ISSN 1520-295X

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Technical Report MCEER-08-0014

April 30, 2008

This research was conducted at the University of Southern California and at the University of Wisconsin-Green Bay and was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation under award number EEC 9701471.

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Publication Date: April 30, 2008
Submittal Date: December 4, 2007

Technical Report MCEER-08-0014

Task Number 10.2.5

NSF Master Contract Number EEC 9701471

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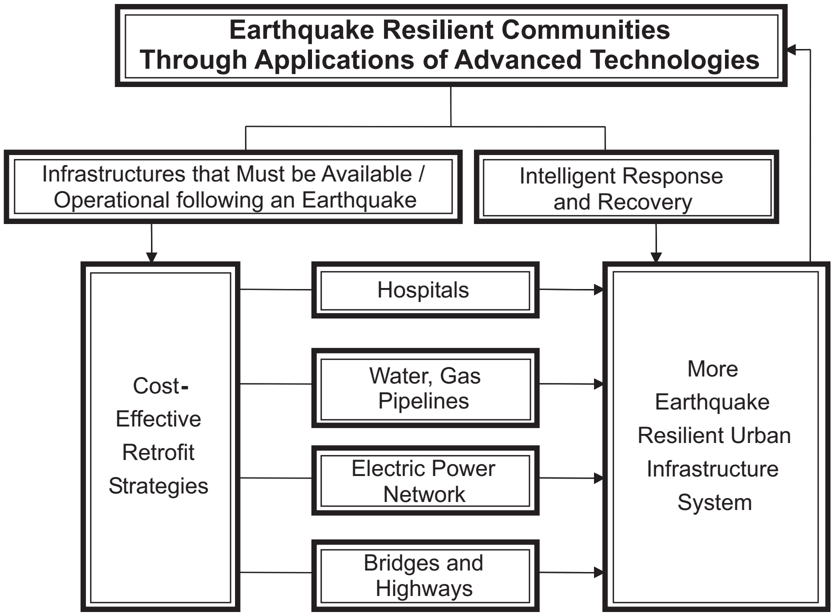
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report explores the challenges faced by engineers and architects to integrate structural and nonstructural elements in the design of earthquake resistant buildings. The authors review the traditional roles and responsibilities of various participants in constructing a modern building, and explore impediments to incorporating nonstructural design into engineering practice. Several possible solutions are proposed, including the creation of a new profession called a "master builder" who would serve as a building systems integrator. However, there is currently no academic program to train this type of professional. Legislation such as California's SB 1953, which brought the problems associated with integrating architecture, structural engineering, and the design and installation of nonstructural components of acute care hospitals into sharp focus, may provide some incentive to academic institutions to broaden current curriculums to be more in line with the needs of professional practice in this area.

ABSTRACT

Structural and nonstructural engineering and design often proceed independently of one another, even for complex structures intended for specialized use. This practice may have developed historically from the development of specialties within the architecture and engineering design industry, but the separation of structural and nonstructural engineering and design has become dysfunctional, particularly for critical, specialized facilities subject to the forces of an earthquake.

Buildings intended for complex, specialized use should no longer be conceptualized or designed apart from their intended operating environment, functions, and contents except at one's peril; neither structural nor nonstructural engineering and design should proceed apart from the other. Buildings are complex systems in which the performance of structural and nonstructural systems and components must be integrated with one another. The many components cannot be designed, installed, or operated in isolation from the rest of the building. The complexity of contemporary and anticipated technologies employed in creating integrated facilities increasingly demands more complete integration from concept to end use.

The issue is not a matter of a need for improved engineering knowledge: the need is for integrating structural and nonstructural system design. However, recognition is only the first step in bringing about better integration. Disciplinary practices, contracting procedures, and education programs must change to create a culture that demands improved system performance through better integration and practice.

ACKNOWLEDGMENTS

This report was prepared under the auspices of the Multidisciplinary Center for Earthquake Engineering Research through a grant from the National Science Foundation Earthquake Engineering Research Centers Program. Opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the view of the sponsors or the Research Foundation of the State University of New York.

The authors gratefully express their sincere appreciation to the many professional structural engineers, architects, and others who willingly shared their views of the difficulties associated with integrating structural and nonstructural engineering to enhance seismic safety.

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SECTION 1
THE PROBLEM

It has become increasingly clear in meeting the demands of an earthquake environment that architectural design, structural engineering, and the design for installation of nonstructural elements in buildings cannot proceed independently from one another. Each of those activities has clear implications for the others, as well as for the overall resilience of the building system. For example, initial conceptual design decisions on a building project can do much to determine its ultimate seismic performance. Architectural decisions early in the design period may commit a project to a building configuration or design concept that makes effective lateral-force resistance difficult to achieve. Accordingly, close collaboration from the outset between the architect and structural engineer is understood to be highly desirable and, to a considerable extent, has become practice within the United States. Unfortunately, this has not been the case with the design and installation of nonstructural elements. Even though it is important to do so, there is often a lack of design integration of the structural engineering and the engineering of nonstructural elements. Design integration is important, because some techniques for installing nonstructural components can actually diminish structural integrity, while at the same time, structural engineers can create unnecessary problems for those charged with the engineering design of nonstructural components. And, as buildings become increasingly complex, integrating architectural design, structural engineering, and the design of mechanical, electrical, plumbing, and other nonstructural systems becomes increasingly important if a building is to perform as expected when subjected to seismic forces.

When building in areas subject to earthquakes, one must be concerned with the safety of persons both within the building and in its immediate environment, as well as the likelihood that the building will continue to provide for the performance of its functions following the earthquake. Functionality of buildings subjected to the extraordinary forces of earthquakes depends on not only how the structure itself performs, but also depends on how the nonstructural components of the building perform. Enormous progress has been made in structural engineering design in recent decades to enhance the resiliency of building structures to the forces of earthquakes. These advances mean that building structures designed with today's engineering knowledge and standards are much more likely to survive modest and moderate seismic forces than buildings built only a few decades ago. However, requiring that a complex building system, such as a hospital, continue to support its pre-event functions immediately following an earthquake is a demanding standard. Functionality is highly dependent upon the performance of all systems and subsystems, in particular both the building structural system and the nonstructural elements and equipment installed in the building. The California legislation requiring retrofit of all hospitals built before 1973 (SB 1953) requires improvements in the functionality and performance of both structural and nonstructural elements of these older buildings.

Failure of nonstructural components of buildings in earthquakes can result in considerable deaths, injuries, and loss to building contents. Whittaker and Soong (2003) emphasize that nonstructural elements of buildings "are subjected to the building dynamic environment caused by, for example, an earthquake. Typical examples of nonstructural components include architectural partitions, piping systems, ceilings, building contents, mechanical and electrical equipment, and exterior cladding."

> The importance of nonstructural component issues in seismic design and performance evaluation is now well recognized by researchers as well as practicing engineers. The subject received special attention after the San Fernando earthquake in 1971 when it became clear that damage to nonstructural components not only can result in major economic loss, but also can pose real threat to life safety. For example, an evaluation of various Veterans Administration hospitals following the San Fernando earthquake revealed that many facilities still structurally intact were no longer functional because of loss of essential equipment and supplies (Whittaker, A. S., and T. T. Soong, 2003).

Also following the 1971 earthquake in San Fernando, California, the U. S. Veterans Administration recognized the need to understand buildings as complex systems when they developed the guidelines for design of hospitals. In their guidelines they state: "There is nothing new about the notion that a building is a collection of systems: a structural system, a mechanical system, an electrical system, and so on." The report goes on to state that "Of particular interest is how the characteristics of each component directly or indirectly affect the performance of the others and of the total building" (Joint Venture of Building Systems Development and Stone, Marraccini and Patterson, 1977).

Consequently, economic loss due to seismic nonstructural damage can also be considerable. A case in point is the seismic damage sustained by buildings during the 1994 Northridge earthquake. With the loss of approximately $18.5 billion due to building damage, nonstructural damage accounted for about 50% of this total (Kircher, 2003).

Concern over the role of nonstructural systems and components in earthquake safety had existed for some time and the question of how to integrate the design of structural and nonstructural components of buildings to enhance seismic safety had been simmering in the background for some time. As noted above, it was brought to focus in California as State officials sought to implement the law known as SB 1953, the California statute that established performance goals and objectives for all acute care hospital buildings constructed prior to 1973.

SB 1953 states that retrofitted hospital buildings and newly designed and constructed acute care hospital buildings are to ensure prevention of structural collapse (life safety) as a minimum condition for functionality, and nonstructural elements and systems are to continue to function when subjected to earthquake forces in the building. This public policy requires appropriate attention be given to ensuring responsible structural and nonstructural design.

Prior to 1988, the Uniform Building Code (UBC) applied to all new construction in California. The code, however, did not provide adequate guidance on the seismic design requirements for nonstructural elements. The code simply required that nonstructural elements be designed in accordance with national design standards and did not establish specific design requirements for seismic environments. The California Office of the State Architect, responsible for regulating school building and hospital design in California, employed UBC standards. In about 1980 the Office of the State Architect did try to add nonstructural seismic design requirements for schools and hospitals in earthquake environments, but the effort did not come to fruition.

The 1988 UBC included a beginning framework in which a conscientious structural engineer could address nonstructural seismic requirements by requiring that seismic design considerations be applied to nonstructural elements and systems. Work by the Building Seismic Safety Council (BSSC), a not-for-profit organization established by the National Institute of Building Sciences (NIBS), on how to promote building earthquake risk mitigation led to more detailed code requirements which were incorporated into the first edition of the International Building Code (IBC) in 2000.

In 2004, the Federal Emergency Management Agency (FEMA) recognizing the importance of both structural and nonstructural elements as critical to the performance of a building system stated:

> Seismic considerations should apply to every building system, subsystem, and component, and the performance of each component or system is often interdependent. The traditional organization of the design team and the assignment of responsibilities to the architect, structural engineer, MEP (mechanical, electrical, and plumbing) consultants, and other specialty consultants (e.g., geotechnical engineer, curtain wall consultant, elevator consultant, or security consultant) is critically important to address cross-cutting seismic design issues or problems." (FEMA, 2004)
>
> As the servicing needs of contemporary buildings continue to increase, the impact of the MEP (mechanical, electrical, and plumbing systems) consultant's work on seismic design becomes increasingly important. An example of this is the need for penetrations or blockouts in the structure to accommodate ductwork, piping, and equipment, which requires early design consideration. These penetrations are fundamental to the integration of the structural and mechanical system, and their size and location should be carefully worked out between the architect, structural, and mechanical engineers. There are many instance of damage to buildings in earthquakes caused by structural member penetrations that have not been adequately coordinated with the structural design (FEMA, 2004).

As noted, FEMA emphasized the need for the seismic design process to include every building system, subsystem, and component in enhancing seismic safety. It is important to note that seismic design for every nonstructural building system, subsystem, and component is not a straight forward matter of pointing to a building code as the solution to the problem. Nonstructural building systems, subsystems, and components can be classified into at least three general categories, each requiring special seismic design knowledge and skills:

1. Design of anchorage and bracing for "off-the-shelf" fabricated systems (e.g., HVAC),
2. Design of internally constructed support systems or subsystems (e.g., fire suppression systems) each designed to meet specific performance requirements, and
3. Manufactured systems, subsystems and components that must meet seismic performance qualification requirements.

In addition to the three general categories of nonstructural systems, subsystems and components, each building will contain many pieces of specialized equipment not physically attached to the building structure, but critical to the building's functionality following an earthquake. The 2006 International Building Code is the most current code enforced through out the United States. The International Building Code references the design guideline document, Minimum Design Loads for Buildings and Other Structures, prepared by the American Society of Civil Engineers (ASCE 7-05).

> ASCE 7-05 contains specific requirements for nonstructural components in essential facilities so that these components would maintain their function following design earthquake level events. In the past, the design of nonstructural components focused only on the design of anchorage and bracing. This is no longer the case. The ASCE 7-05 seismic provisions include seismic qualification requirements for critical active mechanical and electrical equipment by shake table testing or experience data. In addition, non-critical equipment is also permitted to satisfy seismic design requirements by testing or experience rather than by prescriptive requirements (this is referred to as alternate means). A shake table testing protocol (AC-156) has also been developed that is consistent with the ASCE 7-05 seismic provisions and many equipment suppliers are now in the process of qualifying their equipment to satisfy it. The combination of specific code requirements and alternate mean requirements and the existence of a standard acceptable test protocol has greatly increased the interest of suppliers in seismic testing of their products. (Bachman, 2007)

Effective January 1, 2008 the California Building Standards Board adopted the IBC as the governing code for California meaning the IBC is the model code for use in California.

Following legislative enactment of SB 1953, the California Office of Statewide Health Planning and Development (OSHPD) established retrofit regulations required for implementation of the law. The regulations were to be based upon accepted, consensus-based standards for both structural and nonstructural design. OSHPD relied on guidelines published by the Federal Emergency Management Agency (FEMA). OSHPD's requirement that nonstructural performance be considered when retrofitting pre-1973 acute care hospital buildings was a major step leading to the requirement for integrating the seismic design of structural and nonstructural components in buildings. The same requirements are *currently required* on new hospital construction in California, with the State adoption of the IBC.

To ensure proper interpretation of the American Society of Civil Engineers ASCE 7-05, California's OSHPD has initiated a Code Application Notice which states that beginning 2008

> every structure, and portion thereof, including nonstructural components that are permanently attached to structures and their supports and attachments, shall be designed and constructed to resist the effects of earthquake motions in accordance with ASCE 7. Editions of the California Building Code prior to 2007, based on the Uniform Building Code, had a direct correlation between the nonstructural component importance factor and building occupancy categories for essential facilities. The 2007 California Building Code, which is based on the 2006 International Building Code, refers to ASCE 7-05 for the component importance factor. All nonstructural components for OSHPD 1 facilities shall have an importance factor of 1.5, except when a justification by the architect or engineer of record in general responsible charge demonstrates that their failure will not impair the continued operation of the facility and which is accepted by OSHPD. Item 3, Section 13.1.3, ASCE 7-05 provides for flexibility in using a component importance factor lower than 1.5 for essential facilities provided that the component is not needed for continued operation or the component failure will not impair the continued operation of the OSHPD hospital facility. This Code Application Notice provides general guidelines for determining the component importance factor. (OSHPD, 2007)

Particularly in California, the question of who should be responsible for integrating structural and nonstructural seismic design has generated much discussion and confusion. The prospect for a simple, timely resolution of the issue seems unlikely. Structural engineers appear to be in general agreement that nonstructural elements are a key to building functionality following an earthquake. However, most of them seem to believe that structural engineering and nonstructural engineering are separate design tasks and the integration of structural and nonstructural design should not be viewed as the inherent responsibility of the structural engineer. Despite the general perception of structural engineers, the State of California requirements set forth in the 2001 California Building Standards Administrative Code (Part 1, Title 24), also referred to as the California Building Code, sets forth specific duties and responsibilities governing the design of buildings requiring all engineering and analysis to be detailed on the building drawings governing the design and installation of nonstructural systems and components. Specifically, Code Section 4-217 (a) states that "The architect or registered engineer is responsible to the owner and to the enforcement agency to see that the completed work conforms in *every material respect* (emphasis added) to these regulations and the approved plans and specifications." Code Section 4-217 (b) specifies that the project's "architect or registered engineer shall prepare the plans, specifications, design computations and other data and shall prepare documents authorizing changes in the approved drawings and specifications when so directed by the owner or as required by *conditions on the project* (emphasis added)." (State of California, 2001)

With regard to nonstructural design, Code Section 4-218 states that "The architect, structural engineer or civil engineer in general responsible charge *retains overall responsibility* (emphasis added) for the mechanical and electrical portions of the work when the design responsibility for that work has been delegated and the plans have been prepared by registered mechanical and electrical engineers." (State of California, 2001)

Therefore, the architect or registered engineer, defined here as the building designer, has the responsibility for both the structural and nonstructural seismic design for buildings and ensuring that the completed work conforms to the State's codes and standards. The responsibility for nonstructural seismic design may not be explicitly considered a part of the contract for structural engineering work. In practice, the nonstructural engineering design work is generally done by a subcontractor who should have a sign-off by a registered engineer licensed in California. Typically, the structural engineer does not have control over the design of nonstructural elements and, unless the structural engineer directly supervised the nonstructural design work, the engineer is not able to sign and stamp a design drawing for nonstructural work. In practice, the structural engineer only "accepts" the nonstructural design work and puts a shop drawing stamp on the design drawings noting work done by the subcontractor. Problems arise when the nonstructural subcontractor (designer) follows national standards for installation of nonstructural systems and components and includes the standard design details on how to brace or mount nonstructural elements that are spread throughout the building design drawings. Given the current understanding of a building as a complex system and the need for integration of structural engineering design and the design of nonstructural building components, and the evidence of significant shortcomings in integrating those activities, two questions come to mind. First, why is it that these important elements of building design are not more closely integrated? Second, what might be done to help ensure the integration and coordination of structural design and the design and implementation of nonstructural building components?

SECTION 2

WHY IS IT THAT THE STRUCTURAL AND NONSTRUCTURAL SEISMIC DESIGN OF BUILDINGS IS NOT INTEGRATED ADEQUATELY?

2.1 Traditional Roles and Responsibilities and the Increased Complexity of Buildings

Over the past decades, building codes and requirements governing seismic design of buildings has become increasingly complicated resulting in design professionals becoming increasingly specialized, with each group focusing on a particular aspect of the building. As buildings became more specialized to house specific, often critical activities, the array of engineering professionals increased, with each becoming an important actor in the process. Historically, all this took place under the direction of an on-site architect. It is not uncommon to see many participants involved in the process, sometimes tripping over one another in an attempt to finish his or her part of the design of a building. Each seems to be busy sub-optimizing the process to his or her benefit without examining his or her contribution to the performance of the building system as a whole.

Increasing building complexity and the number and variety of subsystems that comprise them increasing substantially has made the process of integrating the seismic design of all those subsystems difficult, time-consuming, and, often, expensive. The demands of integration seem to have grown beyond the capability of traditional engineering professional roles and responsibilities, demanding new approaches. Further, it is frequently argued that large and complex buildings are each “one of a kind”, each designed and built and not necessarily replicated. Mass-produced products are integrated in engineering departments to keep assembly lines moving and the operation profitable. It is extremely time-consuming and costly to integrate all of the subsystem interfaces down to the last detail in a large, one of a kind building.

2.2. Economic Pressures in the Design and Construction Process

The ideal is not always realized, often because of the exigencies of cost and the desire to maintain or enhance profit margins. In its 1991 report the California Seismic Safety Commission (SSC) recognized the problem. The Commission states that one "consideration arises from economic pressures in the design and construction process. In California this is a particular cause for concern, because of possible effects on the seismic resistance of structures."

> It needs to be more widely understood by owners that simply complying with minimum requirements of the Uniform Building Code may not result in an appropriate seismic design for all situations. Careful attention by qualified and experienced practitioners having a broad knowledge of seismic design is also essential . . . Economic constraints on design and construction practices may result in structures that comply with codes but are nevertheless susceptible to significant damage. They may cause many severe casualties when an earthquake occurs. Even if no lives are lost, poorly performing buildings and their contents can suffer major damage, which can be devastating to occupants, e.g., tenants or businesses forced to vacate or suspend operations.
>
> In the prevailing circumstances, the fees public and private owners appear willing to pay for architectural engineering work are often insufficient to provide the levels of professional service needed for adequate attention to seismic resistance. Consequently, at the outset the buyer or owner should understand the relationship between design and construction costs, and the levels of quality control and building reliability being purchased with the fees budgeted.
>
> While improving building performance is likely to mean some increase in construction and design costs, these added expenses may not be significantly more than those of a structure built to minimal seismic standards. Furthermore, typical kinds of earthquake damage are controllable for very little added expense. In short, owners' decisions to go for the lowest fee in design contract negotiations may save little at the beginning, while proving very costly later in the event of a damaging earthquake (California Seismic Safety Commission, 1991).

2.3 Traditional Roles Cloud Responsibility

Four major stakeholders involved in the traditional building design process seem likely candidates as the participants who should be responsible for ensuring that the integration of structural and nonstructural elements to enhance seismic safety. These are the building owner, the architect, the structural engineer, and the set of contractors and subcontractors designing nonstructural components.

Ultimately, the person or organization contracting to have the structure designed and built might be considered the primary responsible party for ensuring seismic design integration of all the building components. Some owners build many buildings and are or should be experienced in ensuring integration. For others, however, contracting to have a building built is a one-time experience. They assume that those they hire to design and build the structure will ensure that the designs are appropriately integrated so as to achieve a building with seismic design integrity necessary to meet the requirements of all the applicable codes and meet the desired seismic performance requirements.

For some owners, cost is the primary consideration, but those who contract to have buildings built are not uniformly motivated by a single interest. Almost all have an interest in the final cost per square foot of building space, but not all building owners trade off cost per square foot equally against other features of the building. Some owners value safety, aesthetics, long economic life, system resilience, or other features more highly than others and, as a result, will accept an increase in cost per square foot to obtain a safer building, a more aesthetically appealing building, or to obtain more of some other valued feature. Only rarely, however, is a building owner prepared to spend more money per square foot without some assurance that the extra cost buys him or her something. Consequently, there is pressure to keep costs under control and most owners, while they will do whatever is required by code, are unlikely, on their own accord, to decide they ought to go beyond code requirements to ensure a higher level of seismic safety. Many may simply assume that the government codes embody the most current knowledge and best reasonable standards.

According to the 2001 California Building Code, seismic design is to be the responsibility of the building designer with responsibility for both the structural and nonstructural design for buildings and ensuring that the completed work conforms to the appropriate codes and standards and that overall building design is in accordance with the state's statutes and regulations governing the professional registration and certification of architects or engineers. However, it does not appear that this requirement has led to adequate oversight of nonstructural seismic design. In practice, new building construction is generally under the direction and oversight of a project architect who is responsible for project management. Some would argue that the project architect should be responsible for ensuring that the overall design concept, structural engineering, and nonstructural engineering are fully integrated.

Architects, however, are rarely engineers. Typically, the architect is awarded a contract owner after which he or she contracts with a structural engineering firm to provide the design of the building's structure capable of withstanding some specified level of shaking and ground motion. Sometimes the structural engineer is designated as being responsible for ensuring that the seismic design for the nonstructural elements and systems within the building is appropriate for the design seismic environment. Rarely, however, are structural engineers experienced in specifying appropriate seismic design and installation of plumbing, heating, venting, electrical, and a half a dozen other nonstructural specialties Further, when others design such subsystems, the work is generally not done under the supervision of a structural engineer and, consequently, the structural engineer is unable to certify to the adequacy of work and is unable to apply his or her professional engineer license stamp to certify that the design meets all appropriate codes and standards.

Structural engineers we interviewed indicated that they are often expected to take on responsibility for nonstructural engineering without sufficient or additional fee. Moreover, some structural engineers with whom we spoke indicated that they do not want to work on nonstructural seismic design problems. They want to work in their area of specialty—earthquake structural design—which they consider to be more challenging and interesting. A change in perception would presumably alleviate the situation, but such a change would require significant changes in emphasis in formal education and in peer expectations and reinforcement.

The engineers we interviewed generally believe that the project architect should be responsible for ensuring that the nonstructural components in the building design meet all required seismic design standards. They agree with the position taken by the Seismic Safety Commission in its 1991 report:

> As prime design professionals, architects have a unique role in design and construction. The architect is often the only professional with an overall view of all aspects of the design and construction process. The architect serves the client, brings in the structural engineer and other engineering specialties, works closely with the contractor, and ideally, orchestrates the project to facilitate performance and achieve good results. Architects are therefore in a crucial position to influence the seismic safety of structures (Seismic Safety Commission, 1991).

Specifically, nonstructural engineering contractors should be held accountable for ensuring the adequacy of the seismic design of their specialty systems and components. After all, trade associations have defined standards for both design and installation of those systems and components. However, since only a few parts of the United States experience frequent earthquakes, national standards rarely address the special design requirements necessary to meet earthquake ground motions expected in those areas. Moreover, because a myriad of plumbing, electrical, heating, venting, air conditioning and other subsystems must be integrated within the structure, it may be unreasonable to assume that, without some overall experienced project management, all of those parts will perform properly in an earthquake environment without at least some of those installations resulting in dysfunctional consequences for others. Consequently, it appears that someone will have to be in charge with the task of ensuring adequate building system resilience in earthquake zones.

The challenge seems to be that none of the present actors in the complex building design and construction process seems to be in a particularly good position or adequately trained or compensated to take responsibility for ensuring that the building is conceptualized, designed, and built to be a complex, functioning and resilient system.

2.4 Other Practical Concerns

Fee structure. Who should pay for nonstructural engineering design? Obviously, the building owner will bear the ultimate cost burden, but once fees have been negotiated, disputes about which professional group should bear the cost for nonstructural design and integration begins. Some structural engineers consider nonstructural design as a part of their responsibility, but, most nonstructural work is viewed by structural engineers as an add-on to structural work without sufficient compensation. When required to do nonstructural engineering design, those we interviewed indicated that the work was often passed off to the junior engineering staff.

Concerns About Liability. A large gray zone exists in terms of responsibility. Is the electrical engineer responsible for the installation of electrical equipment? Is the mechanical engineer responsible for the installation and performance of mechanical equipment? Many are not experienced in design for a seismic environment and buy off the shelf equipment. Further, equipment manufacturers have generally shown little interest in voluntarily accommodating special nonstructural seismic design requirements. Structural engineers fear they may be held responsible if they design or change the mounting or attachments of nonstructural elements in an attempt to increase seismic performance if those elements fail in an earthquake. No one in the design and construction process is interested in taking on added liability.

As noted above, the seismic code requirements for seismic design for nonstructural components has been focused only on the design of anchorage and bracing. This led to concerns that the design engineer could be required to take on liability for nonstructural system performance beyond the requirement for anchorage and bracing, especially if building system functionality is the standard of performance. This concern may now be somewhat alleviated with the adoption of the IBC. The new IBC (with ASCE 7-05 by reference) provides for seismic performance qualification by the manufacturer of critical active mechanical and electrical equipment through shake table testing or with experience data.

Codes. Although nonstructural seismic requirements have been in building codes since the 1970's, with nonstructural performance expectations as part of the published code, specific performance objectives have been poorly defined. Generally the requirements have applied to components and systems representing only a small risk to life safety. Code design rules for the design earthquake imply that a) anchored components will where anchored, b) important "designated systems" will stay operational, and c) components subject to drift will experience only minimal damage. Previous codes did not make reference to performance objectives aimed at continuing functionality and minimizing economic losses. Since codes have not addressed the issue of nonstructural system seismic design and performance adequately, there is little basis for regulatory enforcement. It is expected that with nonstructural design requirements being added to the 2006 International Building Code, there will be a basis for oversight of both structural and nonstructural design for new building projects.

Business and Professions Codes. Licensing establishes codes of conduct for various professions, establishing a basis for professional conduct and responsibility when doing work for which a license is required (e.g., a structural engineer is not permitted to certify a nonstructural design unless the structural engineer has directly supervised the work). This would seem to suggest that the professional engineers should work together with the architect as the "Building Designer" to make sure that design criteria developed by the structural engineer are used by the other professional engineers in their designs.

SECTION 3

CONCLUSIONS FROM OUR RESEARCH

All buildings, especially hospital buildings and other critical facilities, are dependent upon the earthquake resistance of both structural and nonstructural elements and systems if they are to remain capable of performing their primary functions following an earthquake. Research following California earthquakes indicates that the risk of failure or significant damage of nonstructural elements and systems is higher than the risk of structural collapse during moderate earthquakes.

For many reasons, structural engineers do not appear to be particularly interested in and pay little attention to earthquake design of nonstructural elements and systems. The vulnerability (risk of failure) of nonstructural elements and systems is directly connected to the structural design performance of a building. That is, how a structural engineer approaches the challenge of designing a structure to withstand earthquake forces has direct implications for the design of the buildings nonstructural systems and components. For example, changes due to design in the dynamic response of the main structural frame of a building to earthquake caused ground shaking and acceleration may result in significant increased floor acceleration and, consequently, heavy loads placed on nonstructural elements.

It is clear that the professions involved in creating buildings have not fully resolved the issues associated with integrating building design, structural engineering, and nonstructural engineering and installation. It is equally clear that ensuring appropriate performance of both structural and nonstructural components essential for enhancing seismic safety and post-event functionality of critical facilities continues as a major challenge for the building profession.

Structural engineers with whom we spoke in the course of our research suggested several approaches to dealing with the need for greater integration of structural and nonstructural design.

One recurring suggestion is that those who administer the design and construction process should have responsibility for ensuring that nonstructural design meets the building performance requirements of the owner. It was stated that a new ‘discipline’ may be necessary within the building profession to oversee the certification of equipment and then assure that equipment and systems (including but not limited to supports, anchorage and bracing) are designed, reviewed, and constructed in a manner that provides the required level of system reliability in meeting the demands caused by the design earthquake. Some suggested that the person to do this might be a structural engineer, provided he or she is compensated for the responsibility. Others suggested that it might be done by an architect who is sufficiently trained in that role. Others suggested that what the profession needs is a system integrator, a professional who has sufficient knowledge, skills and attributes to lead a group of individual professionals in achieving system level performance from a building when subjected to a seismic environment. All of our respondents agreed that people who can perform such a task are in short supply at this time.

Following that line of thinking, several respondents voiced the opinion that a new profession or discipline is needed for system integration. One called for the creation of a senior consultant position to cover “System Integration.” Others opined that creating a new professional will require the development of a position description detailing roles, responsibilities, and skill sets. Most agreed that there exists a need for a change in the culture of the design and build industry for buildings in earthquake country.

It was suggested by another person we interviewed that we examine university programs in Architectural Engineering. Architectural Engineering programs are designed to prepare students for professional work in the design and construction of buildings. Students focus on design principles and practice to gain a basic understanding of building systems by studying the technical and economic aspects of design and construction of buildings. Many programs make use of CAD systems. A web based survey revealed that approximately 18 – 20 universities in the USA have degree programs under the heading Architectural Engineering. Within California, only one university identifies a program in Architectural Engineering with its program focused on the structural engineering of buildings. Of those listed, the Pennsylvania State University, School of Engineering provides a program description that would appear to lead to development of the type of professional referred to above. Following is an excerpt from the Pennsylvania State University web site.

> Architectural Engineering is the application of scientific and engineering principles to the design and construction of buildings and building systems, including topics from various disciplines, including architecture, structural engineering, mechanical engineering and electrical engineering. The program emphasizes the engineering aspects of the building design and construction process, while an architecture program concentrates on the aesthetics and the functional/ spatial layout of buildings. Contemporary buildings are designed by teams of professionals. These teams include designers with distinct responsibilities and expertise. Architects, engineers and other specialists work together to turn ideas into reality.
>
> Architectural Engineering refers to the collective efforts of many engineering disciplines which are necessary to turn the architect's building concepts into reality. These disciplines include structural, building mechanical, electrical, lighting, fire protection and construction. The Architectural Engineering program at Penn State prepares engineers to meet these challenges. The architectural engineers are responsible for the different systems of building, structural, mechanical, electrical, etc. (*www.engr.psu.edu/ae/advising/prospective_faq.asp*).

Other respondents looked at regulations as a likely solution. One respondent said, "I see certified equipment, standard details, etc. being used more and more to circumvent having to qualify every piece of equipment and /or its installation. It is done now. It will be done more in the future, even over the objections of equipment manufacturers who don't want to fuss with this seismic stuff just in California."

The International Seismic Application Technology (ISAT) approach is being used by many of the structural engineers in the hospital design area. ISAT is an organization that specializes in addressing the seismic design for non structural elements in buildings. It creates designs for seismic bracing for mechanical, electrical, plumbing, and piping systems. The organization assists the industry's contractors, engineers, inspectors, and facility owners in using the ISAT approach code compliance. It has certainly facilitated hospital design and system integration in hospital construction and retrofit in California. The ISAT Design, Installation and Inspection Manual, OPA-0485, is considered the most comprehensive OSHPD pre-approval in existence. ISAT OPA-0485 pre-approval, combined with current OSHPD experience, appears to have been an effective tool in streamlining the OSHPD document review and plan approval process.

Another respondent echoed the belief that regulation and pre-approval is likely to contribute to improved integration of structural and nonstructural design. He stated, “I think we are headed for a requirement that all permanent building equipment and major medical equipment must be approved and certified by OSHPD prior to use. Such approval might be gained by analysis, by testing, or by experience data. There is a level of criticality where this may be warranted.. My worry is that the zealots will want us to design and test the drinking fountain. Or the light switch.”

A third set of ideas about how to better integrate structural and nonstructural design focused on the possible implications of innovations in the building industry. Some sophisticated owners are now asking for three dimensional computer assisted design models for their buildings.. This is leading to the use of “Building Information Models” and software and “Lean Construction” systems. Either may have significant potential for improving the practice of how issues associated with integrating nonstructural seismic design into the building system design are addressed. Others believe that the movement toward performance based engineering design will lead to addressing the problem because performance of nonstructural elements are key elements to building performance in term of reducing “deaths, dollars, and downtime.”

3.1 Reframing the Problem

There is no doubt that better integration is needed between architecture, structural engineering, and the installers of nonstructural systems, subsystems and components. Post-earthquake analysis of structures drives home the point. Nor is there much doubt that it is necessary to approach buildings intended to house complex processes and critical services as systems, not just as assemblages of components.

To a considerable extent, the failure to achieve the desired integration of structural and nonstructural design in structures subject to earthquakes reflects and is reinforced by professional traditions and practice, and by engineering and architectural education and training. The shortcomings in integrating the component parts of buildings seems to reflect behavioral, organizational, and educational problems more than it does a lack of understanding about how to integrate all those component parts.

In our research and discussions with architects, structural engineers, and providers of nonstructural systems and components, most of the emphasis and discussion about this general problem is aimed at attempting to fix responsibility for integration on one or another of the actors in the process. Illustrative of the focus on the discussion on the appropriate locus of professional responsibility, a recent FEMA publication on Communicating with Owners and Managers of New Buildings on Earthquake Risk noted:

> Protecting against nonstructural damage requires clear allocation of roles and responsibilities. An important question is: Is the structural design of mechanical equipment supports the responsibility of the equipment vendor, the mechanical engineer, or the structural engineer? Similarly, is the design of the connections for precast concrete cladding the responsibility of the precast element vendor or the building structural engineer? And, is the layout and design of bracing for ductwork the responsibility of the mechanical contractor or the building structural engineer? If these responsibilities are not called out at the outset of the job, the result will be disputes, extra costs, and potentially serious omissions (FEMA, 2004).

It seems clear that ensuring the seismic resilience of nonstructural components regularly falls through the cracks as buildings are designed and built. If it were to happen only occasionally, then one might conclude that it might occur because of oversight or incidental conflict or confusion over respective roles. Since it happens regularly, if not systematically, attempts to resolve, or at least understand, the phenomenon have focused on trying to ascertain which role in the process should be tagged with the responsibility. As might be expected, most in the various professions involved in the process indicate that those in another profession should bear the burden of responsibility. Our research suggests that neither architects nor structural engineers are particularly interested or well-equipped to address the seismic concerns associated with nonstructural design and installation issues. And, the myriad of nonstructural subsystem designers and installation subcontractors are unlikely to do much other than comply with equipment standards as referenced in the codes in the design and installation of their own products. This could change with a enforcement of the new IBC.

Based on information gathered from a review of the literature and interviews with architects, structural engineers, and nonstructural engineers, we concluded that successfully implementing changes in the practice of architectural design, structural and nonstructural earthquake engineering requires new ways of thinking and working. The current approach to the problem — focusing on assigning responsibility — seems not to have resulted in significant changes in practice. We think that it would prove useful to reframe the problem.

We suggest that it may be more fruitful to examine the design and construction *process*, rather than the roles of various actors, to understand how to better integrate the essential roles in building design and construction. The following paragraphs summarize our understanding of the design and construction process as it relates to the immediate problem under consideration.

3.2 Pressure on Traditional Approaches and Processes

Change usually comes about when there is significant and increasing discomfort between what is happening and what people expect or want to have happen. It appears to us that this will be the case in integrating architecture, structural engineering, and nonstructural component design and installation. There seems to be pressure for change from at least two sources.

One source of pressure for change is the dissatisfaction noted above by participants in the building design process as expressed by those we interviewed, in what we've read, and by those who spurred us to undertake this project. In terms of functionality, buildings are not being designed and built to be as resilient as they might be, not so much because money is not being spent on design, but because finished buildings are more an assemblage of parts than an integrated system. The dominant process being employed to create those structures is not resulting in integrated resilient systems. As a society, we are much better creating airplanes, automobiles, and washing machines as integrated systems than we are at creating buildings as integrated systems. The discontent among professionals seems to be growing, particularly in California and particularly because of the demands of SB 1953.

The more dominant and widespread force for change, however, appears to be the economics of the design and construction process. The dominant paradigm today is the "design-bid-build" model. It is a top-down process in which the building or facility is conceptualized and goes through a series of design iterations involving a large number of people and organizations specializing in the design of various subsystems of the facility. Subsequent to design, the project is sent out for competitive bids. Typically, the bids are developed by general contractors, who draw upon a large number of subcontractor specialists, who then submit a package bid to the owner. After a bid is selected, construction begins.

Frankly, the traditional approach is both time-consuming and costly. This process, while it has endured for a long time, has several undesirable characteristics. First, it demands long lead times, resulting in design and construction timetables that are often significantly longer than they ought to be. Second, the various subcontractors tend to plan their work independently of one another, resulting not only in delays, but in limited integration of critical subsystems. Finally, the design-bid-build process seems to cost more than some alternative approaches.

> The process of designing, constructing and managing buildings is fragmented. It involves many participants interacting in complex ways over a prolonged period of time. Currently, sequential communication among the participants is the norm. Consequently, while individual parts of the project may be optimized, the optimality of the overall project suffers. It is our view that the quality of the overall project can be significantly improved (in terms of time, money, and quality of design) if there was a tighter, non-sequential collaboration among the participants. Additional improvements will accrue if the participants were provided with discipline-specific design and evaluation tools, which assist them in performing their tasks (Kalay, *et.al,* 1998).

In response to the growing dissatisfaction with "design-bid-build" across both the manufacturing and the construction industries, new approaches are emerging that challenge the traditional approach. At this time, no one knows which of these approaches, if any, will become the dominant paradigm. It is a time characterized by innovation and experimentation. There is little doubt, however, that other approaches will continue to emerge as professionals attempt to devise more effective, efficient processes for creating buildings and facilities.

SECTION 4

NEW APPROACHES CHALLENGE THE TRADITIONAL PROCESS

A primary means for greater integration in design and construction is creating tighter coordination among the discrete engineering design activities conducted by different individuals, disciplines, or organizations, so that a unified building design and construction process is formed. When building design involves many systems and subsystems, there is a need for an approach that creates effective interfaces between the many component parts. Design integration can take place within a single organization or among collaborating organizations, as when various architecture, engineering, and analysis activities are synchronized into a building development process. The underlying theme is that of systems integration. The main argument is that systems designs are imperfectly linked and that the applications of new systems integration tools and processes can help bridge the respective subsystems and help ensure that building design leads to building system resilience, as well as shorter time periods from conception to use and lower total costs.

4.1 Systems Perspective and Performance Based Earthquake Engineering

> Historical applications of performance-based optimal design have ignored nonstructural components in the evaluation of performance. Although the process toward understanding nonstructural component performance was begun some time ago, significant improvements in understanding nonstructural component performance have been made only recently.
>
> Buildings are composed of both structural and nonstructural systems. While damage to the structural system is the most important measure of building damage affecting casualties and catastrophic loss of life, damage to nonstructural systems and contents can result in significant economic and human loss through building-facility downtime, content damage, and injury or death. Typically the structural system represents about 25% of the building's worth (FEMA 2003). Relatively recent urban earthquakes proved that it is very important to consider nonstructural damage in the design phase rather than exclusively targeting structural performance. (Rojas, et al, 2007)

One approach to achieving greater systems integration and better building system performance at the same or lower cost within the seismic safety community is a combination of a systems perspective and performance based earthquake engineering. Performance based seismic engineering is a relatively new approach to designing buildings. It takes into account a desired level of structural performance given specified ground motion at a specific location and, inherently, takes a systems view of structural performance.

The Veterans Administration, following collapse of the Veterans Hospital in Sylmar during the 1971 San Fernando Earthquake, recognized the need for the system approach. It commissioned a report to address the need for system integration in the design and construction of new hospitals. In its 1977 report entitled Research Study Report Application of the Principles of Systems Integration to the Design of VA Hospital Facilities, the Veteran's Administration noted that "the clear need for a more rational approach to the design, construction and alteration of buildings has led to widespread interest in the concept of systems" and

> There is nothing new about the notion that a building is a collection of systems: a structural system, a mechanical system, an electrical system, and so on. What has evolved more recently, however, is the conceptualization of the whole building as a system, and further, the total process of building production and utilization as a system demanding a much higher degree of internal coordination than has been achieved so far. This internal coordination, or integration, begins with an analysis of the building into its components and a study of how well each meets its intended function under real conditions. Of particular interest is how the characteristics of each component directly or indirectly affect the performance of the others and of the total building.

The report went on to capture the critical elements of the argument for greater integration of construction based on a systems perspective: "The systems approach is a strategy of problem definition and solution which emphasizes the interaction between problem elements and between the immediate problem and its larger context, and which specifically avoids traditional methods of independent or *ad hoc* treatment of the various elements."

Performance based seismic engineering has not yet become a dominant approach within the structural engineering profession, even in places like California that are seismically active.

Moreover, the approach focuses only on the design of structures. It does not address the problems of ensuring that design and construction are sufficiently integrated to ensure the desired level of seismic safety.

4.2 Design Build Contracting — the Master Builder Concept

One of the approaches that appears to hold promise for facilitating greater integration from conception to completion and integration of structural, nonstructural, and overall design of facilities is the Design-Build model. According to the Design-Build Institute of America (2007), design-build is a "return to the time-honored approach of the Master Builder, where a single source has absolute accountability for both design and construction." The Institute describes the process as offering "full accountability for architecture, engineering, and construction".

Design-Build has been gaining popularity among building and facility owners who want to accelerate the schedule from concept to completion and who want to reduce contractual and management complexities and save money in the process. The notion is simple: the owner contracts with a single firm to design and build the facility, thus presumably ensuring complete integration of all systems and subsystems because that one firm is responsible completely for the project.

This approach is, as stated, not new. It is a new manifestation of an old tradition. It offers the clear potential for being a process that can ensure integration of component parts, but does not, of course, guarantee complete integration simply because it fixes responsibility. Much depends on how the process manifests itself within the individual firms. That, presumably, depends on the development of congruent training programs, professional standards, and a tradition of employing systems integration methods.

4.3 Systems Integration Tools and Approaches

Several tools have emerged over the past few years that are congruent with and that facilitate both the Design-Build and performance based seismic engineering.

Concurrent Engineering. "Concurrent Engineering— which is sometimes called Simultaneous Engineering or Integrated Product Development (IPD) — was defined by the Institute for Defense Analysis (IDA) in its December 1988 report, *The Role of Concurrent Engineering in Weapons System Acquisition,* as a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements" (Stark, 1998) .

Stark continues to explain that concurrent engineering is an attempt to overcome problems almost inherent in the traditional model in which from different departments work one after the other on successive phases of product development.

> In traditional serial development, the product is first completely defined by the design engineering department, after which the manufacturing process is defined by the manufacturing engineering department, etc. Usually this is a slow, costly and low-quality approach, leading to a lot of engineering changes, production problems, product introduction delays, and a product that is less competitive than desired . . . Concurrent Engineering brings together multidisciplinary teams, in which product developers from different functions work together and in parallel from the start of a project with the intention of getting things right as quickly as possible, and as early as possible . . .A cross-functional team might contain representatives of different functions such as systems engineering, mechanical engineering, electrical engineering, systems producibility, fabrication producibility, quality, reliability and maintainability, testability, manufacturing, drafting and layout, and program management (Stark, 1998).

Concurrent engineering "is only now being carefully applied to the construction sector…It enables developers to consider all elements of a building or structure's life cycle from the conception stage right through to disposal, and to include issues of quality, cost, schedule, and user requirements" (Anumba *et. al.*, 2006).

The concurrent engineering approach advocates the implementation of an interdisciplinary team approach to building design by encouraging collaborative decision making based upon team coordination and information sharing. This suggests that an interdisciplinary approach might be achieved by bringing the owner, architect, structural engineer, mechanical, electrical, and other disciplined engineers, and major subcontractors and suppliers directly into the design and construction process.

Lean Construction. Lean construction is an adaptation to building design and construction of principles and practices developed in "lean manufacturing". Unlike manufacturing, construction is a project based-production process. Lean construction is concerned with concurrent and continuous improvement throughout the design and construction process. It is essentially a management approach and an outgrowth of the Total Quality Management movement.

Lean construction is a "way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value (Koskela, *et al.* 2002) ". Designing a production system to achieve the stated ends is only possible through the collaboration of all project participants (owner, architect, engineers, builders, facility managers, and end-users) at early stages of the project. This goes beyond the contractual arrangement of the design-build paradigm, but is fully congruent with the Master Builder concept. "Essentially, Lean Construction recognizes that desired ends should affect the means selected to achieve these ends, and that available means will affect realized ends" (Lichtig 2005).

Lean construction typically does not include the front-end design tasks, so it would complement, rather than replace, concurrent engineering and other methods for integrating components of the building system prior to actual construction. Nonetheless, the idea of integrating all the actors during the construction process suggests that the basic premises are valuable in ensuring that integration during design extends through construction.

Building Information Models (BIM). BIM is an acronym for a class of three-dimensional computer-driven models that provide information about a building before, during, and after construction. The models typically include information about the site and the geometry, spatial relationships, and quantities and properties of building components. The models can, for example, include information on manufacturers' details of nonstructural building components. These models may be used to examine construction processes and facility operation. The building information models model representations of the actual parts and pieces being used to build a building.

The models are currently used by some professionals engaged in building projects ranging from simple to extremely complex structures, even though they are relatively new and still being developed. One might foresee, however, their application as virtual information models that would facilitate concurrent engineering and integrated design of critical components of building facilities. If the process was adhered to throughout the project, the model of an individual building would identify eliminate disparities between "as designed" and "as being built" because changes would be incorporated in the model; design would presumably be continuous through the life of the project as modifications are deemed essential or desirable. The models would be employed, presumably, by the integrated design team of architects, structural engineers, mechanical engineers, electrical engineers, and representatives of a hundred or more specialized nonstructural component elements. The model would be used directly by those involved in construction and in managing construction and by the owner who, presumably, would have a model that represents the building "as built."

Proponents of building information models claim that they can greatly reduce errors made by design team members and the construction team by detecting conflicts or clashes between design elements. With advances in computing and software, the approach should contribute significantly as a tool to facilitate integration of systems and subsystems.

SECTION 5

WHAT NEEDS TO BE DONE?

Current trends in the design and construction process suggest that a new profession is already emerging—that of building systems integrator. The new profession might be defined as the "master builder" or it may become a specialty within an existing field, such as architecture. There is little doubt, however, that the specialization will emerge and become defined and redefined with experience and research into building design and construction practices, not so much because it is driven by concerns about seismic safety, but because of concern about the amount of time needed from conception to use, about integrating construction activities, and about reducing costs.

Buildings intended for complex, specialized use can no longer be conceptualized apart from their intended function and their contents. They have truly become complex systems in which all the components must be integrated with one another— systems in which components can be designed, installed, or operated in isolation from the rest of the building only at one's peril. The complexity of contemporary and anticipated technologies employed in creating integrated facilities will increasingly demand more complete integration from concept to end use.

The undergraduate and graduate education of architects, engineers, and others involved in the design and construction industry will have to change to adapt to the new realities of practice and, especially, the demands for effective and efficient interfaces between all the component parts of complex facilities. American higher education is organized in terms of disciplines that have been developed in silos and that reinforced a silo mentality because of tradition, accreditation requirements and because of the system of rewards created within those disciplines. Changes in the practices within academic institutions usually occur only painfully and slowly. Isolation and even arrogance within the disciplines often makes it difficult for practitioners, who are often in front of the universities because reality forces them to see across systems, to bring what they have learned to bear on educational curricula and teaching practice. Unfortunately, despite concern expressed by some universities and some attempts by federal agencies that fund research, interdisciplinary education and multi-disciplinary approaches are still the exception and not the rule.

It may be that legislation such as SB 1953 —legislation that emerged from practitioners who were looking at buildings as systems—may be necessary simply to force professionals in building design and construction to view critical facilities as complex systems. This, in turn, may bring pressure on academic institutions and, gradually, lead them to reconsider what they teach and how they teach it. Certainly, the demands of SB 1953 have brought the problems associated with integrating architecture, structural engineering, and the design and installation of nonstructural components of acute care hospitals into sharp focus.

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ISSN 1520-295X