Contemporary Design-Bid-Build Model

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Abstract: Empirical research was performed into the hypothesis that a substantial number of building performance engineering tasks on design-bid-build projects are typically provided by entities associated with the construction phase, not with the architect-engineer (AE) of record. This hypothesis is contrary to the traditional understanding of design-bid-build and is theorized to result from increased time pressures on AEs, decreased AE profit margins, AEs' attempts to minimize liability, increased design and construction specialization, and increased prefabrication. Project technical specifications were analyzed for 20 $5–45M building construction projects and 16 individuals directly associated with these projects were interviewed. It was found that 35 building performance engineering tasks were required by the project specifications to be performed by entities associated with the construction of the buildings. This large number of delegated design tasks suggests the conventional understanding of the design-bid-build process is not accurate. The increasing fragmentation of the design and construction process may have implications for the efficiency of communication on design-bid-build projects, lean construction processes, and constructability.

DOI: 10.1061/(ASCE)0733-9364(2009)135:6(540)

CE Database subject headings: Construction management; Project delivery; Building design; Bids.

Introduction

For the past half-century, the dominant design and construction process for buildings has been understood as a three-step process: architects and engineers (AEs) design the entire buildings, bids are solicited from contractors, and contractors construct the buildings. The process has traditionally been viewed as being linear and compartmentalized, that is, the engineering design is completed by AEs before the construction begins, and the contractors (in conjunction with specialty subcontractors and material vendors) merely implement the AEs' designs. Current design-bid-build models assume that engineering and design are only performed by AEs and their specialty engineering and design consultants. Conversely, general contractors and subcontractors only provide construction services, and material vendors only manufacture and deliver (Tatum 2000).

There is a growing body of literature that describes the driving forces behind the evolution of project delivery in the construction industry. The most notable force is the increase in project complexity (Yates 2003). Improvements in technology, materials, and products have eclipsed the technical capabilities of many AE firms. To compensate, AE firms are left with three alternatives to match their capabilities to the design demand: employ specialists who have expert knowledge of each building component, subcontract portions of the design to specialty engineering firms, or require construction entities (e.g., vendors, suppliers, and subcontractors) to perform required engineering and design tasks associated with the specialty components that their firm manufactures or constructs. Existing literature does not recognize a significant contribution from firms associated with the construction phase despite the potential interest that design firms may have in promoting such a shift.

This paper represents exploratory research to determine if the conventional notion of the design-bid-build process is accurate today. The paper's general hypothesis is that on design-bid-build projects, a substantial number of building performance engineering tasks are typically provided by entities associated with the construction phase, not with the AE of record. It is hypothesized there has been a gradual, but significant, shift in the engineering of a building from recognized design professionals to entities associated with construction of designs, namely, constructors and material component manufacturers.

The idea of construction-related entities becoming increasingly involved in engineering design may not seem new to the reader. One reason is that it is well known that structural steel connections are often designed by the steel fabricator, not by the structural engineer of record. The overall hypothesis of this paper, however, extends well beyond this example. Another reason is that construction-related entities clearly provide engineering in design-build, which is becoming increasingly common. The paper's primary contribution to the literature, however, is to point out that a substantial amount of engineering is being performed by construction entities even on traditional design-bid-build projects. An additional contribution stems from the writers' perceptions that the existing literature does not fully consider the implications of engineering being performed by non-AEs for risk management, quality assurance, or lean construction.

Before proceeding with the paper, it is appropriate to first provide some basic definitions. *Engineering tasks* are defined as discrete processes that require the application of mathematics, science, and engineering principles. The simplest, but not all inclusive, test is whether the task involves the consideration—whether explicit or implicit—of physical forces and stresses. The output or work product resulting from task completion are deci-

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Note. This manuscript was submitted on February 9, 2007; approved on January 20, 2009; published online on May 15, 2009. Discussion period open until November 1, 2009; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 135, No. 6, June 1, 2009. ©ASCE, ISSN 0733-9364/2009/6-540–549/$25.00.

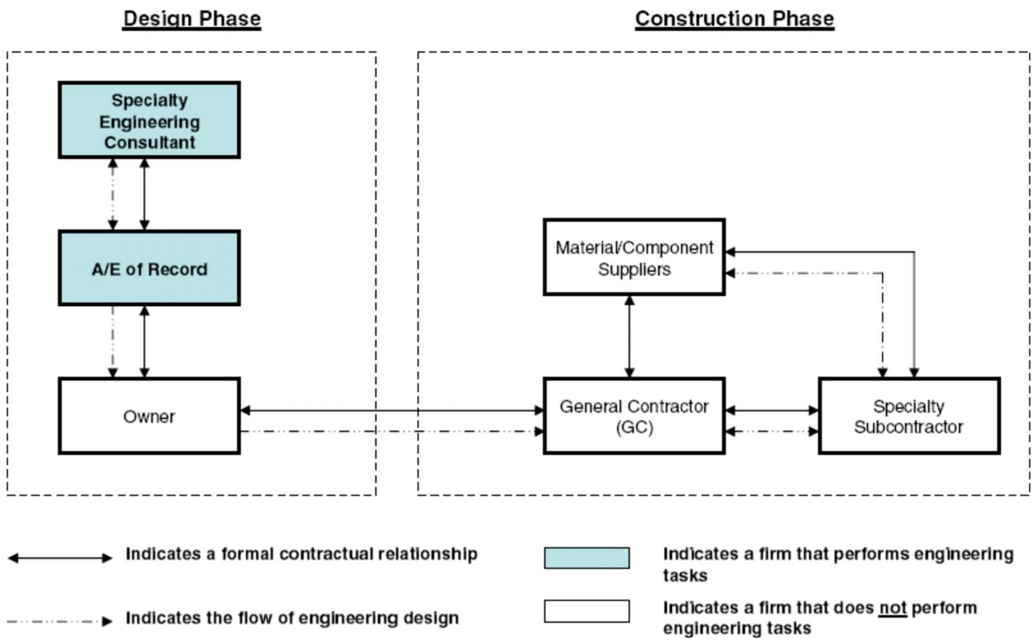

Fig. 1. Traditional design-bid-build model

sions, analyses, drawings, and specifications. There are two types of engineering tasks. One set will be referred to as *building performance* engineering tasks. Such tasks affect the functioning of the completed building, in that building performance engineering tasks have consequences for the building's end users, that is, the building will not perform as intended if these tasks are not completed effectively. The second set of engineering tasks will be referred to as *construction* engineering tasks. This set of tasks only affects the characteristics of the construction process (duration, cost, inherent safety level, etc.). These tasks, therefore, affect the firms and individuals associated with the construction of a building, but not the end users.

Differentiating between the two types of engineering tasks is important because constructors have long been responsible for construction engineering tasks because such tasks are so dependent on the constructors' choices of means and methods. This paper will focus on building performance engineering tasks and the level to which construction entities not associated with the AE of record are required to perform such tasks.

Literature Review

Despite the availability of literature on the topics of historical and contemporary project delivery, very little has been documented regarding the building performance design responsibility of construction entities. Most literature regarding the fragmentation of the construction industry highlights the separation of the master builder into compartmentalized design and construction functions and the subsequent diffusion of designers and builders into increasingly specialized functions (Puddicombe 1993). Examples of this compartmentalization in the design phase are the AE's typical design consultants including geotechnical engineering, structural engineering, and mechanical engineering firms. Similarly, the construction phase, once dominated by the general contractor, now includes a large number of specialty subcontractors.

The traditional design-bid-build model is depicted in Fig. 1 below. This figure indicates the formal and informal transactions of engineering design. As one can see, all formal engineering design is thought to be completed during the design phase. Additionally, all designers (shaded in gray) are thought to be firms associated with the AE of record and *not* with the construction phase.

While the writers are not aware of any literature that explicitly addresses the amount of engineering design being performed by constructors instead of by design professionals, three sets of literature address, sometimes indirectly, the roles of the various entities in the design and construction process. These three sets are guidelines and articles published by professional trade organizations on their specific trade, scholarly articles on design-build construction, and scholarly articles on lean construction.

Well known examples of the first set of documents include the American Concrete Institute's *Manual of Concrete Practice* (ACI 2003) and the American Institute of Steel Construction's *Code of Standard Practice for Steel Buildings and Bridges* (AISC 2003) and *Manual of Steel Construction* (AISC 2006), which are intended to establish custom and practice within their subindustries. Given the detail and size of these documents and the fact that both design engineers and constructors play major roles in the membership of the organizations, one would expect to find language indicating the respective roles of design professionals and constructors.

Several sections, namely, 318 and 347, within the *Manual of Concrete Practice* (ACI 2003) clearly indicate that the contractor is required to perform construction engineering tasks including design of formwork, bracing, and shoring. The manual does not, however, indicate that contractors are expected to engineer the reinforcing steel within the concrete, which is building performance engineering. Similarly, the AISC documents clearly assign all construction engineering tasks to constructors and shop drawings to fabricators, but do not identify building performance engineering tasks that are to be performed by contractors. An AISC document called *Construction Management of Steel Construction* (Mrozowski and Syal 1999) describes, in detail, the steel design and construction process and indicates that all building performance engineering is to be performed by the structural engineer

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of record. Several articles in practitioner-oriented trade journals also indicate custom and practice roles for the steel construction phase. An article on steel design roles published in AISC's *Modern Steel Construction* (Carter 2000) contained no references to construction-related entities undertaking building performance engineering.

A second set of literature relates to the primary integrated project delivery method: design-build (Quatman 2000). This literature points to the many problems that frequently result from the disjointed nature of the design and construction processes in design-bid-build projects. The premise of design-build is that by having one legal entity responsible for both design and construction, seasoned construction professionals may interact with design professionals to ensure the design is practical and cost effective. The premise of integrated project delivery is not that constructors would assume the role of performing building performance engineering design, however. Ideally, construction entities would work with designers to provide constructability input, not substitute as a design firm.

A third set of relevant literature is associated with lean construction, an operations management-based approach that involves radical transformations of facility and construction process design methods, performance metrics, and project controls (Ballard 2000; Ballard and Zabelle 2000; Tsao et al. 2004). This literature identifies the serious problems that result from a fragmented design and construction process and suggest the need for concurrent product and process design. Unlike design-build or construction management/general contracting (CM/GC), which have been implemented on thousands of projects across the U.S., lean construction has only advanced past the theoretical stages in a limited number of projects (Pappas 1990). Some of the principles underlying the lean project delivery system include set-based design, involving foreman during the planning phase, simultaneous product and process design, and work structuring, all of which are not practical within the bounds of the current design-bid-build model.

Research Methods

The exploratory research methodology leading to this paper included a combination of technical specification review and case studies. A total of 20 design-bid-build projects constituted the convenience sample. Four projects (each associated with a different AE firm) were built for Bucknell Univ. (an engineering building, a building housing the offices and laboratories associated with geology and psychology, a dormitory, and a recreation and athletics center). The remaining 16 specification sets were obtained from a local construction manager or Bucknell alumni working for large general contractors or construction managers. The total construction cost of the projects ranged from \$5 to \$45 million. All projects were located on the east coast with the exception of one hospital project in Chicago, Ill. While all of the delivery methods were design-bid-build and were ostensibly designed by a traditional architectural and engineering firm, some diversity existed between the project delivery methods. Two of the projects involved an at-risk construction manager, one involved an agency construction manager, and the final two involved traditional general contractors. In addition to the project-specific specification sets, Masterspec (Salt Lake City, Utah), a common boiler-plate template used to create specification sets for many building facilities, was reviewed as it is an accurate indication of industry practice. For each project, the specific building

DESIGN PERFORMED BY NON–AE

<u>Design Requirement:</u> Aluminum Curtainwalls

<u>Projects Involved:</u> 1,4,5,8

<u>Engineering Intensiveness Rating:</u> 3

<u>Phase Involved:</u> Pre-construction

<u>Required Designer Qualifications:</u> PE

<u>Engineering Principles Involved:</u> Structural Engineering

<u>Actual Qualifications of Individuals Performing Engineering</u>: PE

<u>Who Performs the Engineering and how is it done?</u> Professional engineer pre-designs curtain walls per request of the GC. This component is designed during construction phase after the project has been awarded to the GC. Engineering required includes designing for: dead loads, live loads thermal movements, and structural support movements.

<u>Implications:</u> Quality of final product

<u>Selected Text</u>:

"For installed components indicated to comply with design loadings, include structural analysis data signed and sealed by the qualified professional engineer responsible for their preparation."

(Project 4, 08920-3)

Fig. 2. Specification review sheet

performance engineering tasks performed by entities other than the AE were identified primarily by reviewing the project technical specifications. Specifically, each specification section was read closely to identify language requiring the contractor to perform design and/or engineering, often through an engineering consultant, subcontractor, or material vendor. Specific information for each task was recorded on "specification review sheets" and cataloged (Fig. 2). The following information was recorded for each task:

- The text in the specifications that referred or alluded to the engineering task;
- Which entity (GC, engineering consultant retained by GC, subcontractor, or material vendor) was required to or likely to perform the task;
- Whether the specifications required the task be performed by an individual with specific qualifications, such as a professional engineer (not associated with the AE of record);
- The result or work product of the task (calculations, shop drawings, decisions, etc.); and
- The engineering principles underlying the task (engineering mechanics, hydrology and hydraulics, geotechnical, electricity, etc.).

Data collected on the specification review sheets were cataloged and recorded in tabular form. Project specifications sections (e.g., cast-in-place concrete) were first reviewed for whether a professional engineer was required to sign and seal all supporting calculations and design of a particular project component. Second, specifications were reviewed for any explicit language that indicates the requirement of engineering design without the additional requirement of a professional engineer (PE) seal. Specific phrases such as "engineering design," "analyses of forces," and others were used to identify the specific requirement of engineering design. All project components were classified in one of three categories: PE required, engineering design required but no PE, or not applicable to the project.

Following the specification review, five of the 20 projects were

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chosen to be further investigated as case studies. To ensure that interviewees would be candid and capable of remembering fine details, projects that had been recently completed and involved no active litigation were selected. Of these projects, a subset of five projects was chosen that were within a 2-h drive from Bucknell Univ. All five were institutional building projects built in central Pennsylvania over the past 4 years. Four of the projects were associated with Bucknell Univ. and the fifth was a large addition to a community hospital. Project contract drawings and submittals were analyzed to confirm that the technical specifications' requirements that building performance engineering tasks be performed by entities other than the AE were in fact met. Engineering responsibilities identified through these archival documents were confirmed through interviews with 15 key personnel, including owners, AEs, general contractors, subcontractors, and material vendors. The purpose of the case studies was to confirm observations from the construction documentation and to provide an understanding of the phenomena. Interviewees with many years of industry experience were selected, as these individuals would be capable of validating and describing any long-term shifts that have occurred in the industry over the past few decades.

Empirical research to support the secondary hypothesis that there has been a shift in engineering from AEs of record to construction entities was limited to the qualitative interviews. The writers did not attempt to review specifications from a sample of projects built several decades ago.

Data and Results

Specification Review

The specifications associated with the 20 projects and the interviews of the key individuals involved with five of the projects indicate that the number of specific components of building projects that have building performance engineering performed by entities associated with the construction phase is significant. Table 1 includes 36 distinct building components that were designed by entities not associated with the AE for at least three of the 20 projects. This table highlights the project components that were designed during the construction phase and indicates whether a PE was required (designated "PE") or if the specification language identified the need for engineering knowledge but did not require a PE (designated "D"). Blanks indicate that an elaborate discussion of the component was not included in the specifications.

It should be noted that most specifications paragraphs that required a PE specified that the PE must be registered in the state in which the project is built. This point is important to dispute the assertion that Table 1 mostly contains manufactured items that have always been pre-engineered. In fact, many manufactured products or assemblies that clearly require engineering in the product design process were omitted from Table 1. For example, windows are manufactured items that require engineering as part of the product design process. However, it would be inappropriate to include them in Table 1 because integrating the specified windows into the project does not require project-specific engineering.

One may note when reviewing Table 1, that concrete formwork, cutting and patching, and earthwork have been designated as building performance engineering tasks. Although the design of these components may seem to be only construction engineering tasks, it is important to note that the proper engineering design of each of these components has a direct impact on the performance of the final structure. Take, for example, the design of concrete forms. An improper design resulting in excessive deflection before curing would have a negative impact on the appearance and structural capacity of the final structure. Since these three components impact the performance of the final structure, they have been included as building performance engineering tasks.

Of the 36 components listed in Table 1, 10 of them were required by the specifications to be designed by construction entities on at least 50% of the projects. These 10 components are listed in Table 2, in order of the percentage of projects that the component was not applicable on the project. (For example, all but 5% of these projects involved structural steel while only all but 45% of these projects involved steel joists.) This table provides additional information for these 10 components that provides insights into engineering being performed by construction entities. For example, the design of metal stairs was required by all but 15% of the 20 projects and nearly all (85%) of the projects required the design to be completed by a PE. On the other hand, the design of concrete forms was required on all but 20% of the projects yet the majority of these projects did not require this engineering to be performed by a PE (45% versus 35%).

The previous paragraph points at the interesting finding related to how many building components required engineering but not by a professional engineer. Table 3 lists the 14 building components that required engineering design but not by a PE for at least 20% of the projects. This finding is important for two reasons. First, the specific language used to identify required engineering tasks recognizes the importance of the design and the engineering knowledge that must be utilized to adequately design the component, yet PE involvement is not required. The following language regarding cast-in-place concrete provides an example of such a requirement:

> Steel Reinforcement Shop Drawings: Placing drawings that detail fabrication, bending, and placement. Include bar sizes, lengths, material, grade, bar schedules, stirrup and tie spacing, bent bar diagrams, bar arrangement, splices and laps, mechanical connections, tie spacing, hoop spacing, and supports for concrete reinforcement.

One should note that in this example, the contractor was required to perform detailed engineering calculations in order to provide the specific items required. The complete engineering design of the concrete reinforcement was not provided by the AE firm.

Second, the implications of an inadequate design may extend further than the performance of the component and may adversely affect occupant and construction safety, productivity, and the performance of other components. Take the steel reinforcement language above, for example. If a failure of a concrete beam or slab were to occur during construction, workers' safety would be compromised and productivity would decrease due to time lost during the investigation and the necessary repairs. The risk of such a failure may be increased if the individuals that designed concrete reinforcement (including stirrups sizes, depth, and spacing) are not properly trained structural engineers.

Interviews

Following the specification review, structured interviews were conducted to validate the findings from the specification review

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Table 1. Project Components Designed during the Construction Phase

Component	Project																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Earthwork	D							PE						D			D			
Concrete forms	D	D	D	D	PE	PE		D	PE	D	D	PE	D	PE	PE	D				PE
C.I.P. concrete	PE			PE		PE			PE	D		D	D	D	PE	D				PE
Concr. Reinf.	D				PE	PE			D								PE		D	
Precast concrete	PE			PE	PE	PE			PE			PE		PE	PE		PE			PE
Structural steel	PE	PE	PE		PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	D	D	PE
Steel joists		PE			PE				PE	PE	PE		PE		PE		PE		D	
Steel trusses			PE														PE			
Steel deck	D	PE	PE	D	PE			D	PE	D		D	D	PE	D	PE	PE		D	D
Metal framing	PE	PE	PE	PE		D	D	D	PE	PE	PE		PE	PE	PE	PE	PE		D	PE
Metal stairs	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE		PE	PE	PE	PE		D	PE
Metal panels					PE		PE	PE	D	PE	PE	D	PE	PE	PE	PE				D
Metal handrails		PE	PE	PE	PE	PE		PE	PE	PE	PE	PE			PE	PE	PE		D	PE
Metal storefront				D					D	D	D	D		D	PE	PE			D	
Curtain walls	PE	PE		PE	PE			PE		PE		D	PE	PE	PE					
Ladders						PE	D												D	D
Glu-lam beams						PE														
Wood trusses						PE									PE					
Mfr. wall panels		PE			D															
Louvers and vents						PE														
Sprinkler			PE			D								FPE		D	D	FPE		
Fire pump						D														
Fire alarm		D			D	D	D	D								FPE				
Fire protection					PE		FPE			FPE	PE	D		FPE		PE	D	D		PE
Vibration steel			D	D				D			PE	D					D			
Temperature control			D																	
Hydronic piping				D	PE			D					D	D						
Booster pumps				PE																
Pipe expansion					D										D	D	D		D	D
Dewatering	D			PE											PE		D			
Cutting and patching	D			D			D						D	D	D	D				D
Expansion loops	D						D	D		D		D							D	
Vibration isolation							PE	D				D				D	D			PE
Mechanical support	PE						D	PE		D	D	PE	D		D	D	D		D	D
Seismic control							PE				PE	PE	PE			D				PE
HVAC balancing					PE		D									D	D		D	PE

Note: C.I.P.=cast-in-place; Concr. Reinf.=concrete reinforcement; and Mfr. wall panels=manufactured wall panels.

and gain insights into why such a significant portion of engineering tasks are performed by firms not associated with the design phase of the project.

Interviews with representatives of five case study projects confirmed the findings from the specification review. All interviewees indicated that the industry has been shifting, for quite some time, from engineering during the design phase to engineering performed by firms associated with the construction phase. Interviewees were first asked whether the project technical specifications were indicative of actual project processes during construction. The consensus was that technical specifications are always followed because they are legally binding. Some interviewees went as far as to say that the specifications were the "bible of the project." If a firm were to deviate from the design specifications they would have to seek a change order and a change order that reduces the engineering design requirements would never be approved by the AE of record or the owner.

In addition to the general statements that strongly supported the overall hypothesis made in response to initial questioning, interviewees volunteered specific examples of building performance engineering performed during construction or by firms associated with the construction phase. Surprisingly, every major design component (see Table 2) and 75% of all of the tasks (see Table 1) were mentioned by both representatives of AE firms and construction firms, thereby providing qualitative evidence to support the findings of the specification review.

When AE representatives were asked why they required so many design tasks to be performed during construction, they gave two main reasons. First, AE firms are no longer capable of performing all of the engineering design on a project because they cannot realistically employ enough specialists. Second, the specification requirements are a form of risk management. By requiring proof of engineering analysis of prefabricated, panelized, and modular components, AEs somewhat absolve themselves of the legal responsibility for the adequacy of their design.

Interviewees who worked for construction firms discussed sev-

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Table 2. Key Building Components Designed during the Construction Phase

	Percentages of projects			
Building component	Design required but no PE (%)	PE required (%)	No design recognized (%)	Not applicable to project (%)
Structural steel	10	85	0	5
Metal stairs	5	85	0	10
Metal framing	20	65	0	15
Concrete forms	45	35	0	20
Precast concrete	0	50	30	20
Steel deck	45	35	0	20
Metal roof/wall panels	15	45	15	25
Metal handrails	5	70	0	25
Metal storefront	35	10	25	30
Curtain walls	5	45	20	30
Mechanical support	45	15	0	40
Steel joists	5	40	10	45

eral problems that have arisen as a result of the shift to engineering during construction. One case study provided an excellent example of a problem that can arise when design responsibilities for specific project components are transferred. In this project, an expansion loop, essential for the heating system of the entire building, burst within a few weeks of operation. After forensic investigation, the joint was found to have burst because of a design omission. The expansion joint could not withstand the operating pressure because the joint was not properly sized to match the capacity of the heater. Further investigation determined that the loop should have been designed by the mechanical, electrical, and plumbing (MEP) engineer as part of the overall system. Instead, the expansion loop was sized by the plumbing subcontractor, based only on the capacity of the piping network.

Although the MEP engineer designed the pumping and heating system correctly for the size of the building and the plumber designed the expansion loop correctly based on the piping network, combining these two designs resulted in failure. Both firms had overlooked a vital component. The problem arose because the MEP engineer increased the pump size without notifying the plumbing subcontractor who, through the requirements of the specifications, was responsible for the adequacy of the piping network. This design and communication error probably would not have occurred had the entire system been designed by one firm. The lack of communication between the designers and the transfer of partial design responsibility led to a failure of the system.

This example was discussed in detail during the interviews with the architect, construction manager, and the plumbing subcontractor for this project. According to these entities, this type of failure could happen on many project components because of lack of communication between the design and construction firms.

Table 3. Components That Require Engineering Design but No PE Seal

Component	Percentage of projects (%)
Concrete forms	45
Mechanical support	45
Cutting and patching	40
Steel deck	35
Metal storefront	35
Pipe expansion	30
Expansion loops	30
Cast-in-place concrete	25
Fire alarm	25
Metal framing	20
Vibration isolation	20
HVAC balancing	20
Hydronic piping	20

Project Components

To further illustrate the design during construction phenomenon, four project components will be highlighted. The first, structural steel, is a project component that is known to require PE involvement during the construction phase. Structural steel is highlighted because it has traditionally required building performance engineering during construction despite the fact that literature continues to model the delivery of a project as a three-step linear process. The second, aluminum storefront, has been selected because it represents a project component that is designed in the construction phase by someone other than a professional engineer on seven of the nine projects that had storefront. The third, precast concrete, represents a precast component designed by a PE employed by (or consulting to) the component manufacturer. Last, sprinkler systems are unique in that they consistently require engineering design in the construction phase by a fire protection engineer (FPE).

Structural Steel. As stated earlier, it is well known within the industry that steel connections are often not designed by the AE of record. In fact, the steel connection design was the responsibility of a contractor or fabricator in each of the 19 projects that included structural steel. The specification sections call for shop drawings of steel connection details, but did not indicate a responsible party. Because there was not a specific responsible party listed for steel connections, one must assume that design of connections is not typically provided by the AE in the contract documents.

Interviews revealed that the design of structural steel connections is typically a three-step process. The structural engineer designs the structural steel members and provides the fabricator

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with the reactions at the connection locations and the size of the members to be connected. The fabricator then designs the connections to "max out," that is, the fabricator designs the steel connections to fail at a higher load than what the structural steel members will fail at. Once the connection is designed and detailed, the shop drawings for that connection are returned to the structural engineer of AE "for approval only." It should be noted that the steel fabricator is typically a subcontractor to the GC and is involved *only* during the construction phase. While this phenomenon may not be news to experienced professionals, the design of structural steel is highlighted in this paper because it is a well understood and common practice that is counter to the traditional models provided in the literature.

Aluminum Storefront. Aluminum storefront can be defined as the facing or cladding that covers the front of a structure when a large amount of fenestration is desired. Storefront can theoretically be made of a variety of materials, but in all of the projects reviewed, the structural framing material designated was aluminum. In order to properly design a storefront, many structural calculations should be made to assess the adequacy of the storefront to withstand wind loading, shear, dynamic loading, deflection, and dead loading. The storefront was designed by an entity involved exclusively during the construction phase for each of the nine projects that included this component. There were no projects in which the AE designed the storefront. Yet three of the nine projects that had storefront did not recognize engineering design requirements in the specification language. That is, the technical specifications did not require submittals that would provide the AE with sufficient documentation that the storefront had been properly engineered. Of the nine projects that included aluminum storefront as part of the structure and had specification language that recognized the need for engineering knowledge, a PE was required for only two of these projects.

Precast Concrete. Precast concrete components range from wall panels to stairs and include almost any part of a project that can be cast-in-place. Precast's speed of construction is its chief advantage over cast-on-site but it often costs more than cast-on-site. Specification review revealed that 10 of 20 of the projects that included a precast concrete component required engineering calculations be submitted. Of those that required engineering submittals, all required the precast manufacturer to include professional engineering calculations in the submittals.

One architect stated that the design of precast concrete is similar to other prefabricated components such as steel or wood stairs and roof panels. That is, the design of the concrete component is produced by an employee or consultant to the prefabricator. This firm is charged with the responsibility of both design and construction for any project component they manufacture.

Sprinkler. While the specification review indicated that no FPE was required on 10 of the 20 projects, interviewees agreed that, as a general standard within the industry, a FPE licensed in the state where the project is to be built (or a PE) is responsible for the complete design of sprinkler systems. This design includes hydraulic calculations, such as head loss, and conformance with codes. The AE of record typically does not provide any information beyond the architectural drawings to the sprinkler subcontractor. In fact, all of the architects interviewed indicated that they never are involved with sprinkler design. The typical procedure, as indicated by an architect with over 20 years of experience, has always been to have the systems designed and constructed by a specialty sprinkler subcontractor. This design is completed and provided to other subcontractors such as plumbing and HVAC subcontractors for reference in coordination drawings and meetings.

In summary, over 20 project components were identified through specification review and confirmed through interviews to have been designed during the construction phase. The four phases of projects discussed above serve as examples that support the conclusion that many engineering tasks are indeed being performed by individuals not directly employed or hired as consultants by the AE of record.

Potential Factors Driving the Shift

Based on the interviews conducted for this research and the writers' prior research, it is the writers' perceptions that the shift in engineering from AEs to construction-related entities reflects four factors: increased pressure on the AE to produce a design quickly, increased specialization of engineering, increased effort by design professionals to minimize liability, and construction prefabrication. These factors, which are already known by many industry professionals, will be discussed one at a time.

The first factor is the increasing pressure on designers by owners to complete the design in the shortest possible time and for the lowest possible cost. By performing only slightly more than conceptual design and leaving detailed design to construction entities on some building components, AEs can reduce their total design hours and, therefore, their design fees without reducing their profit margins.

The second perceived factor is the increasing specialization of the engineering and construction process. According to two of the architects interviewed, it is nearly impossible to employ enough engineering specialists in one AE firm that would be capable of completely designing a structure. Increasing complexity of individual components has led the AE firm to delegate the responsibility of engineering design to the firms that understand the components best. For example, an AE firm will delegate the design of vibration and seismic control to a firm that specializes in the design and construction of those components. In many instances, these manufacturers or suppliers have a PE on staff or have a consultant that is exceptionally proficient in the design of a specific component. These individuals also have a much better understanding of the means and methods required to construct and install the component. Similarly, general contractors and steel fabricators will often hire engineering consulting firms that specialize in the design of specific components, such as storefront, curtainwalls, and steel connections.

The third factor is the increased effort by design professionals to minimize liability. Increased litigation associated with design and construction projects has resulted in risk management pervading the entire design process (Hinze 1997). It is easier for an AE to deflect liability when the AE can point to project specifications, explicitly assigning design responsibility for a portion of a project to an entity associated with the general contractor. Liability was cited by all of the contractors but none of the architects as being one of the major forces causing the AE to delegate engineering design responsibility to construction entities.

The fourth factor that has driven the shift in engineering is prefabrication, that is, the shift in location of large portions of the work from the project site into the factory. Accompanying this shift in location is an increase in the complexity of prefabricated systems. That is, prefabricated assemblies often are based on sys-

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tems design principles and feature innovative materials (Toole 2001). As such, many prefabricated systems, particularly involving HVAC, fire protection, and electrical work, are proprietary to some degree and typically designed by the manufacturers or their consultants. Because these systems still need to be installed by constructors, it may be easier for the AE to postpone the design of work associated with these systems to the construction stage.

Implications

The apparent shift in engineering from design professionals to constructors and manufacturers has implications for the alternative contractual arrangements on design and construction projects. If fragmentation is defined as the extent to which a thing or process is broken up into discrete pieces, the tentative findings clearly indicate the traditional design-bid-build process is becoming increasingly fragmented. Not only are more entities providing building performance engineering than before, engineering entities are also becoming increasingly split between three different groups: design professionals who produce contract documents, engineering consultants hired by constructors, and component manufacturers. There has traditionally been insufficient communication between these groups, so the increased fragmentation will likely lead to increased inefficiencies in the design and construction process.

Two specific examples of project inefficiencies were mentioned during the interviews conducted for the research. One well-understood example involves steel connections. As mentioned earlier, structural engineers hired by architects often size the wide flange beams and columns but assign the design of connections to steel fabricators. Notes on the drawings or the specifications often direct the fabricator to, "ensure the adequacy of the steel connections" to withstand loads provided by the AE of record. Since structural steel members are commercially available in discrete sizes, the members are typically overdesigned. The structural engineers' directions to "max out the connections" rather than designing connections to meet the actual design loads result in additional inefficiency in the structural steel frame.

The reference to the lack of sufficient communication between design and construction entities and the specific example mentioned above would seem to point towards the inherent superiority of design-build over design-bid-build. In addition, one could argue that the tentative findings reported in this paper indicate that design-bid-build is slowly being transformed into design-build because construction-related entities are increasingly being associated with the design of specific parts of the building.

The negative implications of the tentative findings for design-bid-build and design-build suggest that it is time for a radical re-engineering of the design and construction process, as proposed by the lean construction literature. While lean construction is still largely in its infancy, the writers believe that many issues associated with project organization and communication may be solvable using lean techniques. Unfortunately, however, the findings of increasing fragmentation also suggest problems for a lean construction delivery system. Design professionals and manufacturers provide only building performance engineering. Constructors, through permanent in-house staff and through hired engineering consultants, provide some building performance engineering and all construction engineering. The lean construction literature suggests that the design and construction process will be most efficient if the two types of engineering are coordinated and simultaneous. Yet the fragmentation due to increasingly technical specialization and complex prefabrication observed in this exploratory research is likely to prevent the engineering and construction industry from moving toward this ideal process.

If this shift in engineering from design professionals to construction entities is indeed occurring, two critical research questions arise. One question is whether the shift has resulted in engineering being performed by individuals or organizations that do not possess the qualifications traditionally associated with engineering design. Based on the fact that the vast majority of engineering tasks performed by construction-related entities in this study were required to have a professional engineer supervise the design, the apparent answer is no. However, several interviewees hinted that the qualifications on smaller projects, especially design-build projects with tight timelines, are not always as strict.

Another issue that warrants additional research is the risk that one or more engineering tasks will fall through the cracks on individual projects. This possibility seems real given two factors. One factor is that the fear of litigation has caused entities to attempt to reduce the boundaries of their responsibilities. Both design and construction entities may attempt to avoid legal responsibility for an engineering task unless forced by a contract to assume it. A related factor is that the primary instruments for forcing construction-related entities to perform building performance engineering design are project specifications. Specifications, however, are often the weakest aspect of contract documents because creating project specifications is a mundane, thankless and underpaid activity. It seems likely, therefore, that some AEs may produce plans that in effect delegate engineering of some portions of the project to construction entities, yet fail to adequately assign this responsibility within the specifications.

Conclusions

Exploratory research provides preliminary support for the hypothesis that a considerable number of building performance engineering tasks are provided by entities associated with the construction phase of a building, not by entities associated with the design phase. Empirical data to support this hypothesis included review of the technical specifications from 20 building projects and interviews of key individuals and further document review of five of these projects. In most cases it was found that engineering calculations or analysis was required to be provided in the form of submittals. Therefore, each of the 36 tasks included in Table 1 provides specific evidence of engineering performed by entities other than the AE of record. Interview data confirmed that each of these phases indeed were typically designed by individuals retained by entities other than the AE of record or their structural, MEP, and geotechnical engineering consultants.

Based on the empirical evidence, three preliminary specific conclusions can be drawn. First, over 30 engineering tasks that affect building performance were performed by individuals not retained by the AE of record. While the external validity of this finding is limited by the fact that the research sample was a convenience sample of 20 building projects, the data likely point to an important trend in the commercial construction market. The vast majority of construction literature discusses design-bid-build as a linear process: design is *completed* during the design phase, the project is bid, and the design created by the AE is implemented by the contractor. While it is widely recognized that the AE of record will hire geotechnical, MEP, and structural engineering consultants if specialists in these disciplines are not employed in-house, no publication alluded to project components

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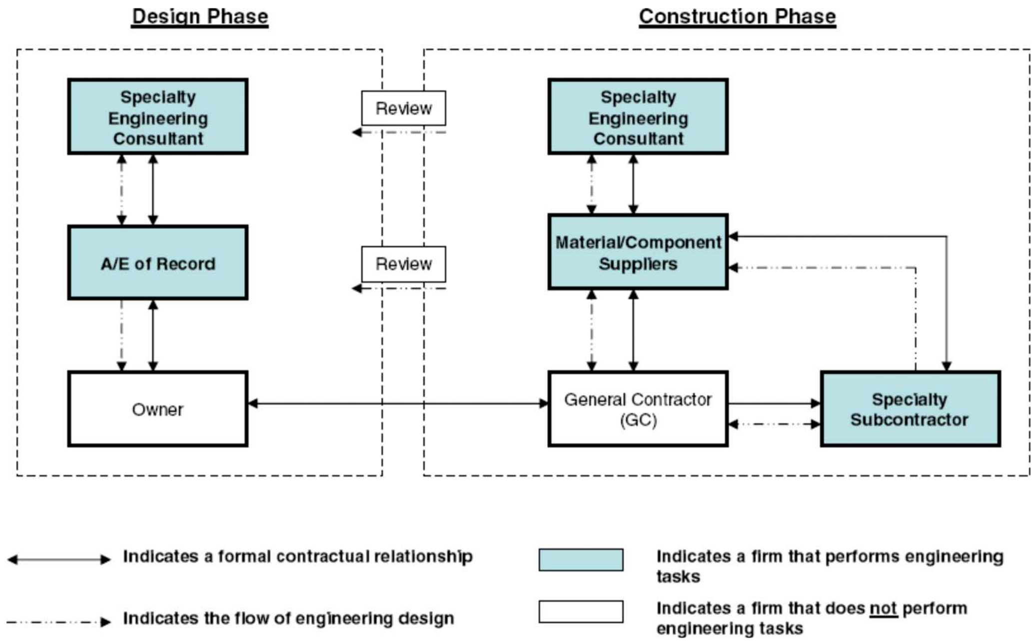

Fig. 3. Contemporary design-bid-build model

that were designed by entities other than the AE of record and their consultants. In fact, some publications explicitly stated that all of the engineering is completed by the AE of record in-house before bidding is begun.

The second preliminary conclusion of this research is that the engineering design of a building is performed by *many* firms, a large proportion of which are associated with the construction phase of the project. Many industry professionals have been aware that design has been increasingly fragmented, as indicated by the number of design specialists typically engaged by the AE of record. This study indicates design is even more fragmented than assumed in that there are many entities performing design associated with the construction phase, not just with the design phase of a project.

The first two conclusions are summarized in Fig. 3. This figure models the actual relationships between firms in the typical design-bid-build project delivery for building projects and is intended to be contrasted with Fig. 1. Dashed arrows indicate the flow of engineering design that impacts building performance while solid arrows represent formal contracts. One should note the presence of multiple firms that perform building performance engineering during the design phase. The titles "specialty subcontractor," "component suppliers," and "specialty engineering consultants" are intended to represent multiple firms. For example, "specialty subcontractor" represents many individual firms such as mechanical subcontractors, carpenters, and electrical subcontractors.

The third preliminary conclusion of this research is that a substantial number of project components that require building performance engineering are not designed by a professional engineer. As shown in Table 3, 14 of the building components were required to be designed by construction entities on four or more of the 20 projects reviewed but did not specifically require a PE seal. Interviewees confirmed this finding matched their experiences and agreed that, when not explicitly mandated by the specifications, a licensed engineer will generally not be involved in the design of a component. The interviews also indicated that components that have no engineering design requirements in the specifications are also typically designed by individuals without any formal engineering education.

In addition to providing qualitative confirmation of the quantitative data, the interviews provided additional insights relevant to the overall hypothesis. That is, the specification review helped to understand *what* components were designed during the construction phase (see Table 1), while the interviews validated these findings as standard industry practice, identified *who* performs these engineering tasks, and explained *why* these components are engineered after the design phase has been completed. These interviews with experienced industry professionals pointed at two important trends. One trend is increasing prefabrication. A large number of components are being designed and constructed offsite by independent manufacturers. Components such as stairs, storefront, roof and wall panels, and concrete are being prefabricated on an increasing number of projects. Although these components were only prefabricated for some of the projects studied, every interview confirmed that there is an increasing use of prefabrication. A second trend is the use of engineering consultants hired by the general contractor and subcontractors. In addition to the well known example of steel connection design, the research indicates the design of concrete reinforcement layouts, steel connections, railings, mechanical hangers, and HVAC balancing are also components of projects that are typically designed by a consultant to the GC or subcontractors during the construction phase.

Researchers and industry practitioners are aware that engineering design and construction processes are constantly evolving. This exploratory research paper suggests the traditional understanding of engineering design associated with design-bid-build projects is increasingly diverging from reality in ways that have not been acknowledged in the literature. The implications of the paper's findings appear to be sufficiently broad and important to warrant a substantial number of confirmatory investigations.

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