law are user-defined. The elastic buckling of a member is tracked by updating both exterior and interior nodal coordinates at each iteration of a time step, and checking force equilibrium in the updated configuration. Inelastic post-buckling response is captured by fiber yielding, fracturing, and/or rupturing in the nonlinear segments. Key features of the element include the ability to model each member using a single element, and easy incorporation of geometric imperfection, partial fixity support conditions, member susceptibility to fracture defined in a probabilistic manner, and fiber rupture leading to complete severing of the member. The element is calibrated to accurately predict the Euler critical buckling load of box and I-sections with a wide range of slenderness ratios (L/r = 40, 80, 120, 160, and 200) and support conditions (pinned-pinned, pinned-fixed, and fixed-fixed). Elastic post-buckling of the Koiter-Roorda L-frame (tubes and I-sections) with various member slenderness ratios (L/r = 40, 80, 120, 160, and 200) is simulated and shown to compare well against second-order analytical approximations to the solution, even when using a single MEF element to model each leg of the frame. The inelastic behavior of struts under cyclic loading observed in the Black et al., Fell et al., and Tremblay et al. experiments is accurately captured by single MEF element models. A FRAME3D model (using MEF elements for braces) of a full-scale 6-story braced frame structure that was pseudodynamically tested by the Building Research Institute of Japan subjected to the 1978 Miyagi-Ken-Oki earthquake record, is analyzed and shown to closely mimic the experimentally observed behavior.

(c) Krishnan, S. (in review). "A Benchmark Problem for Collapse Prediction of Steel Structures", Journal of Structural Engineering.

ABSTRACT: To aid in the evaluation of the collapse-prediction capability of competing methodologies, a benchmark problem of a water-tank subjected to the Takatori near-source record from the 1995 Kobe earthquake, scaled down by a factor of 0.32, is proposed. The water-tank, supported by a 5-segment steel lattice tower, is so configured as to have a collapse mechanism that is always triggered due to catastrophic column and brace buckling at the bottom-most segment under all forms of ground motion. A FRAME3D model of the tank reveals severe buckling in the bottom mega-columns on the west face of the tower, followed almost instantaneously by compression brace buckling on the north and south faces, when the structure is hit by the Takatori near-source pulse, resulting in a tilt in the structure. Subsequent shaking induces $P-\Delta$ instability resulting in complete collapse of the tank.

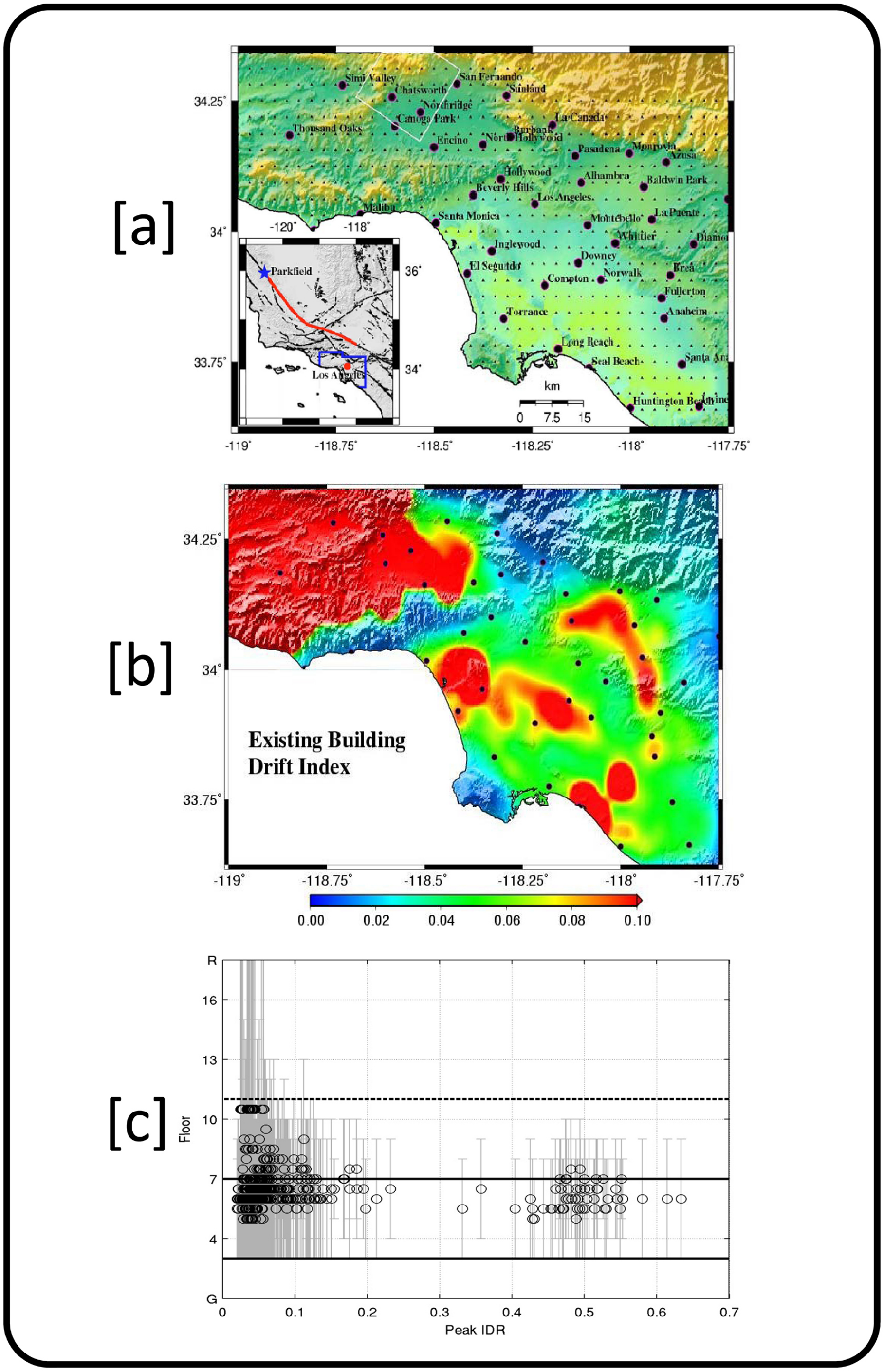
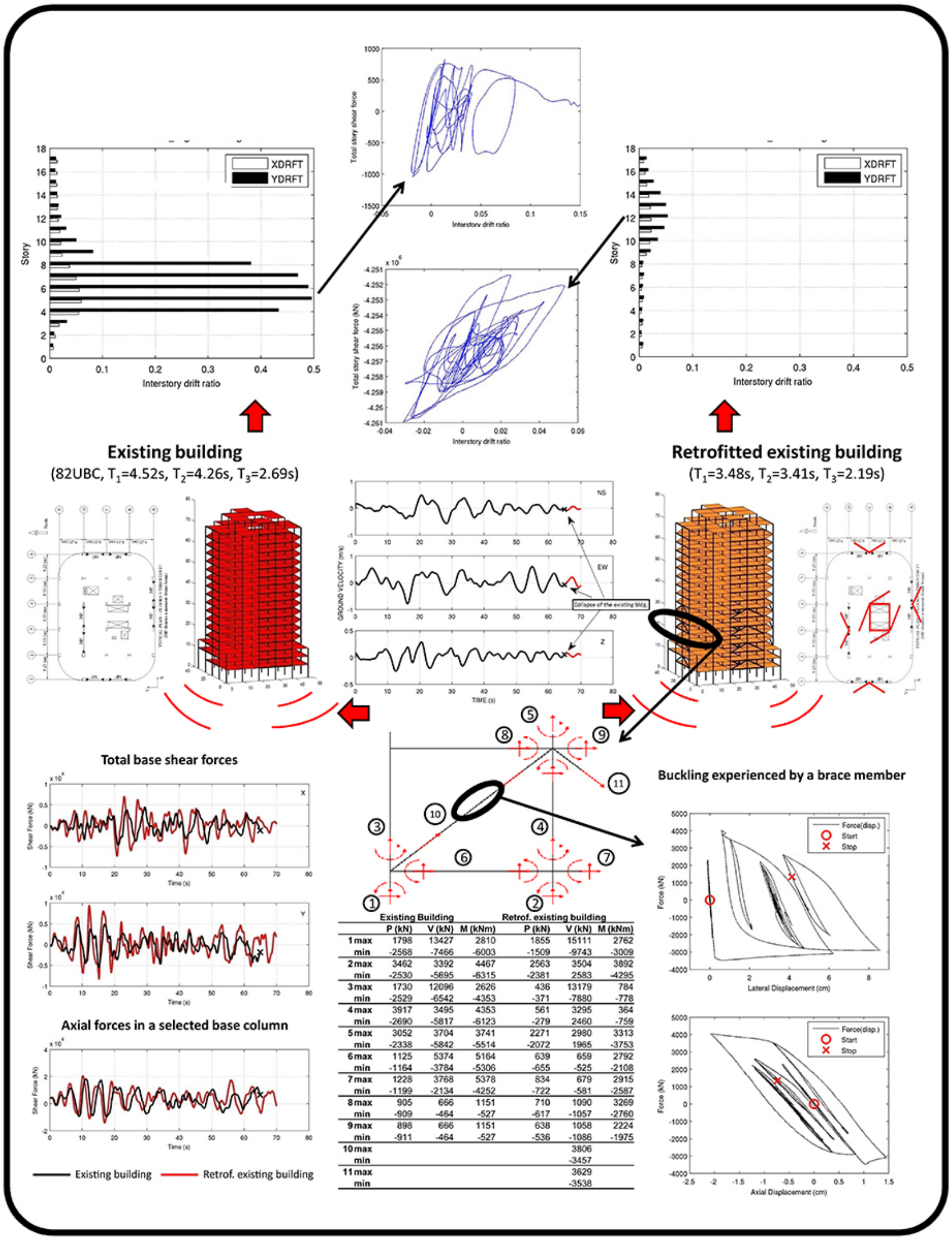


Figure 1: [a] An 1857-like hypothetical magnitude 7.9 earthquake on the San Andreas fault, initiating at Parkfield and rupturing in a southeasterly direction with a peak displacement of 2 m and peak velocity of 2 m.s^{-1}. The Los Angeles and the San Fernando basins, have been divided into a spatial grid of 636 sites (marked with black dots) where the ground motions are calculated. [b] Resulting IDRs when an existing 18-story steel moment frame building is subjected to the calculated ground motions at each site. The color bar refers to the peak IDR at each site. [c] The unique CoMPLY observed beyond IDR=0.05 that is reasonably well predicted by the simple plastic analysis (black dashed lines) and moment equilibrium (black solid lines) approaches.



	Existing Building			Retrof. existing building		
	P (kN)	V (kN)	M (kNm)	P (kN)	V (kN)	M (kNm)
1 max	1798	13427	2810	1855	15111	2762
min	-2568	-7466	-6003	-1509	-9743	-3009
2 max	3462	3392	4467	2563	3504	3892
min	-2530	-5695	-6315	-2381	2583	-4295
3 max	1730	12096	2626	436	13179	784
min	-2529	-6542	-4353	-371	-7880	-778
4 max	3917	3495	4353	561	3295	364
min	-2690	-5817	-6123	-279	2460	-759
5 max	3052	3704	3741	2271	2980	3313
min	-2338	-5842	-5514	-2072	1965	-3753
6 max	1125	5374	5164	639	659	2792
min	-1164	-3784	-5306	-655	-525	-2108
7 max	1228	3768	5378	834	679	2915
min	-1199	-2134	-4252	-722	-581	-2587
8 max	905	666	1151	710	1090	3269
min	-909	-464	-527	-617	-1057	-2760
9 max	898	666	1151	638	1058	2224
min	-911	-464	-527	-536	-1086	-1975
10 max					3806	
min					-3457	
11 max					3629	
min					-3538	

Figure 2: An example of a simple retrofitting measure which aims to stabilize the CoMPLY of an existing moment frame building directly with minimal intervention. Braces are added within the moment frames and around the stair case core on alternate stories within the CoMPLY (from the 3rd floor extending to the 10th). When subjected to a ground acceleration time history which drives the existing building to collapse the retrofitted building stays up. Ground motion velocity histories are provided below. While the retrofitted building shows improved collapse resistance it increases the demands at the on the foundation as well as in the existing members and connections. The existing elements need to be evaluated for the increased force demand. We compare element forces in one particular bay of the existing and retrofitted building.