THE INFLUENCE OF PERFORMANCE ENGINEERING ON DISASTER RECOVERY: PRIORITIES FOR LIMITING DOWNTIME

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SUMMARY

In recent years—after staggering economic losses accompanied physical damage in the Northridge, Los Angeles, and Kobe, Japan earthquakes—earthquake engineering practitioners and researchers proposed to change the way buildings, bridges, and other structures were designed. Instead of leaving safety questions to the code writers, researchers proposed "performance-based engineering"—the development of a set of trade-offs between initial design standards, expected post-earthquake functionality, and cost.

The application of performance standards is exemplified in the design choices for new construction and retrofits of existing buildings made by the University of California, Berkeley, located in a high hazard zone near the Hayward fault. The University has invested in what may be the single largest program of seismic improvement of existing buildings in the world. The investment was justified by the need to protect the safety of students, faculty, and staff, and the preservation of research and the stature of the university. In the 1990's (after the Northridge and Kobe earthquakes) life-safety specific seismic upgrading of existing buildings was the first priority, but now that a number of buildings have been strengthened, the focus has shifted to limiting losses among valuable contents and business recovery planning. The University used the Disaster Resistant University (DRU) Initiative together with research at the Pacific Earthquake Engineering Research (PEER) Center to evaluate the performance of contents in modern laboratory buildings in order to develop strategies to limit downtime in future seismic events. The research involved detailed surveys of building contents, modeling of structural performance and shake table testing of key equipment to inform the loss models. The process included the use of GIS software to map the building contents and the impact of equipment vulnerabilities, not only in a single building, but also in laboratory building across the campus. The outcomes informed the development of nonstructural retrofit strategies and research recovery planning. In addition, the research provided an analytic base-data set for future loss modeling efforts.

1. THE U. C. SEISMIC RETROFIT PROGRAM

The concept of "performance-based engineering design" suggests a dialogue between engineer and client on what to expect from different levels of design. Using a performance-based model, engineers and architect quantify the technical needs and costs associated with expected outcomes. The client then makes a conscious choice between code-mandated minimum level building code standards (where front end costs are lower, but the building is likely to sustain damage in an earthquake) and a variety of enhanced performance levels with proportionately higher costs, and the expectation that the building will be functional and useable immediately after an earthquake.

The issue is exemplified at the University of California, Berkeley, a world-class institution sitting astride the Hayward fault—a fault which seismologists estimate will rupture sometime in the next fifty years. The central campus houses over 30,000 students, and more than 13,000 faculty and staff in more than 100 academic departments and research units. The central campus has 114 buildings on 177 acres, with about 5 million net square feet of classrooms, libraries, offices, research laboratories, and other specialized facilities. The annual campus operating budget is about $1 billion, and the sponsored research awards average about $400 million per year.

Although the Berkeley campus began seismic review of its buildings in 1978, and embarked on a program of upgrades in the 1980s, the key policy change came after a 1997 review of the structural conditions of all buildings. At that time, nearly one-third of the space on campus was rated poor or very poor—subject to potential collapse in earthquakes. The Seismic Action Plan for Facilities Enhancement and Renewal (SAFER) policy [1] was developed and implemented, with a commitment of investing $20 million per year over 20 years. The University of California, Berkeley SAFER program is the single largest program of seismic improvement of existing buildings in the world (see Table 1). The investment was justified by the need to protect the safety of students, faculty, and staff, and the preservation of research and the stature of the university. Initially, the existing buildings selected for structural retrofits were designed to meet code-specified life-safety criteria, but additional research from the Disaster Resistant University (DRU) study helped to shift the focus to combine performance engineering with risk management in order to reduce downtime and limit the loss of valuable contents [2].

Table 1 Seismic Rehabilitation Building Areas at U. C. Berkeley

Time Frame and Buildings	*Total Area Affected*
Pre-1997: Libraries, Residence Halls, Administration Buildings and Wheeler Hall	
In Construction 1997: Libraries, Residence Halls, Hearst Mining, McCone Hall	1,257,084 s.f.
SAFER Projects Completed 2003: Art Museum, Barker, Barrows, Hildebrand, Latimer, Silver, Wurster Hall	1,316,682 s.f.
Phase 2 SAFER currently under construction	971,669 s.f.
Phase 2 SAFER in design	95,700 s.f.
Phase 2 SAFER in planning stage	367,574 s.f.
Phase 3 SAFER planned	1,332,485 s.f.
	735,813 s.f.
TOTAL SEISMIC CORRECTIONS	
	6,077,007 s.f.

2. THE DRU LOSS ASSESSMENT

The DRU campus loss study addressed the economic impact of potential losses under various earthquake scenarios. In addition to the cost of repairs, it considered the time needed for repairs to make the campus habitable and operational. Even in a moderate earthquake, the study estimated that 19 percent of laboratory space could require more than 20 months for repair. In a magnitude 7.0 earthquake on the Hayward fault, the estimates ranged from 30 percent to 50 percent of all spaces needing more than 20 months for repair. Although the downtime estimates would clearly be reduced by the aggressive seismic strengthening program on the campus, the potential loss of habitable buildings remained a serious issue for the university. The DRU study further suggested that the true economic loss from earthquakes would be in the reduction of research and in the loss of highly trained graduates who remain to work in the region. These finding prompted to campus to develop business resumption plans for the teaching and research as well as administration and operations. Additional investments were made in upgrading campus infrastructure, performance enhancements were reviewed along with retrofit priorities, and nonstructural retrofits were studied further.

Even though most contemporary building codes do contain provisions aimed at controlling damage to nonstructural (as well as structural) building systems, there are no similar requirements for a building's contents. In certain building types, such as museums, high-technology fabrication facilities, and research laboratories, the contents may be far more valuable than the building, and in some circumstances, may represent a potential hazard to the occupants and the general public. At the University of California, Berkeley, laboratories occupy 30 percent of the overall net usable space on campus. Fifty percent of the research on the U.C. campus is conducted in 7 buildings, 75 percent in 17 buildings. Seventy-two percent of the approximately $400 million in research funded each year is concentrated in science and engineering. The value of the laboratory contents is estimated at $676 million, or 21 percent of the total insured assets.

Equally important is the inestimable value of the research itself. Refrigerators and freezers contain irreplaceable specimens. Computer hard drives store data for research in progress. Laboratories represent both a concentration of research (as measured by annual funding) and a concentration of valuable equipment and ideas. In a preliminary PEER-funded study of laboratories on the campus, Comerio and Stallmeyer [3] estimated that the average laboratory contents were valued at $200 to $300 per square foot. By comparison, in a typical office space the value of the contents is usually $25 per square foot.

Additional research funded by the Federal Emergency Management Agency (FEMA) and the Pacific Earthquake Engineering Research (PEER) Center focused on limiting downtime in modern laboratory buildings by protecting contents. The research involved detailed surveys of laboratory contents [4], modeling of structural performance and shake table testing of key equipment to inform the loss models [5], and development of design standards for contents anchoring [6]. The process also included the use of GIS software to map building contents and the impact of equipment vulnerabilities on downtime. The outcomes inform the development of nonstructural retrofit strategies, research recovery planning, and they provide an analytic base data set for future loss modeling efforts.

3. THE PEER TESTBED LABORATORY BUILDING

The case study building is located in the southwest quadrant of the campus, within 2 km of the Hayward fault. The building was completed in 1988, intended to provide high technology research laboratories for organismal biology. The building is essentially rectangular in plan and is nominally 100 feet wide and 300 feet long, and 6 stories, plus a basement. The lateral force (seismic) resisting system consists of discrete concrete shear walls in the transverse direction and exterior concrete wall-frames (or "punched shear walls") in the longitudinal direction as shown on the plans, Figure 1. These shear walls provide great lateral stiffness to the building, on the one hand preventing large lateral displacements between floors ("drift"), but on the other hand enabling the building to transmit and amplify strong ground motions to each floor level. Walls, other than the concrete shear walls, exterior walls, and shaft walls, are made of steel studs and gypsum board and are considered nonstructural (although, in some cases they can provide support for contents). Typically, ceilings are open with exposed mechanical piping in the laboratories. Some offices contain acoustical drop ceilings, but most are exposed. The floor is either vinyl tile or exposed concrete. The mechanical systems are sophisticated, as one would expect of a modern laboratory building.

3.1 Contents Inventory and Retrofit Costs

The building contents are typical of a wet laboratory: lab benches with storage shelving above, and very densely packed equipment. In total, there are about 10,500 items in the building, of which, 44% is furniture and 56% is equipment. Shelves and work benches dominate the equipment category, while computers, heavy equipment such as refrigerators, freezers, and centrifuges, and bench top item such as microscopes dominate the equipment group. After analyzing the contents for life safety concerns, the project team looked at the value of the each item and its importance to the research. Not surprisingly, computers, refrigerators and freezers dominated the "Important" category because they contained data on research in progress or customized genetic materials.

It was interesting to note that only a small percentage of the equipment in the building was extremely specialized and valuable. More significant was the concern voiced by researchers that the loss of the contents of a refrigerator or freezer, or the loss of a hard drive, could effectively curtail their research.

Figure 1. Location of Testbed Building Relative to the Hayward Fault

In terms of equipment anchorage, if we gave priority to those items that posed a life-safety threat, or were categorized as valuable or important to research, then we would only need to retrofit about 40% of the building contents. The total cost to retrofit the entire contents of the building would be about $20 per assignable (net) square foot, the cost to retrofit the group of high priority items would range from $2.50 for the "important" category to $13 per assignable square foot for "important, chemical, and life-safety hazard" categories [4].

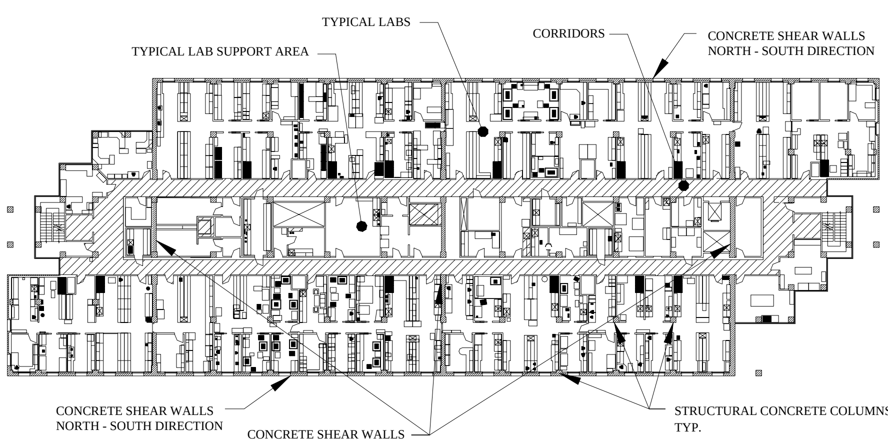

Figure 2 Typical Floor Plan 2nd through 5th Floors

3.2 Structural Analysis and Testing

The building was analyzed using the PEER OpenSees structural methodology by Khalid Mosalam [7] at University of California, Berkeley to produce roof and floor displacement data (known in the PEER terminology as Engineering Demand Parameters or EDPs) to be used by Nicos Makris [8] (U. C. Berkeley) and Tara Hutchinson [9] (U. C. Irvine) who did laboratory tests of critical heavy floor-mounted equipment and bench-top configurations and equipment. Both sets of researchers postulated that the seismic excitation would result in sliding-dominated (rather than rocking dominated) responses based on size and configuration of typical components. For simplification, neither testing program considered vertical motion input. Similarly, each researcher used different earthquake input motions because the objects and the shaking table capacities were different. The horizontal displacement capacity is approximately six inches for the Berkeley table and ten inches for the Irvine table, so tests were only done for ground motions within the limits of the tables. Numerical simulations were necessary to project equipment behavior for larger displacements.

Figure 3 Bench and Shelf system on the Shake Table at U. C. Irvine

The results of the shake table tests for bench-top equipment show that the maximum displacement (based on an average of multiple positions) relative to the bench surface is less than 10 cm (4 inches) for a Peak Horizontal Floor Acceleration (PHFA) below 0.8g. Based on the ground motions, using Peak Horizontal Floor Acceleration as an EDP, the amplifications at the bench tops and the coefficients of friction, the seismic fragility curves were created. The results of the tests for heavy equipment produced results of peak sliding distance (PSD) ranges between a low of about 2.5 cm (one inch) to a high of almost 61 cm (24 inches).

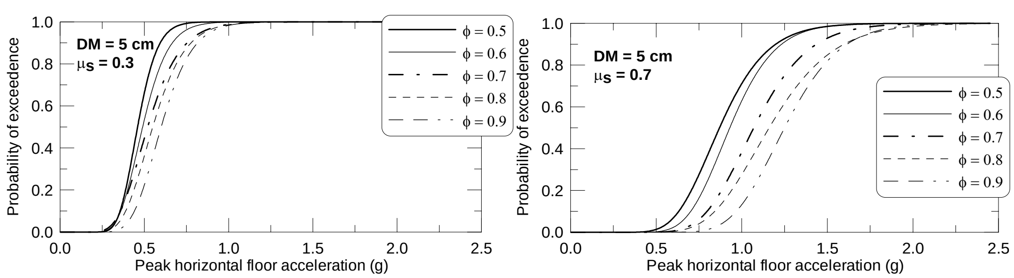

Figure 4 Sample probability of small equipment exceeding displacement of 5 cm, given a range of φ values and: (a) μ_s = 0.3 and (b) μ_s = 0.7 [9]

Figure 5 Heavy Equipment on the Shake Table at U. C. Berkeley

3.3 Relating Contents Losses and Downtime

In the PEER methodology, a fragility function typically expresses the probability of exceeding a specified Damage Measure (DM) for a given EDP. Damage is then used to estimate potential losses in one of three areas: repair costs, casualties (or the occurrence of life-threatening damage), or downtime (or the loss of operability). In the testbed, the California Institute of Technology researchers, Jim Beck and Keith Porter [10], were interested in the impact of equipment damage on downtime. The researchers evaluated operational failure based on the probability of loss of equipment categorized as important, and life-safety critical. Table 2 shows the failure probability for sample laboratory types, conditioned on the Intensity Measure (IM) or ground motion. The results suggest high failure probabilities. Even at the lowest hazard level, the probability of life-safety failure exceeds 20% for all four labs examined here. Operational failure becomes likely in the 10%/50-yr event or higher. From both perspectives, mitigation is probably called for, but the decision would have to be balanced against cost, and improvements in operability resulting from the mitigation.

Table 2. UC Science Building failure probabilities at three hazard levels [10]

		Hazard level					
		S_a = 0.71g 50%/50 yr (0.0139 yr^{-1})		S_a = 1.62g 10%/50 yr (0.0021 yr^{-1})		S_a = 2.74g 2%/50 yr (0.0004 yr^{-1})	
Lab	Floor	Operability	Safety	Operability	Safety	Operability	Safety
S	1	0.2%	20.4%	1.2%	74.2%	7.2%	94.1%
M	3	7.8%	48.4%	41.6%	93.7%	73.3%	99.5%
LL	4	4.7%	56.2%	14.2%	95.9%	44.8%	100.0%
LO	4	11.8%	43.2%	45.0%	95.3%	91.8%	100.0%

4. USING RESEARCH TO INFORM DESIGN AND RETROFIT DECISIONS

The university allowed researchers to use actual building conditions and data for research with the understanding that the research would be brought back to inform the SAFER program decisions. In general, limiting downtime—the time buildings could be closed as a result of structural and non-structural and contents damage, together with the time needed to mobilize financing, design and construction work for repairs—is critical to maintaining university functions such as teaching and research. Numerous business resumption planning studies within University of California, Berkeley suggest that operations would cease if more than 25% of any functional space was closed for an extended period. Obviously, the dense urban setting precludes the use of extensive temporary facilities, so the university focused on the performance of existing facilities.

Overall, the planning performance goal was to limit a campus closure to 30 days or less, so that a semester would never be cancelled due to earthquake damage. For each major function, classrooms, laboratories, libraries, offices, etc.—space was analyzed in terms of its structural and non-structural performance and retrofit priorities were adjusted to reflect the overall risk. Laboratories were particularly vulnerable. Three of the five key laboratory buildings were collapse hazards and a decision was made to replace these buildings with new structures rather than risk post-earthquake damage that could result in closure of retrofitted buildings. Similarly, critical computing services were moved to a new facility. New food service buildings were also designed to be operational after an earthquake.

Figure 6 Demolition and Replacement of a Critical Laboratory Building

Another risk-management approach to performance-based engineering focused on contents damage in laboratory buildings. Data from the PEER testbed was compared to laboratory buildings throughout the campus to analyze the impact of contents damage on laboratory closures. Table 3 shows an analysis of 598 labs (defined as the lab space under the management of a single researcher) on the campus.

Table 3 Campus Labs Operational and Closed due to Earthquake Damage in Three Scenarios

	50%/50yr	10%/50yr	2%/50yr
Operational	390	15	0
Closed due to structural damage	176	305	494
Closed due to nonstructural dmg.	32	278	104
TOTAL	598	598	598

The high proportion potentially closed due to contents damage fostered a program of seismic improvements for lab contents. Technical guidance was developed by PEER researchers in the form of an implementation manual [6] and training for campus construction staff.

Overall, the University of California, Berkeley planning and construction staff, the consulting engineers and architects working on campus projects, and PEER researchers have collaborated to effectively introduce the concepts of performance based design and risk management into the development planning for the university. The traditional engineering methods of identifying seismic hazards by building construction, and the risk management approach to identifying critical operations combined to create a new mitigation methodology. The result provides a unique example of early adoption and implementation of performance-based engineering research in a way that benefits the client and serves as a model for risk management and engineering practice.

5. ACKNOWLEDGEMENTS

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