

PARTIALLY AUTOMATING THE DESIGN-CONSTRUCTION INTERFACE: CONSTRUCTIBILITY DESIGN RULES FOR REINFORCED CONCRETE STRUCTURES

by Martin Fischer, Graduate Research Assistant

and C.B. Tatum, Professor

Construction Engineering and Management Program,
Department of Civil Engineering,
Stanford University, Stanford, CA 94305-4020, USA

ABSTRACT

Design and construction are highly fragmented for many types of projects in the US construction industry. This vertical and horizontal fragmentation leads to inefficiencies during construction. Knowledge based systems provide a means to partially automate the process of construction input to design and assist in reducing the adverse impact of fragmentation on project performance. This paper describes early results from a research project at Stanford University to develop an expert system containing constructibility design rules that support the preliminary design of reinforced concrete structures. The major topics covered are: a background review of design-construction integration; a description of the structure of constructibility knowledge and its role in the design process, using reinforced concrete structures as an example; implications for performance improvement on projects; and insights for future research. The conclusions concern challenges and potential benefits from using knowledge based systems for integration at critical project interfaces.

Introduction

The design and construction processes in the US construction industry are highly fragmented for many types of projects. In any project phase, many professionals from several organizations work together. These professionals often participate and are responsible only in one phase of the project. This vertical and horizontal fragmentation leads to inefficiencies causing low productivity in the planning, design, and construction phases of a project. These inefficiencies include redesign or engineering change orders because construction requirements have not been considered in the design phase and execution of a suboptimal total project.

In a fragmented process, each professional tends to optimize his own solution. However, the combination of all these optimized single solutions might not yield an optimal completed project, since an apparently optimal solution to a problem in an early phase might introduce unfavorable constraints for latter project phases. Examples are [4]: a design requiring a construction scope greater than the minimum necessary, increased construction difficulty, and missed opportunities for the application of advantageous construction methods.

Increased design-construction integration could help reduce these inefficiencies. This type of vertical integration will benefit a construction project by increasing the productivity in the planning, design, and construction phases of a construction project, and providing the owner with a better overall solution to his needs for a constructed facility. Constructibility input to the structural design of reinforced concrete buildings is one example of a beneficial application.

Design-construction integration can help achieve these goals through early consideration of construction requirements. Structural designers should have access to constructibility expertise from the beginning of their task. Expert systems are one way of making expert knowledge available. This new software is one of the most important new technologies to increase productivity for office workers like design engineers [2]. Knowledge based systems provide a means to partially automate the process of construction input to design and assist in reducing the adverse impact of fragmentation on project performance. This paper describes early results from a research project in the Center for Integrated Facility Engineering (CIFE) at Stanford University to develop an expert system containing constructibility design rules that support the preliminary design of reinforced concrete structures.

Design-Construction Integration

Design-construction integration can be defined as "the interdisciplinary sharing of data, knowledge, and goals between design and construction" [3]. Constructibility improvement is a major goal for integrating design and construction. Figure 1 [1] summarizes the different opportunities for integrating design and construction and shows the means of incorporating constructibility knowledge during a project.

Generally speaking, design and construction can be integrated before, during, or after the design. Information can flow from design to construction only (one way), some feedback from construction to design might be possible (formal two way), or information might flow freely in both directions (two way). In a typical, fragmented project, we normally find *implicit constructibility knowledge*, *construction flexibility*, and *change orders*. In more integrated projects, we find *early preparation for construction* and *design reviews* through the early involvement of a contractor or the use of a construction manager. In some integrated projects, such as design/build projects, we find *common objectives between design and construction* and *common design teams*.

Design-construction integration can be achieved through organizations communicating with each other, professionals communicating with each other, learning, and technology support. The first two require contractual measures in one form or another. Learning requires educational programs that support integration, job rotation etc., and a lot of time is needed to make a person knowledgeable. This paper focuses on the application of a knowledge base system with *constructibility design rules* as a means of design-construction integration in order to enhance the sharing of knowledge between design and construction through technological support.

Structure of Constructibility Knowledge

Different constructibility knowledge is needed depending on the phase of the project and the decisions to be made. Appendix 1 outlines constructibility factors that capture these differences. These factors are classified into two major groups: factors exogenous to the design, and factors indigenous to the design.

Figure 1: Opportunities for Design-Construction Integration

when way of Integr.	Pre-design	During Design	Post-Design
One way	implicit constructibility knowledge	early prepara- tion for construction	construction flexibility
Formal two way	constructibility design rules	design reviews	engineering change orders
Two way	common objec- tives between design and construction	common design teams	common project appraisal

Factors Exogenous to the Design

The exogenous factors are often given for a particular project and are taken as input or constraints to the design problem. The factors presented in Appendix 1 have been listed with construction in mind. Therefore, factors (such as seismicity) that influence only the design but rarely the selection of construction methods for reinforced concrete structures, have been left out. Based on input from several structural designers, the following exogenous factors are mostly considered during structural design: availability of labor and material, average temperature, requirements to maintain the operation of an adjacent facility, type of facility, cost and schedule priorities, deflection, tolerance, and finishing requirements, codes and laws, and design for repetitive work tasks. However, these (and the other exogenous) factors often also influence whether a certain construction method is applicable or not. This is often not considered during the preliminary design stage and a structure is proposed that requires the use of a construction method inappropriate for the given site or climate for example. This results in additional expense during construction (to make a certain method applicable) or in redesign (to consider the applicable construction methods). Both solutions require more money and time to complete the project.

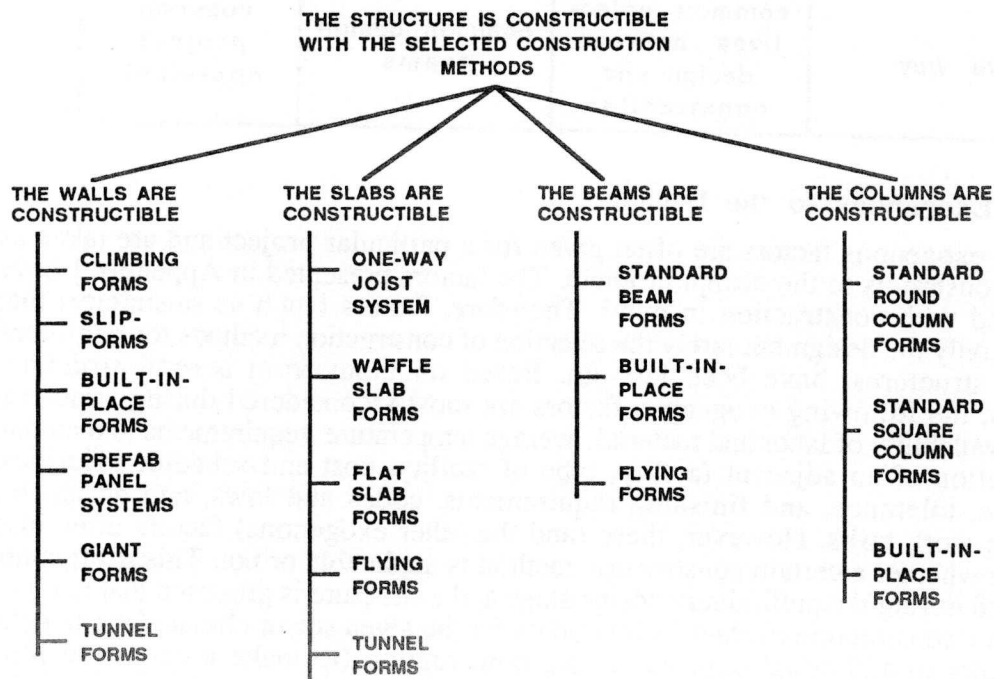
Factors Indigenous to the Design

Whereas the designer cannot control the exogenous factors, he/she can directly influence the indigenous factors with design decisions (e.g. core layout, column dimensions). Special construction methods (such as different forming systems, see Figure 2 for examples) normally require a specific geometry of the structure. By considering these requirements in the early phases of a design project, the designer can substantially enhance the constructibility of the design. This will very likely result in lower cost, less time consuming construction methods, and less change orders.

Sample Knowledge

The following is an example of this process. When designing the core of a building, the designer has to make decisions about which walls of the core will be structural or not, what materials to use for non-structural walls, and the wall thicknesses. If the designer wants to anticipate the use of a slipform for the construction of the core, he/she can include the following construction considerations in the design: 1) a uniform layout of structural walls will make the lifting of the slipform easier and avoid rocking; 2) if the core contains many in-side corners, it will be difficult to slipform, because the forms tend to get stuck in the corner; 3) non-structural concrete walls less than 8" thick and with nominal reinforcement are difficult to slipform, because the reinforcement is not strong enough to hold the form, and therefore the wall surface will be bumpy; and 4) the core should be at least 100' high. Considering these requirements allows the use of slipform techniques. Reduced cost and schedule and improved quality are likely to result.

Figure 2: Examples of Construction Methods for Structural Elements

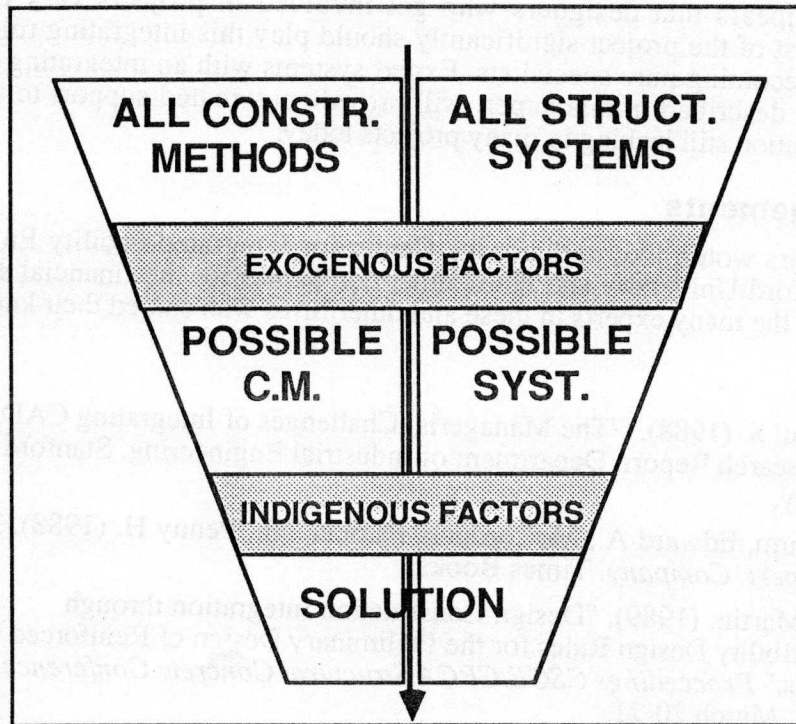


Role of Constructibility Knowledge in the Design Process

An ongoing research project sponsored by CIFE involves compiling a construction knowledge base for a number of construction methods. This construction knowledge base consists of the requirements of construction methods in terms of the factors presented in Appendix 1. Therefore, for each construction method and for each factor, the researchers are compiling a list of values of these factors and conditions under which certain values are true. These construction requirements can then be checked against the conditions of a particular project in order to determine if a certain construction method is applicable or not. This knowledge can be used to assist the designer during the design decisions in a way shown in Figure 3.

The exogenous factors first limit the number of possible construction methods, the indigenous factors then support the evaluation of design alternatives. In a prototype application, this knowledge base system will be linked to a CAD system in order to automate as much of the process as possible. Such a system will be part of the technology that will bring about productivity increases in all the phases of a construction project. In addition, the quality of the design and therefore the constructed project are likely to increase.

Figure 3: Application of Constructibility Knowledge in Design Process



Constructibility knowledge can serve two basic roles in the design process. On one hand, it can be used in a goal directed way. That means that the designer designs for the use of a specific construction method. In other words, he is thinking early about future constraints. In an expert system, this would require a backward-chaining inference engine. On the other hand, constructibility knowledge can be used in a data driven way. That means it shows the designer the range of possibilities for construction for a given design solution. In this way, the designer is thinking early about the future implications of his present decisions. In an expert system this would require a forward-chaining inference engine.

Practically, constructibility knowledge will probably be used in a mixed way, i.e. the designer might have some general ideas about the kind of construction system that he would like to use. But within this idea he might want to explore all the possible opportunities. That means the constructibility design rules will be used to chain forward and backward.

Conclusions

The application of a constructibility expert system to the design of reinforced concrete structures will certainly have an integrating effect (see definition of integration above). As for most expert systems, the acquisition of the relevant knowledge is the most difficult task in the development of such a system. This task is further complicated by the current high degree of fragmentation of the construction industry and the expertise required (after all that is the root of the problem). The number of construction materials and methods is constantly increasing. For construction professionals, it is increasingly difficult to keep abreast of new developments. Further specialization seems inevitable. Somebody, however, needs to perform an integrating role in the project processes. It appears that designers who get involved in projects very early and influence the rest of the project significantly should play this integrating role, if they want to avoid becoming pure specialists. Expert systems with an integrating function, such as the one described in this paper, will provide automated support to achieve a degree of integration still lacking in many projects today.

Acknowledgements

The authors would like to thank the Center for Integrated Facility Engineering (CIFE) at Stanford University and its member companies for the financial support of this project and the many experts in these and other firms who shared their knowledge.

References

1. Adler, Paul S. (1988). "The Managerial Challenges of Integrating CAD/CAM." Draft. Research Report. Department of Industrial Engineering. Stanford University.
2. Feigenbaum, Edward A., McCorduck, Pamela, Nii, Penny H. (1988). *The Rise of the Expert Company*. Times Books.
3. Fischer, Martin. (1989). "Design Construction Integration through Constructibility Design Rules for the Preliminary Design of Reinforced Concrete Structures." *Proceedings CSCE/CPCA Structural Concrete Conference*. Montreal. March 20-21.
4. Tatum, C. B. (1987). "Improving Constructibility During Conceptual Planning." *Journal of Construction Engineering and Management*, ASCE, 113(2).

Appendix 1: Outline of Constructibility Factors

I. FACTORS EXOGENOUS TO THE CONTROL OF THE DESIGNER

A. Area Conditions and Resources

1. Availability of Critical Resources
 - a. labor, skills
 - b. material
 - c. equipment
 - d. special services, such as machine shops
 - e. fabrication capabilities
2. Access to Site and Traffic Restrictions
 - a. restrictions of weight, height, length, width of loads
 - b. time restrictions on transportation

3. Available Modes of Transport
 - a. truck
 - b. rail
 - c. water
4. Climate Conditions in the Site Area
 - a. average temperature
 - b. maximum possible wind
 - c. average and peak values of precipitation

B. Site Conditions

1. Adjacent Facilities and Population
 - a. proximity of power lines
 - b. proximity of airports
 - c. population in the site vicinity
2. Proximity of Existing Facilities
 - a. need for passing rights or other special permission
 - b. requirements to maintain operation of adjacent facilities
3. Space Available at the Site
 - a. for laydown and fabrication
 - b. for construction operations and buildings
 - c. restrictions based on topography
4. Environmental Restrictions
 - a. need to protect flora or fauna
 - b. limitations on noise, vibration or pollution

C. Owner's Objectives

1. Type of Facility and Functionality
2. Cost and Schedule Priorities
3. Quality
 - a. deflection, location tolerances, and surface finish
 - b. durability of the structure
4. Demolition
5. Functioning of Existing Parts of Facility
 - a. operations of existing facilities
 - b. relationship with other operations

D. Regulatory Influences

1. Restrictions in Codes and Standards
2. Local Laws and Regulatory Requirements

E. Good Construction Practice

1. Construction Safety
2. Proven Technologies
 - a. materials and construction methods
 - b. equipment: hoisting, forming, finishing
3. New Technologies
 - a. materials and construction methods

- b. equipment
- 4. Productivity
 - a. repetitive work tasks
 - b. crew balance for operations and over the construction period

F. Type of Contract

II. FACTORS INDIGENOUS TO THE DESIGN CONFIGURATION

A. Basic Configuration

- 1. Layout, Complexity
- 2. Plan Dimensions and Configuration
 - a. columns and walls
 - b. core and perimeter
 - c. number of surfaces, changes in direction
- 3. Height of the Building
 - a. total
 - b. story
- 4. Materials
 - a. columns
 - b. walls
 - c. beams
 - d. slabs

B. Preferred Details

- 1. Connections
- 2. Blockouts
- 3. Reinforcement
- 4. Post-Tensioning

C. Size, Quantity of Elements

- 1. Maximum Weight
- 2. Extensions

D. Modularity

- 1. small scale (elements)
- 2. large scale (preassemblies)

E. Simplicity

- 1. Shapes
- 2. Layout

F. Standardization

G. Repetition

H. Interaction with other Functions