# SET-BASED DESIGN: CASE STUDY ON INNOVATIVE HOSPITAL DESIGN

**Kristen Parrish[1], John-Michael Wong[2], Iris D. Tommelein[3] and Bozidar Stojadinovic[4]**

## ABSTRACT

This paper describes collaboration efforts of a project team that implemented lean concepts in the course of structural system selection during the design phase of a hospital project. Out-of-the-box thinking, contractual incentives for team work, early collaboration, and a set-based design approach led to the development of an innovative and cost-effective structural system that may set precedent for other medical facilities to be constructed in seismically active zones.

The structural design team on this project rigorously explored the design space and tested design alternatives against project value propositions. When pushed by the owner to think more broadly, the structural engineer proposed using a new technology, namely viscous damping walls. This concept was developed in Japan but has not yet been tried on projects in the United States. Because it is a first, this solution requires not only rigorous analysis and testing by the structural engineer but also detailed investigation by the state's regulatory agency that issues building permits. This paper describes the team's efforts at defining the design space and the set-based design approach they used. A key lesson from this case study is that teams have a lot to learn about how to make requests and commitments while pursuing set-based design to be lean.

## KEY WORDS

lean construction, coordination, collaboration, set-based design, stakeholder value, integrated project delivery, relational contracting, viscous damping walls, seismic design, structural engineering

## INTRODUCTION

Structural system selection during the design phase of a hospital project is no small task. The system must meet many requirements imposed by owners, architects, engineers, and others, most notably in the case being studied: California's Office of Statewide Health Planning and Development (OSHPD)(http://www.oshpd.ca.gov/). OSHPD serves the state in the process

[1] Graduate Student, Civil and Environmental Engineering Department, University of California, Berkeley, CA, kristen_parrish@berkeley.edu

[2] Graduate Student, Civil and Environmental Engineering Department, University of California, Berkeley, CA, jmwong@ce.berkeley.edu

[3] Director, Project Production Systems Laboratory http://p2sl.berkeley.edu/ and Professor, Civil and Environmental Engineering Department, 215-A McLaughlin Hall, University of California, Berkeley, CA 94720-1712, Phone +1 510/643-8678, FAX +1 510/643-8919, tommelein@ce.berkeley.edu

[4] Professor, Civil and Environmental Engineering Department, 721 Davis Hall, University of California, Berkeley, CA 94720-1710, Phone +1 510/643-7035, FAX +1 510/643-8928, boza@ce.berkeley.edu

of building permitting by verifying that hospital designs comply with its legislative framework for seismic safety. The Hospital Facilities Seismic Safety Act, SB 1953 (1994)(Safety 2001), requires that acute care facilities remain functional during and following an earthquake. In order to meet these stringent requirements, owners, architects, structural engineers, contractors, and other specialists alike have been forced to re-think their design and construction strategies. An accepted structural design solution to achieve seismic performance in California has been to use base-isolated structural systems (see e.g., http://nisee.berkeley.edu/lessons/kelly.html). These systems tend to be cost effective, but not necessarily on all hospitals. For example, on sites with a steep grade, as is the case here, it is difficult to build the moat around the facility as needed to allow the base-isolated structure to slide. This paper reports on how a structural design team developed an innovative alternative solution on their project.

## CASE STUDY BACKGROUND

The California Pacific Medical Center's (CPMC) Cathedral Hill project is a new 600-bed hospital in San Francisco, California, budgeted at $1.7 billion (Figure 1). The hospital is 93,000 m$^2$ (1,000,000 ft$^2$) with 555 parking stalls with a total of 13 above and below grade stories. The project is sited on sloping terrain, 18 km (11 mi) from the nearest active earthquake fault. Design of the Cathedral Hill hospital began in 2005 and the project is expected to complete in 2013.

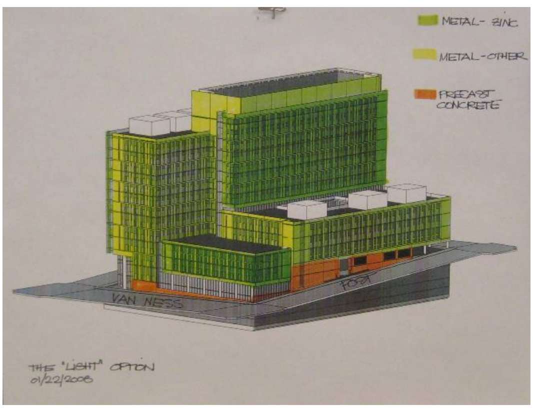


Figure 1: Schematic Building Shape and Skin (Photo taken by John-Michael Wong 2/25/08).

Figure 2: Viscous Damping Wall Model (Photo taken by John-Michael Wong 2/25/08).

CPMC is an affiliate of Sutter Health, a major healthcare provider in Northern California. Sutter Health has shown a commitment to lean practices in its hospital design and delivery processes (Lichtig 2005b) and is managing a portfolio of lean projects (e.g., Mikati et al. 2007). As a part of this lean implementation, Sutter Health encourages project teams to implement the 'Five Big Ideas' (Macomber 2005): (1) Collaborate, Really Collaborate;

(2) Manage as a Network of Commitments; (3) Increase the Relatedness of the Project Participants; (4) Tightly Couple Learning with Action; and (5) Optimize the Project as the Whole. These ideas, implemented using a relational contract called the Integrated Form of Agreement (IFOA) (Lichtig 2005a, 2005b, 2006), have fostered an environment of collaboration and innovation on the project.

Cathedral Hill project participants include CPMC (owner), SmithGroup (architect), Degenkolb (structural engineer), Herrick (steel fabricator), Dowco (steel detailer), Dynamic Isolation Systems (supplier of viscous damping walls)(Figure 2), Pankow (concrete subcontractor), Herrero/Boldt (general contractor), and other companies.

## RELATED WORK

### DESIGN MANAGEMENT THEORY

The design of a project in the Architecture/Engineering/Construction (AEC) industry, like the development of a new product in other industries, can be managed in different ways. Terwiesch et al. (2002) characterize iterative and set-based design management approaches in new product development projects in terms of ambiguity and uncertainty as defined by Schrader et al. (1993). Uncertainty is defined as a lack of information. Ambiguity is defined as a lack of clarity. Terwiesch et al. explain that iterative design strategies work best in ambiguous environments while set-based design strategies work best in uncertain environments. They explain that starvation (lack of work for the downstream participants) can occur as a result of too little detail being available in a set-based design environment. Similarly, rework can result in an iterative design environment when the upstream suppliers of information pass on specific yet incorrect detail. These observations are pertinent to this case study.

Collaborative team work has been studied widely. Of particular note here for its application in AEC is Lottaz et al.'s (1999) use of a constraint-based approach to manage the fabrication of beams for a steel frame building with ductwork holes cut into them. Lottaz et al. suggest that all project participants use an internet based collaborative tool to decide on diameters and locations of ductwork holes. This tool tracks constraints concerning ductwork as well as the abilities of each project participant to change the design. Their implementation of a constraint-management system allowed for postponement of commitment to specific diameters and locations. This, in turn, reduced rework as the steel fabricator was able to fabricate components based on reliable information, rather than with assumed values that later changed.

Macomber and Howell (2003) critique the activity-centred management paradigm defining projects as a series of transformations of "energy to 'materials'" and suggest that projects are actually a "network of commitments," a notion rooted in linguistic action. Whereas the critical-path method perspective on project management views a project as a network of activities, the linguistic action perspective views projects as networks of requests and promises. Macomber and Howell stress the need for reliable promising—clearly communicating requests and reliably committing to deliver on those requests—in lean project delivery.

Gil et al. (forthcoming) discuss design postponement on large infrastructure projects. They develop a set of propositions detailing use cases of iterative design, set-based design, buffers, and modularization. Using the notions of uncertainty and ambiguity defined by Schrader et al. (1993), Gil et al. explain that iterative design is favourable when "they [upstream developers] believe that the assumed benefits of adapting their designs outweighs the costs". They go on to propose "upstream developers will not invest in set-based exploration when they expect downstream uncertainty and ambiguity to remain unresolved until late in the implementation of the upstream design." Similar phenomena were observed on the project documented here.

## SET-BASED DESIGN METHODOLOGY

In current design practice, many designers follow a point-based methodology, exploring one or multiple alternatives, but developing each one separately from the others. They select a design, or point, early in the process and then develop that design in more detail. When input from others is received, that design may prove to be infeasible or require significant rework in order to remain acceptable. By contrast, designers may use set-based design and postpone committing to a specific design, allowing them to consider multiple alternatives for longer than is typical with a point-based methodology. A design team can then review sets of design alternatives available to each team participant, integrate these sets to find compatible combinations and weigh input from several project participants at the same time, early on, and throughout project delivery, while studying tradeoffs between what individual participants value and what is of value to the project as a whole. Set-based communication helps participants avoid rework and, through teamwork, develop a more globally satisfactory design than would otherwise be the case.

Set-based approaches have been pursued in a variety of domains, such as data interpretation to infer protein structures (Altman and Jardetzky 1986), and construction site layout (Tommelein et al. 1991). It has been used in new product development by Toyota engineers (Kennedy 2003; Sobek et al. 1999; Ward 2007; Ward et al. 1995). Toyota's approach has inspired the development of a set-based methodology for rebar design (Parrish et al. 2007, 2008), and it forms the basis for the case study presented here.

## RELATIONAL CONTRACTING

Relational contracts (MacNeil 1978, Goetz and Scott 1981) can be used to spur the formation and effectiveness of integrated project teams. Lichtig's (2005a, b) relational contract, the IFOA, basically manages two risks: (1) the risk of defects and (2) the risk of cost overruns. On the Cathedral Hill project, risks and their associated costs are shared amongst team members. The owner jointly with members on the integrated project team, put money into a shared risk pool. Each member of the team commits 25% of their fee towards the risk of cost overruns. Unforeseen project costs are paid out of the risk pool. The owner's portion of the risk pool is spent first, followed by the team members'. The IFOA also has an incentive sharing provision. If the owner's portion of the risk pool is not spent, that money is divided up among the team members according to the risk that they took. This pay structure supports collaboration and innovation, as there is an incentive for the entire team, not just one team member, to reduce risks. The IFOA mandated that all project participants collaborate and use set-based design as soon as they are brought onto the team.

The IFOA is being used on this project in conjunction with target costing (Ballard 2006). Cost targets are set for the scope of the work, and each set of design alternatives gets evaluated. The aim of target costing is not to minimize project cost; rather, it is to maximize value generation while remaining within the allowable budget. This effort may result in shifting costs from the construction phase to the design phase, or between target cost categories; e.g., on Cathedral Hill, fabrication drawing production, which typically is accounted for as a construction cost, took place during design. The owner's willingness to invest upfront, pays for production of details well before construction begins.

## SET DEFINITION—MAP DESIGN SPACES

The following set-based design examples reflect decisions made during the Concept/Schematic Design (SD) phase and the Preliminary Design/Design Development (DD) phase. During SD, the material and structural system were decided. During DD, the structural system details and preliminary mechanical, electrical, and plumbing (MEP) layouts were decided.

The first step in set-based design is to map the design spaces in order to define (1) the decision(s) to be made and (2) the available design options. As a project progresses, the sets examined at each phase become increasingly more detailed. Clearly articulating the level of detail and accuracy necessary to define alternatives at a given point in time during design requires open communication and understanding of the values each party can bring and constraints that affect them. Lack of clarity on these is an obstacle to set-based design. Each project participant must understand not only what is asked, but also the level of detail (precision) and accuracy that is required for the purpose at hand, given requests for handoffs made by others on the team, in order to make a reliable promise. Too much detail too early forces unrealistic and undesirable commitment, while too little detail may result in otherwise avoidable rework.

### PROBLEM OF TOO MUCH DETAIL OR PRECISION TOO GREAT

The difficulty of defining the level of detail (precision) and accuracy needed for reliable promising to be made is illustrated by conversations that occurred during project team meetings discussing (1) openings in walls and (2) the exterior skin system.

**Example 1 - Wall Penetrations:** In order to define the structural system details, the structural engineer needed to know the location of wall openings required by the MEP team. In the spirit of collaboration, the MEP team started to precisely calculate their penetrations; they thought that locations of openings down to ±10 cm (±4 in) had been asked for. This was a difficult if not an impossible task to do so early in the design process because other system parameters had not yet been pinned down. That is, there was still too much uncertainty in the design for the MEP team to confidently give the structural engineer the location of all of the wall openings. This roadblock was resolved when the structural engineer realized that only locations of openings on the order of 2.4 m × 2.4 m (8 ft × 8 ft) or larger were of consequence to develop structural system details. With this clarification, the set definition proceeded for structural system detailing.

**Example 2 - Skin of the Structure:** The weight of the exterior skin affects the building loads and the demands on structural elements at the periphery of the structure. In order to develop structural system details, the structural engineer asked the architect for this information, but at that time the skin weight was still uncertain.. This roadblock was resolved when the structural engineer clarified that the exact weight was not needed, but rather only whether the skin was 'heavy' vs. 'light,' i.e., on the order of 1200 N/m$^2$ (25 lb/ft$^2$) vs. 3600 N/m$^2$ (75 lb/ft$^2$). The architect's clarification that the skin would not be of the heavier variety, allowed the structural engineer to continue with detailing while the architect could postpone commitment to a particular skin type and manufacturer.

**Lessons Learned:** In both of these examples, one party assumed that more detail (precision) and accuracy was needed than was necessary for the other party in that phase of design. Such uncertainty supports the use of a set-based design approach, as commitment to very specific values for wall openings and skin weights can be postponed. Designers must learn to articulate what they really need for their own work and what they should request from (give to) others with reasons why, in accordance with their modelling capabilities, while recognizing that their and others' needs change with different project phases. Simply stated, meter-level details may be appropriate in early phases whereas centimetre-level details may be appropriate later. Degrees of required specificity must be articulated not only for geometric but also for non-geometric design attributes.

### PROBLEM OF TOO LITTLE DETAIL OR ACCURACY TOO SMALL

**Example of Beam Layout:** The choice of floor-system beam depth and spacing are important to resolve early in design since they impact how ductwork gets laid out. The structural engineer and MEP wanted to coordinate their parameter choices so that the ducts could fit in-between the beams, thus saving floor height (no additional vertical space needed to fit ducts). The structural engineer and MEP coordinated their work and chose an option that satisfied both duct depth and structural requirements.

However, the team initially failed to discuss another variable: beam orientation. The MEP team assumed that the beams would be laid out perpendicular to the external wall so that ducts could run from the building interior through the length of the patient rooms. The structural engineer assumed that beams would run parallel to the external wall. Each took it for granted that the other would intuitively opt for the same orientation, so neither party thought it important to specify up front what orientation they planned to work with. Here, the set parameter specification should have included beam depth, spacing, and orientation. However, the team did not realize that all three were required at this stage of design, until they discovered the conflict later.

**Lessons Learned:** Both parties specified less than they actually required at this stage in the process and this miscommunication resulted in negative iteration (Ballard 2000) to find a satisfactory design. This breakdown in communication illustrates the importance of defining the set properly and exploring it to obtain input from other project participants before proceeding with decisions. If the two sets' definitions had included the variable 'orientation,' options could have been evaluated and decided on without requiring rework.

## SET EXPLORATION AND SET NARROWING

### STRUCTURAL SYSTEM SELECTION

In the validation phase of design, structural systems (Figure 3) were compared on a whiteboard matrix (Love 2008). Each system controls inter-story drift using a different mechanism. The moment-resisting frame uses special connections to resist lateral deflections by flexure throughout the whole building height. The piston-damper system adds supplemental damping for energy dissipation and resists displacement like a braced frame by concentrating large axial loads through the connection points. The lead-rubber bearing base isolation system reduces inter-story drift by concentrating large displacements at the base level; accommodating this large base-level displacement requires a special moat around the perimeter of the building. The viscous damping wall (Figures 2 and 3) resists displacement by shearing and distributes the force transfer along the entire wall length along the top and bottom connections to beams.

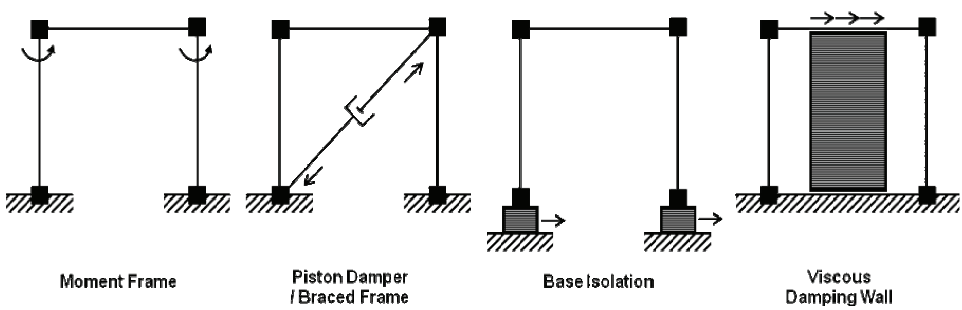


Figure 3: Options for Structural Systems

Although a base isolation system was the initial choice (Morgan 2007, Naeim and Kelly 1999, Tuholski et al. 2008), this plan was scrapped due to the cost associated with building and maintaining the displacement moat. This structure would need a 76 cm (30 in) moat around the building and excavating such a moat on a sloping terrain (as is the case on the Cathedral Hill project) is a challenge. This moat would require complicated stepping, special piping detailing, breakaway sidewalks, and special loading docks to accommodate large trucks, thereby imposing challenges on many project participants. The base isolation system would also be taller than the other options and require special 2-story trusses to accommodate a mid-height mechanical floor.

Using a moment-resisting frame would have required about 50%-75% more steel than, e.g., viscous damping walls would, in order to meet inter-story drift limits. This extra steel is necessary because lateral stiffness must be added by increasing flexural stiffness, whereas the other systems rely on effects like damping and axial forces.

As an alternative, viscous damping walls were chosen. These walls are full-story height and are bolted to steel beams on the top and at the bottom. The viscous material inside the wall is polyisobutylene (Aseismic Device Company Ltd. 2008). In Japan, such walls have been used in high rise buildings, but in the United States, their use on Cathedral Hill will be a first. This structural system does not require a displacement moat. Furthermore, a viscous damping wall is self-contained inside a wall which reduces the likelihood of clashing with MEP and architectural features. The viscous damping wall is also considerably less expensive, saving about 1% of the total project cost. Furthermore, after a seismic event, the bolting system allows for easy bolt replacement if necessary. Tthe structural steel frame is expected to remain elastic and therefore would not need to be replaced. Thus, from a lifecycle perspective, this system is favored, as the expected repair costs are lower than those of most other systems.

Figure 4 illustrates the narrowing of the set of alternative structural systems. Initially, four systems were considered. As constraints and metrics were applied, and alternatives discussed, design options were eliminated. In the end, only the viscous damping wall met the lateral force resisting requirements and was economical enough to be selected.

The viscous damping walls, providing a critical damping ratio of about $\beta = 15\%$ (Love 2008), were developed by Sumitomo in Japan (Aseismic Device Company Ltd. 2008). For this project the walls will be fabricated by Dynamic Isolation Systems in the United States and prototypes will be tested for structural performance at the University of California, San Diego. Cathedral Hill has three different floor heights for which three different heights of walls need to be fabricated: 4.3 m (14 ft), 4.9 m (16 ft), and 5.2 m (17 ft). To ease and suppress the cost of testing, the structural engineer is limiting the number of widths of the walls to be used. The frame is designed to remain mostly elastic; therefore its restoring force is expected to re-centre after an earthquake.

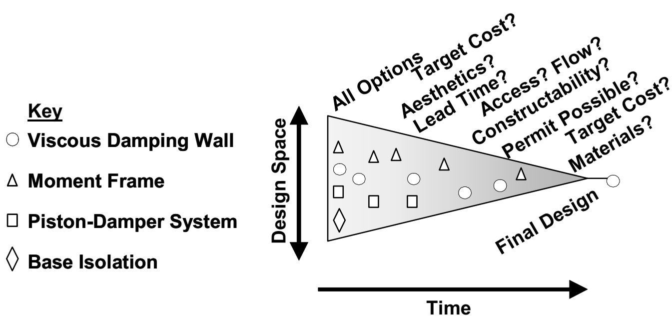


Figure 4: Set Narrowing Scheme for the Structural System Selection

Use of innovations like the viscous damping wall requires analysis in order to justify the system's ability to meet structural performance goals. This innovation is not part of the 83 seismic force-resisting systems of ASCE 7-05 for which design coefficients and factors are given (ASCE 2005). Additional design time is therefore needed to resolve modelling issues and ensure the solution will meet all project-specific requirements. On Cathedral Hill, the owner is encouraging the structural engineers to carry out additional analysis by paying them on a time-and-materials basis. If engineers are not paid for the additional time that may be required to develop innovations, they will be more likely to stick to 'conventional' systems that may not be as optimal for the entire project. By rewarding design teams for innovation, system-optimal solutions can be developed for the owner.

### PERMITTING

The process for permitting this project is also innovative because of the consideration OSHPD is giving to the use of the new structural system and their adoption of phased review. An preliminary design submittal was sent to OSHPD in order to get buy-in and concept approval on basic issues. This first stage of permit submittal contains mostly structural design information such as design criteria, gravity system, and loading. Loading is an important area to reach agreement on, because if different spaces are classified for different occupancy, the required loads can change substantially (e.g., roof area vs. outdoor courtyard area).

It is almost always better to negotiate changes during design than during construction. The process for making changes to construction drawings, especially once field work has begun, could take up to two weeks for a minor design change and possibly more than months if not years if drawings need to be re-submitted to OSHPD for permitting. The long turn-around time for permitting can cause major delays in the schedule. Problems during construction often involve differences between typical details and the real conditions in the field. This is another example of the too-little-detail problem.

## CONCLUSIONS

Sutter Health created a collaborative and innovative project team to build the Cathedral Hill project through the use of their 'Five Big Ideas.' The use of set-based design and out-of-the-box thinking enabled the project team to develop a design within the target cost boundaries. Thinking in a set-based manner has changed the conversations between team participants. It has spurred innovation by encouraging consideration of alternatives and evaluating tradeoffs between them, while keeping overall project value in mind. The owner's incentives for teamwork, including payment for additional analysis to develop the viscous damping wall system, led to selection of a system that better meets not only the structural performance but also the project goals than other options would have.

## ACKNOWLEDGEMENTS

We thank David Long of Sutter Health, Steve Peppler of SmithGroup, Jay Love of Degenkolb, Scott Muxen of Herrero/Boldt, Lonnie Andrews of Pankow, and our colleague Glenn Ballard at UC Berkeley for their support in researching and documenting this hospital design process as a case study. This research was funded by grant CMS-0511044 from the National Science Foundation (NSF) whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the writers and do not necessarily reflect the views of the NSF.

## REFERENCES

Altman, R.B. and Jardetzky, O. (1986). "New Strategies for the Determination of Macromolecular Structure in Solution." *Journal of Biochemistry*, 100(6), 1403-1423.

ASCE (2005). "Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05." *ASCE Standard No. 7-05*, American Society of Civil Engineers, Reston, VA.

Aseismic Device Company Ltd. (2008). "Viscous Damping Wall". Available at http://www.adc21.co.jp/ (in Japanese, translated with ), accessed March 12.

Ballard, G. (2000). "Positive vs Negative Iteration in Design." *Proc. 8th Ann. Conf. Int'l. Group Lean Constr.* Brighton, UK, 12 pp.

Ballard, G. (2006). "Rethinking Project Definition in Terms of Target Costing." *Proc. 14th Ann. Conf. Int'l. Group Lean Constr.* Santiago, Chile, 13 pp.

Gil, N., Beckman, S., and Tommelein, I. (forthcoming). "Upstream Problem-Solving under Uncertainty and Ambiguity: Evidence from Airport Expansion Projects." *IEEE Transactions on Engineering Management*, in press.

Goetz, C.J. and Scott, R.E. (1981). "Principles of Relational Contracts." *Virginia Law Review*, 67(6), 1089-1150.

Harris, R.B. (1978). *Precedence and Arrow Networking Techniques for Construction*, John Wiley & Sons Inc., New York, 429 pp.

Kennedy, M.N. (2003). *Product Development for the Lean Enterprise*, Oaklea Press, Richmond, VA, 254 pp.

Lichtig, W. (2005a). "Ten Key Decisions to a Successful Construction Project." *Proc. American Bar Association Forum on the Construction Industry*, Toronto, Canada, 27.

Lichtig, W.A. (2005b). "Sutter Health: Developing a Contracting Model to Support Lean Project Delivery." *Lean Construction Journal*, 2 (1) 105-112.

Lichtig, W.A. (2006). "The Integrated Agreement for Lean Project Delivery." *Construction Lawyer*, 26 (3) Summer, American Bar Association, 8 pp., available at http://www.mhalaw.com/mha/newsroom/articles/ABA_IntegratedAgmt.pdf.

Lottaz, C., Clement, D.E., Faltings, B.V., and Smith, I.F.C. (1999). "Constraint-Based Support for Collaboration in Design and Construction." *J. Comp. Civ. Engrg.,* ASCE, 13(1), 23 - 35.

Love, J. (2008). Personal communication, "Viscous Damping Wall Discussion". Degenkolb Engineers, Oakland, CA, February 25.

MacNeil, I.R. (1978). "Contracts: adjustments of long-term economic relations under classical, neoclassical and relational contract law." *Northwestern Univ. Law Rev.,* 72(6) 854-905.

Macomber, H. (2005). "LCI 7th Congress Keynote Address." Reforming Project Management, http://www.reformingprojectmanagement.com/2005/09/21/513/.

Macomber, H. and Howell, G.A. (2003). "Linguistic Action: Contributing to the Theory of Lean Construction." *Proc. 11th Ann. Conf. Int'l. Gr. Lean Constr.,* Blacksburg, VA.

Mikati, S.O., Roller, T.G., Tommelein, I.D., and Khanzode, A. (2007). "Priority Conversations: A Case Study on Priority Walls." *Proc. 15th Ann. Conf. Int'l. Group Lean Constr.,* East Lansing, MI, 431-441.

Morgan, T.A. (2007). "The Use of Innovative Base Isolation Systems to Achieve Complex Seismic Performance Objectives," PhD Diss., Civil and Envir. Engrg. Dept., Univ. of Calif., Berkeley, CA.

Naeim, F. and Kelly, J.M. (1999). *Design of Seismic Isolated Structures: From Theory to Practice*, Wiley, New York, 289 pp.

Parrish, K., Wong, J.-M., Tommelein, I.D., and Stojadinovic, B. (2007). "Exploration of Set-Based Design for Reinforced Concrete Structures." *Proc. 15th Ann. Conf. Int'l. Group Lean Constr.,* East Lansing, MI, 213-222.

Parrish, K., Wong, J.-M., Tommelein, I.D., and Stojadinovic, B. (2008). "Proof of Concept of the Use of Value Propositions in the Rebar Supply Chain." *Proc. 16th Ann. Conf. Int'l. Group Lean Constr.,* Manchester, UK.

Safety (2001). "Findings and Recommendations on Hospital Seismic Safety". California Seismic Safety Commission, available at http://www.seismic.ca.gov/pub/HospSeismicSfty.pdf. Accessed June 6.

SB 1953 (1994). *SB 1953—Hospital Facilities Seismic Safety Act FACT SHEET.* California Healthcare Assoc., available online at http://www.calhealth.org/public/press/Article%5C103%5CSB1953factsheet%20-%20Final.pdf visited February 10.

Schrader, S., Riggs, W.M., and Smith, R.P. (1993). "Choice over Uncertainty and Ambiguity in Technical Problem Solving." *J. of Engrg. & Tech. Mgmt.,* 10(1), 73-99.

Sobek, D.K., Ward, A., and Liker, J.K. (1999). "Toyota's Principles of Set-Based Concurrent Engineering." *Sloan Management Review*, 40(2), 67-83.

Terwiesch, C., Loch, C.H., and De Meyer, A. (2002). "Exchanging Preliminary Information in Concurrent Engineering: Alternative Coordination Strategies." *Organization Science*, 13(4), 402-419.

Tommelein, I.D., Levitt, R.E., Hayes-Roth, B., and Confrey, T. (1991). "SightPlan Experiments: Alternate Strategies for Site Layout Design." ASCE, *J. of Comp. in Civil Engrg*., 5 (1) 42-63.

Tuholski, S.J., Gursel, A.P., Tommelein, I.D., and Bomba, G. (2008). "'Lean' Comparison using Process Charts of Complex Seismic Retrofit Projects." *J. Constr. Engrg. and Mgmt.*, ASCE, in review.

Ward, A. (2007). *Lean Product and Process Development*, Lean Enterprise Institute, Cambridge, MA, pp. 35-70.

Ward, A., Liker, J.K., Cristiano, J.J., and Sobek, D.K. (1995). "The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster." *Sloan Management Review*, 36(3), 43-61.