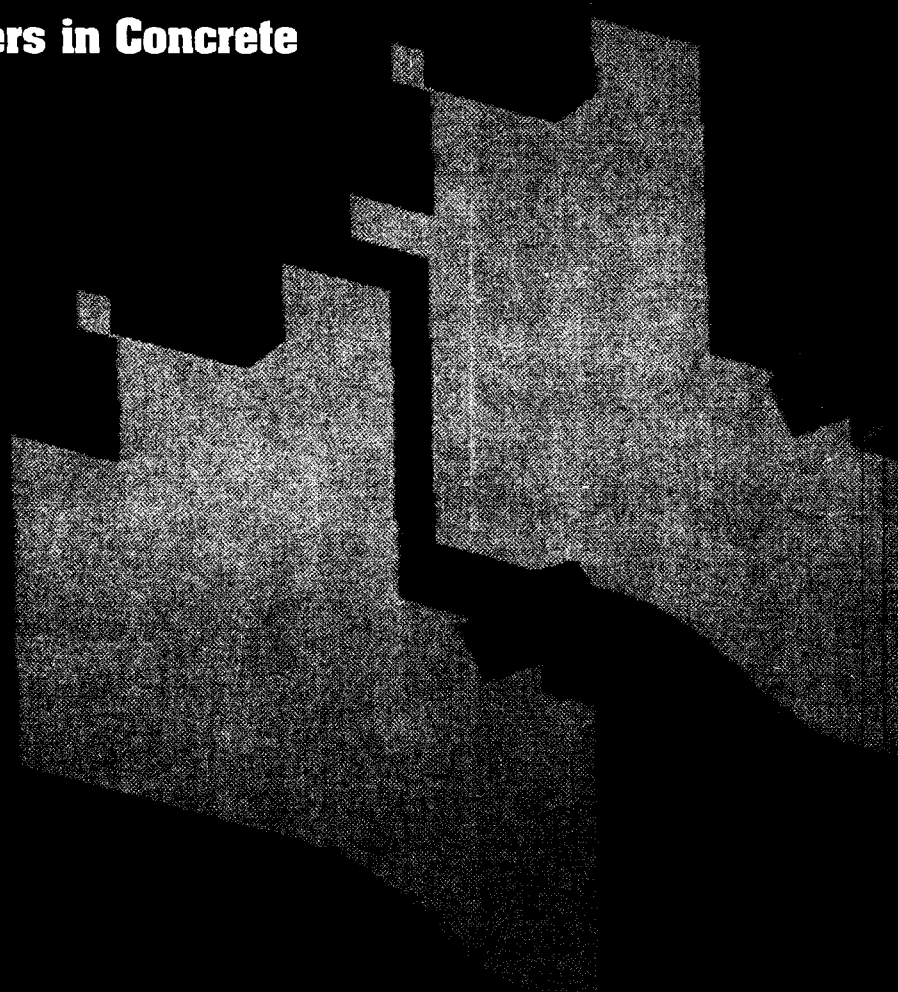


Computers in Concrete Construction

Computers in Concrete



Computers in Concrete Construction

ACI Compilation 15

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Preface

The ACI Compilation Series offers an opportunity to gather together material previously published in Institute periodicals as a compact and ready reference on a specific topic. The material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered a valuable resource for readers interested in the subject.

Victor E. Saouma

Chairman, ACI Committee 118

Use of Computers

On the cover: A three-dimensional stability analysis and design program for concrete monolithic structures was developed by the U.S. Army Corps of Engineers and is now extensively used at the Waterways Experiment Station, Vicksburg, Miss. This program, known as 3DSAD, features special purpose modules to compute quantities of volume, weight, and centroid for general geometry, analysis, and loads of dams, locks, and other structures.

American Concrete Institute, Box 19150, Redford Station, Detroit, Michigan 48219



Computers in Concrete Technology

by M. A. El-Rahman and W. J. D. Shaw

During the past two decades, a dramatic change has occurred in the manner in which engineering projects are designed and managed. Long and tedious calculations have been replaced with fast, accurate, and detailed results. Complex analysis that only a few years ago was thought impossible or impractical now is conducted on a routine basis.

Computers have found their way into nearly every aspect of concrete technology; the extent of this interaction can be seen in Fig. 1. Computer technology has intertwined knowledge and applications in a manner that results in remarkable improvements in efficiency, beginning with a better understanding of material behavior and extending to the design and the construction of structures.

Computer programs have become everyday language and the mystique that surrounded their use in the sixties has been replaced today with a hands-on, do-it-yourself attitude. The complete area of materials science is expanding at a remarkable rate in the use of computer technology.^{1,2} The computing power available in desktop and laptop microcomputers of today rivals the capability of mainframe computers of a few years back. The cost of these systems has in turn decreased such that today this technology is affordable by even the smallest companies. The rate at which computer technology continues to develop points to even further involvement of computers in all aspects of engineering over the years ahead.

Some of the more common applications of computers in concrete technology are testing, material modeling, analysis and design, quality control, construction management, fatigue analysis and pre-

diction, cost estimating, and involvement in codes and specifications.

Testing

The use of computers in the laboratory is vital for testing and evaluation. They are now commonplace in structural testing and are used in several different manners.³

One major use is data acquisition, which usually involves gathering data, its subsequent storage, and sometimes displaying either the data or the current status of the test. An example is that of reading and storing strain-gage data for loaded concrete components either in the laboratory or the field. This replaces the use of data loggers, which require considerable manual handling of data for analysis at the end of the test.

Computers used for data acquisition also are suited to analyzing and reducing test data, tabulating results, and plotting engineering relationships with minimal human involvement.

Microcomputers can be used in computations for test setups as well as verifying the status and zero positions of sensors. Some programs allow for internal calibration and offset conditions prior to testing. Computers also can be interfaced for interactive control of testing machines. Fig. 2 shows a testing system controlled by a microcomputer that also acts as a data acquisition system. A microcomputer, acting as a smart terminal also can feed collected data to a mainframe computer so the data can be added to a data base or used for other analyses.

Another use is determining air-void system parameters or aggregate size and distribution in hardened concrete. These values can be determined easily using a computer-

controlled microscope stage coupled with a video recording and analysis system. These image-analysis systems now are standard items.

Computerized materials-testing systems have paid off in a number of ways. There has been an increase in experimental efficiency and precision and an improvement in the quality of both testing and the analysis of the test results. The test engineer has more information available and more time to visually observe the specimen during testing as well as to consider the significance of the results after testing is complete.

Material modeling

The stress/strain and cracking behavior of concrete and reinforced concrete structures can be described by formulating specific equations of state. These special relations are developed using power law relations or polynomial equations based upon analysis of experimental information.

For cracked concrete structures where analytical relations are not available, or when the exact analysis is tedious and time consuming, the structures' behavior can be simulated through numerical analysis procedures. The state of the art in modeling concrete structures has been basically through two distinct approaches, smeared-crack representations^{4,5} and discrete-crack representations.^{6,7}

Each method has specific advantages and disadvantages, and care must be taken in the selection of finite element size when using the smeared-crack approach.⁸ Because of this, a hybrid model using features borrowed from the two base models has been proposed.^{8,9} This area of modeling continues to evolve.

The DIANA program¹⁰ was constructed according to the smeared-

crack concept to model the nonlinear behavior of reinforced and prestressed concrete elements. Using the discrete approach, conditions for crack propagation in a porous structure have been studied analytically.¹¹

An example of the results of computer simulation analysis using discrete-crack representations for cracking in coarse and fine aggregate is shown in Fig. 3. In addition, three-dimensional elliptical voids have been used as models to study crack problems.^{12,13} Fig. 4 shows the interaction of initiation stress at voids in concrete under biaxial stress fields. These were obtained using the computer program SCATEC.¹²

Computer image analysis also can be used to help investigators assess microcrack patterns in concrete¹⁴ and trace the migration of different chemical species in hardened concrete. Once analysis is complete, complex random-path statistical models then can be constructed and used for behavior prediction in other problem configurations.

Design and structural analysis

The design of structural components always has been a repetitive and time-consuming task; similar analysis relationships are used for most types of members. The loads applied to a structure give rise to stresses, strains, and displacements in the structural elements, which are sized for limiting values of these parameters.

The optimum design of each component in a structure does not necessarily insure the best design of the structure as a whole. Rather, conceptual input from the designer always will be necessary. In statistically indeterminate structures, the interaction of stiffness in adjacent members also must be considered.¹⁵ In problems such as this where iterative analysis is required, the use of computer programs has a definite advantage.

An overall computer flow diagram for the design of engineering structures is shown in Fig. 5. Such

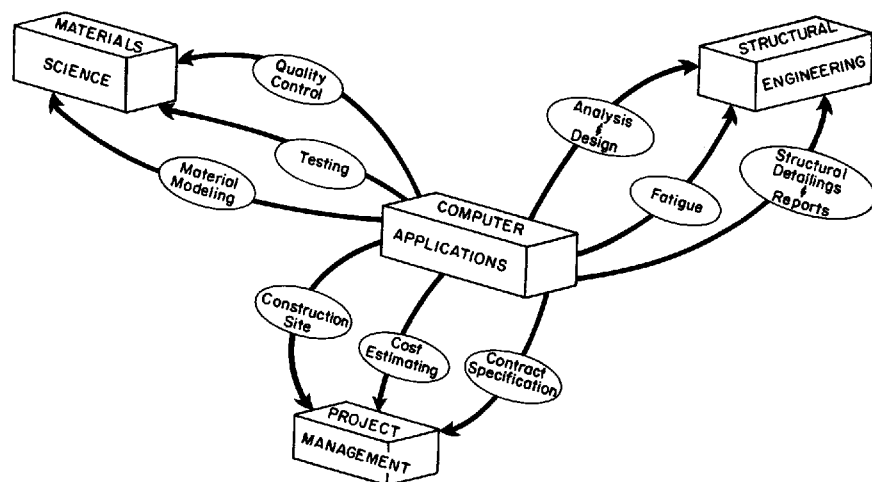


Fig. 1—Applications of computers in concrete technology.

a process always involves an interactive approach with the designer and incorporates a redesign portion. Many computer programs, classified as inhouse, university, or commercial, are available for the design of concrete structures.

Two of the most important criteria for selecting a design program are user interaction and program flexibility. These two features allow a designer to alter a design solution easily as a project progresses. For iterative programs the efficiency of convergence to a final solution is an important attribute.

Quality control

Concrete, as compared with other engineering materials, is inherently a largely variable material. When tested, two identical concrete samples can show moderate but substantial variations in mechanical properties. Variations in strength, workability, and durability of concrete are caused by many factors that should be corrected quickly by adjustments in mix proportions and close supervision at the time of mixing and placement.

Consistency in the properties of the tested concrete specimens is a prime objective at concrete batching plants, which leads to a need for a high degree of quality control during the manufacture of concrete. Computer programs can provide better control in obtaining good quality concrete and programs are able to perform virtually any operation that might be required.^{16,17}

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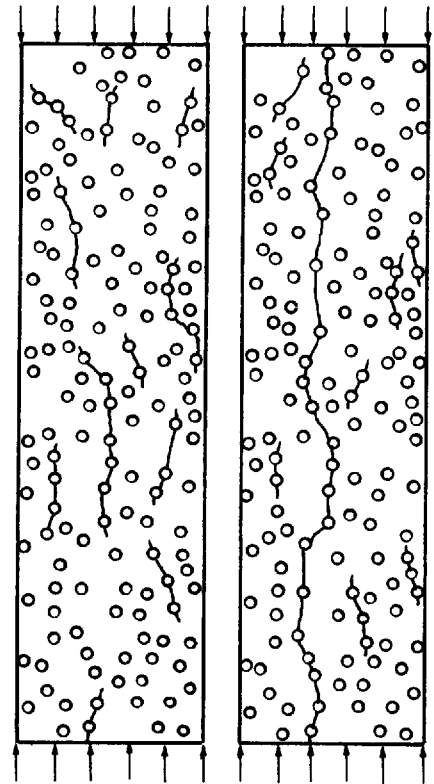
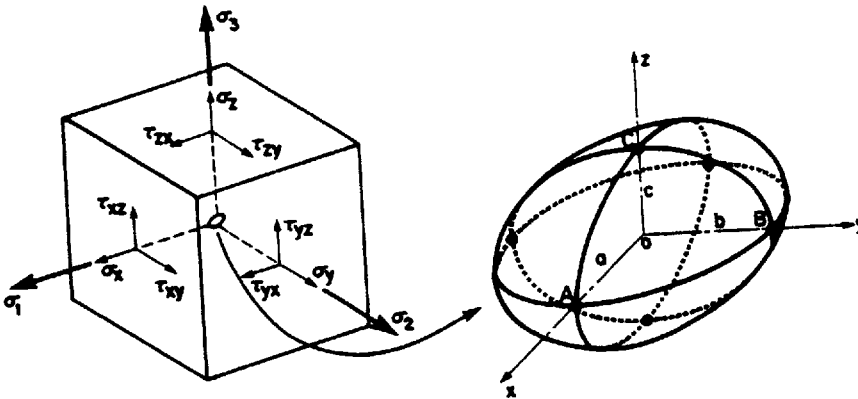
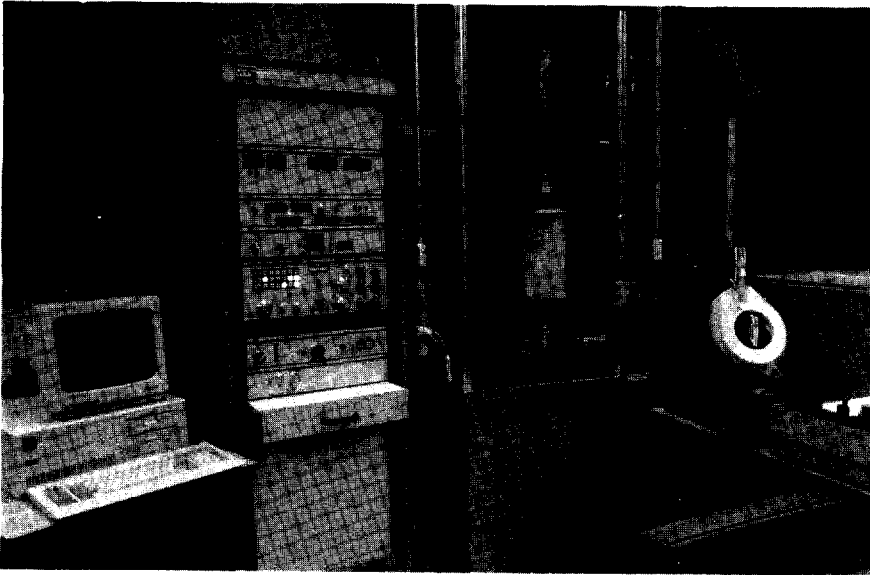
Fig. 2—(top left) Computer controlled concrete testing.

Fig. 3—(right) Compressive load crack patterns using a computer simulation technique:¹¹ a) hardened cement paste; b) concrete.

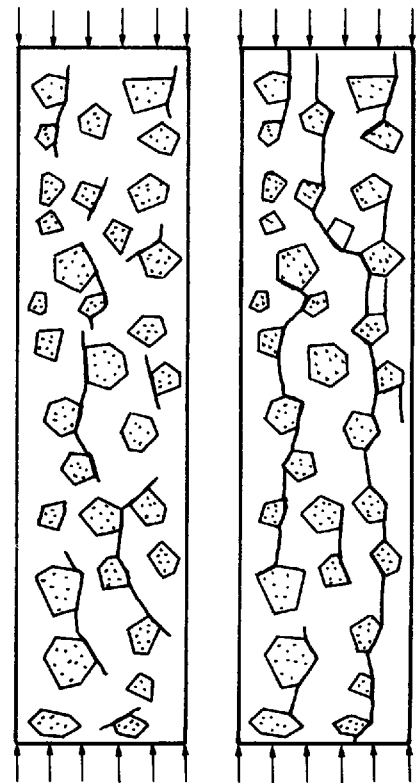
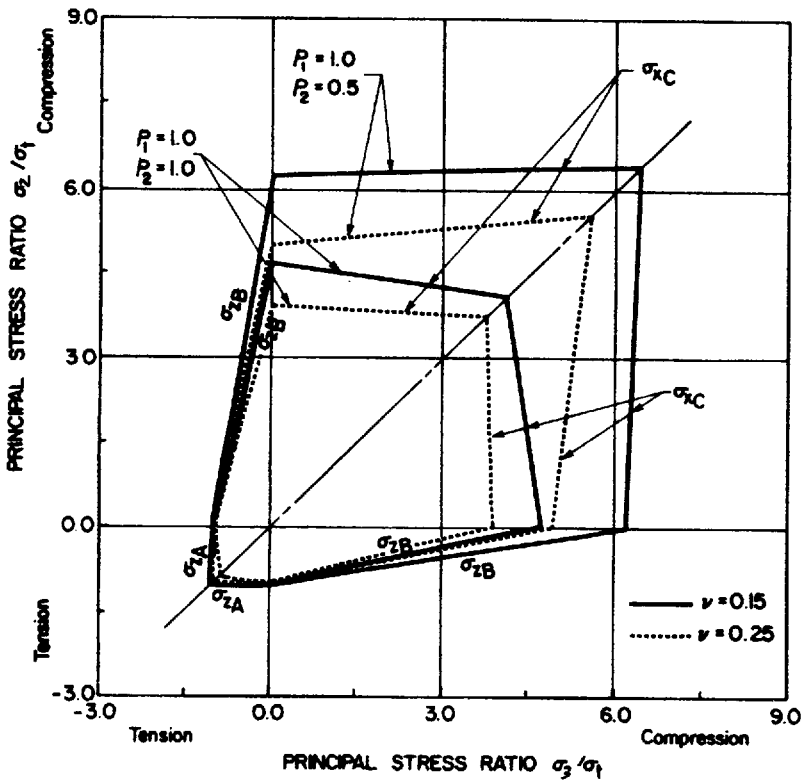
Fig. 4—(bottom left) Crack initiation stresses at voids under biaxial conditions.¹²

For example, the Project Concrete Quality Control System program,¹⁶ PCQCS, written in FORTRAN, was developed to provide information on controlling specific properties of concrete. It incorporates gradation commutations and proportions and adjustments of mix proportions for scale weight, gradation summarization, and compressive strength data. The program also can compute and store data for monthly summaries and make the necessary mix proportion adjustments for gradation and moisture. The overall structure of the program is shown in Figure 6.

Another program, COPMIX,¹⁷ written in BASIC, allows an automated step-by-step procedure for the design of normal weight concrete. The ACI, CSA, and British design procedures were incorporated into the program, which allows the user to design a mix according to a specific code. Once the mix is designed, it can be modified for partial replacement of cement by flyash. The program also



(a)



(b) Documents

low the target strength to be calculated and gradation of fine aggregates to be analyzed in detail.

Integrated software is available that combines separate programs into a unified versatile program. Thus spreadsheet calculations, graphics, word processing, and communication can be used with quality-control software. The main strength in the use of computers for quality control is the ability to execute complex interactive relationships in a quick and systematic manner. Concrete mix computer programs, when combined with good inspections and workmanship, help to obtain the best end result, which is based upon a total approach to quality control.

Construction management

Computers have found their way into construction and are used in job analysis, ordering materials, and bookkeeping and also as a tool to coordinate geometry, control alignment, and control reference points.

For large-scale construction projects, planning and organization are vital and construction and materials scheduling using critical path planning is essential. This method is available in commercial programs that prevent unplanned time delays and provide the most efficient path for job progress.

Formwork design is another area that can be improved upon significantly by using computers. Formwork often has been either overdesigned or underdesigned, resulting in wasted time and money or even collapse.

The reluctance to design formwork accurately is associated with the time and effort required to perform the necessary strength analysis. The use of microcomputer programs can lead to the rapid design of more rational formwork systems, resulting in improvements in construction, safety, and cost.

Fatigue

Computers are used in a growing number of applications of concrete

technology with regards to fatigue behavior, resulting in progress in both knowledge and design. Computers often are used to gather and store fatigue information during testing of concrete, reinforced concrete, reinforcement, and post-tensioning rods.

Field loading spectrums for specific structures can be fed back into the testing machine through interactive computer control, allowing the laboratory test component to undergo the same spectrum loading conditions as those occurring in the field.

The analysis of fatigue data also is conducted easily using computer systems. Generally, empirical fitting relationships that allow life predictions can be made. Data bases are compiled for different materials and conditions that later can be incorporated directly into prediction or design programs.

Design and analysis of structures are accomplished easily with specialized computer software. Most design and analysis for fatigue conditions involves an iterative process to predict the fatigue life of the structure. This is particularly true where fatigue cracks exist in the structures as life prediction depends upon crack propagation.

In many respects, concrete is similar to such other materials as metals, ceramics, and polymers when fatigue behavior is involved. The use of computers for fatigue testing, analysis, and life prediction can be extended easily from metals to concrete structures.

Cost estimating

Estimating a price during the tender process is a difficult and time-intensive job. Accuracy is required if a low tender is to be achieved and a profit maintained. Contractors are able to derive considerable benefit when using a computer program or special computer and takeoff pen system for estimating the costs of projects. The return from using such a system can be measured in terms of success in winning contract awards, efficiency, accuracy,

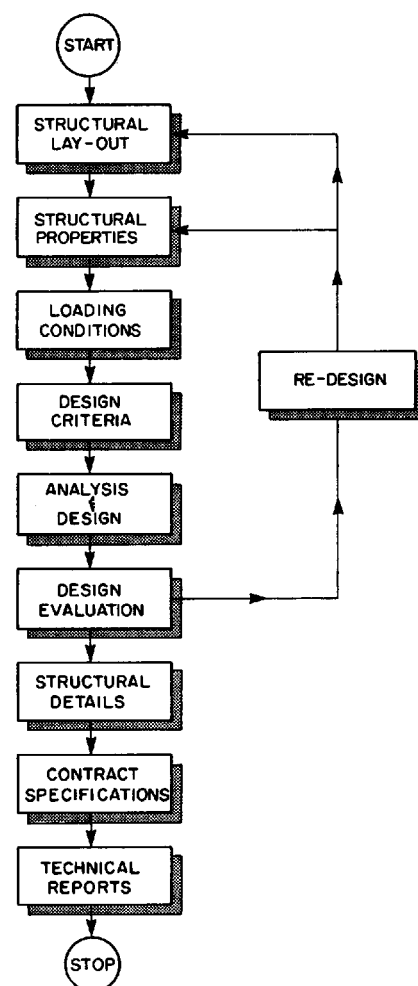


Fig. 5—Structural design process flow chart.

and time savings. In addition, estimating programs are helpful for project supervisors when placing materials orders.

Codes and specifications

In design procedure, the engineer frequently refers to building codes to insure that a structure meets the minimum requirement for safety and performance. This sometimes is a tedious job. Computer programs implementing the code requirements make it possible to search for relevant topics with considerably less effort than usually is involved. Using computer programmed codes also helps to avoid overlooking portions of the code since cross referencing is easily incorporated.

Future directions

The major advance in the use of computers in concrete technology currently is in the widespread use of

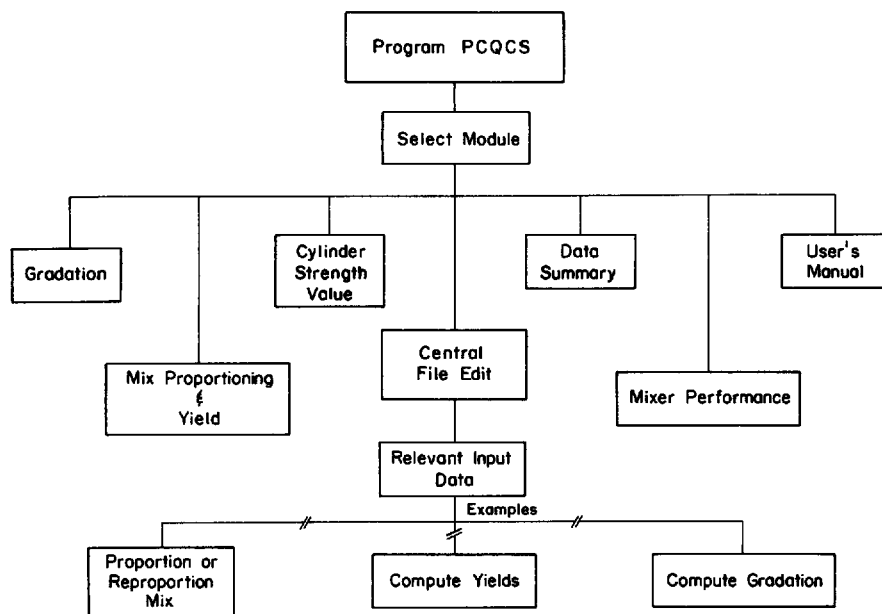


Fig. 6—Project concrete quality control system modules.

personal computer (PC) systems. The increasing capability in computing power and availability of software means that more small companies are able to afford this technology. Future applications for PC use likely will occur first in computer-aided design. Additionally, more testing laboratories will incorporate computer-controlled equipment and data acquisition in their evaluation of material properties.

Computer use can be expected to increase in the areas of fatigue and fracture mechanics. In addition, integrated quality control using feedback circuitry during the mixing of concrete also is likely to grow. Using feedback, either automatic or computer-guided, corrections can be made prior to the completion of mixing so that exacting quality control of concrete strengths and workability can be maintained.

Computer use is a powerful design aid and can be an excellent investment as long as the engineer's judgement is not sacrificed.

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Selected for reader interest by the editors.

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Interactive Vertical Formwork Selection System

Shrinking construction markets and shorter construction periods are driving more and more contractors to execute critical path activities and large cost items with their own forces. Typically, the first item for a general contractor to do in-house is the structural concrete frame. The reasons for this are:

- It is a large cost item.
- It controls the project pace
- It is a phase of the work where labor is exposed to risky or unsafe conditions.
- The quality of the structure can

also dictate the quality of workmanship acceptable on the project to the trades that follow.

A large portion of the cost of the structural frame is the cost of formwork for columns and walls. Typically, the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This article describes a tool that the authors developed to assist the formwork engineer/planner in selecting a vertical formwork system. The tool was developed by systemati-

cally capturing the expertise of people involved in all phases of the life of the formwork, from design through erection and concrete placement to removal. The end result is a body of decision rules and knowledge represented as an expert system.

Vertical formwork systems

Vertical formwork systems are those used to form the vertical supporting elements of the structure such as columns, core walls, and shear walls. The function of the vertical supporting systems is to transfer the floor loads to the foundations and to resist the lateral loads from winds and earthquakes. Consequently, the construction of vertical structural elements precedes flat horizontal work.

Typically, columns and walls are formed and placed one or two days ahead of the floor slab. Some formwork systems, however, offer the contractor an option to construct the vertical structural elements several floors ahead of the flat work, and sometimes to construct the entire core before the horizontal work starts. A field study¹ yielded five vertical formwork systems: conventional, ganged, slip, jump, and self-raising.

Conventional formwork

This all-wood forming system consists of sheathing made of plywood or lumber, supported by vertical wood studs.² Single or double horizontal wales are used to support the studs. Ties may be inserted through holes drilled in the wales (single wale) or inserted between them

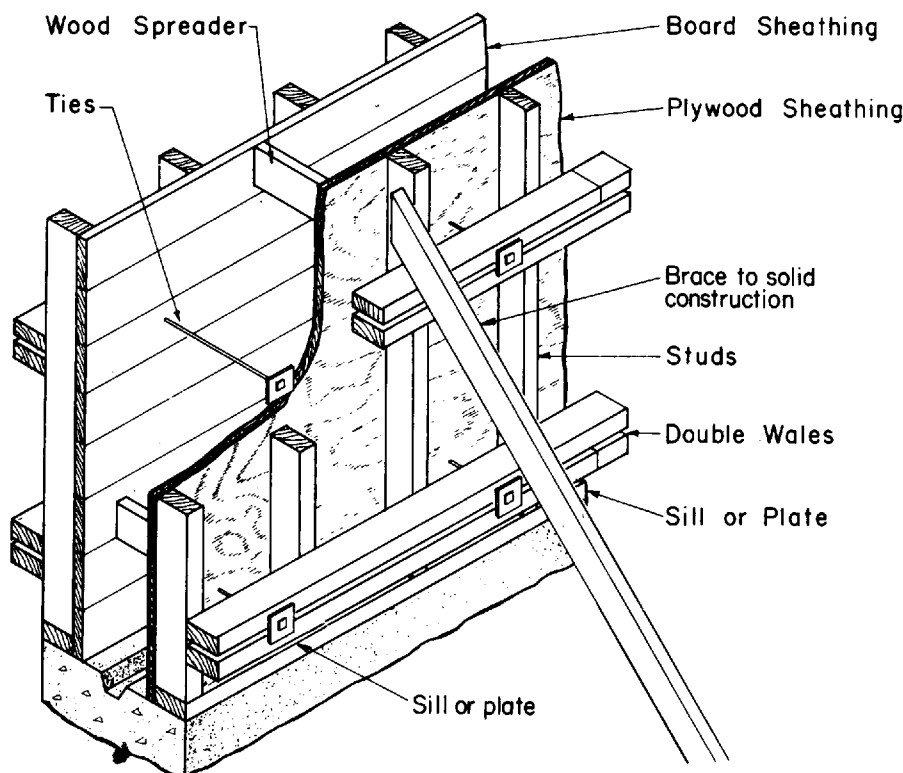


Fig. 1 — Conventional formwork.

(double wale) to resist the horizontal pressure of plastic concrete. An inclined bracing system is used to prevent forms moving (Fig. 1).

Ganged forms

Ganged forms are made of large panels joined together with special hardware and braced with strongbacks or special steel or aluminum frames. These large panels are usually built or assembled on the ground and raised into place by crane. In high wall construction, the ganged panels are frequently raised by crane to the next placement position and supported by steel brackets fixed to the lift below. Figure 2 shows some of the standard ganged forms available for contractors.³

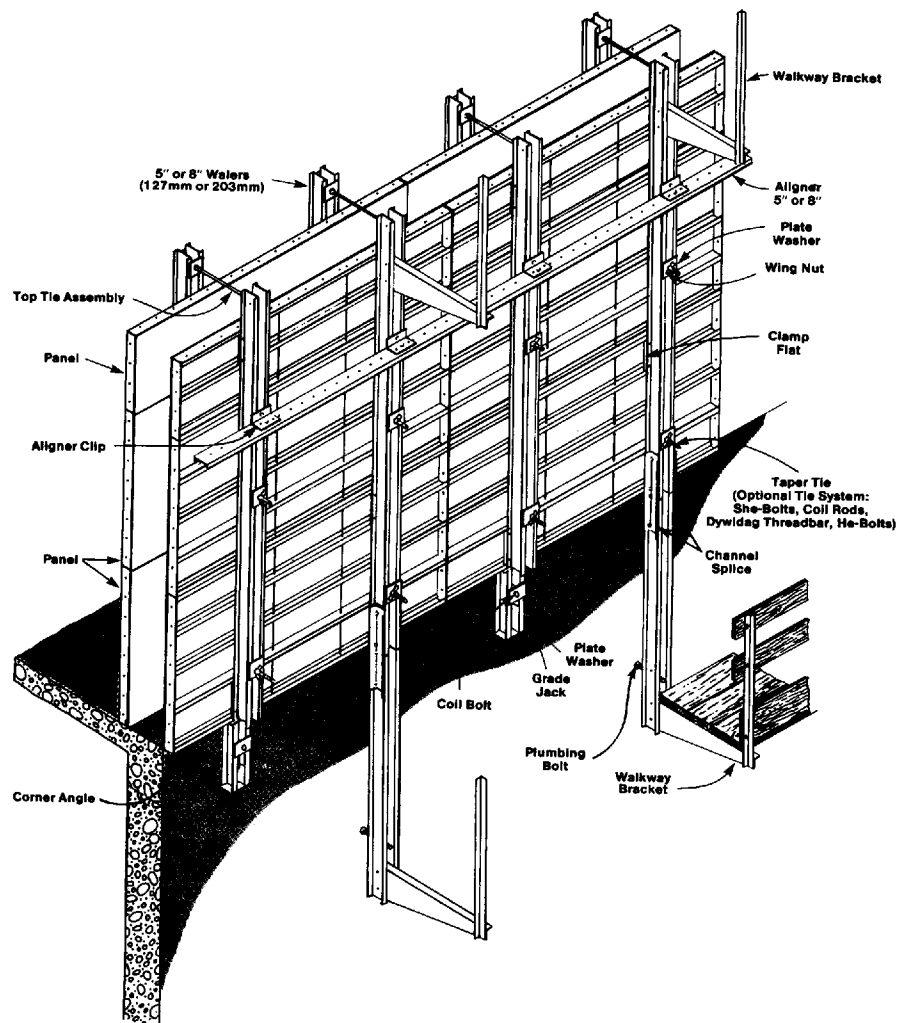


Fig. 2 — Ganged forms.

Slipforms

Slipforms are usually used to cast walls, piers, towers, and structural cores. Slipforms consist of inner and outer forms, 3.5 to 6 ft (1 to 1.8 m) high, using 1-in. (2.5-cm) thick lumber. Forms may be fabricated from wood or steel, and are supported by strong vertical yokes. The yokes are tied together at the top to give the form sides the rigidity needed.

Vertical sliding is accomplished by jacks climbing on smooth steel rods or pipes anchored at the base of the structure and embedded in the concrete (foundations) below the forms. The jacks may be hydraulic, electric, or pneumatic and operate at speeds up to 24 in./hr (61 cm/hr). Jacks usually have carrying capacities between 3 and 25 tons (2.7 and 22.7 Mg) and are spaced 4 ft (1.2 m) on centers (Fig. 3).

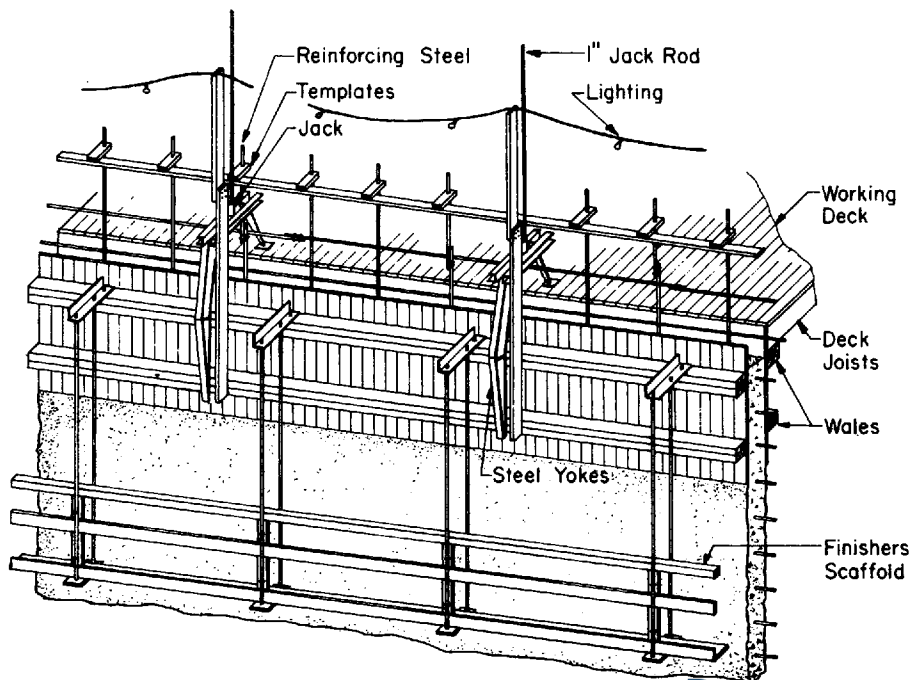


Fig. 3 — Slipforming system.

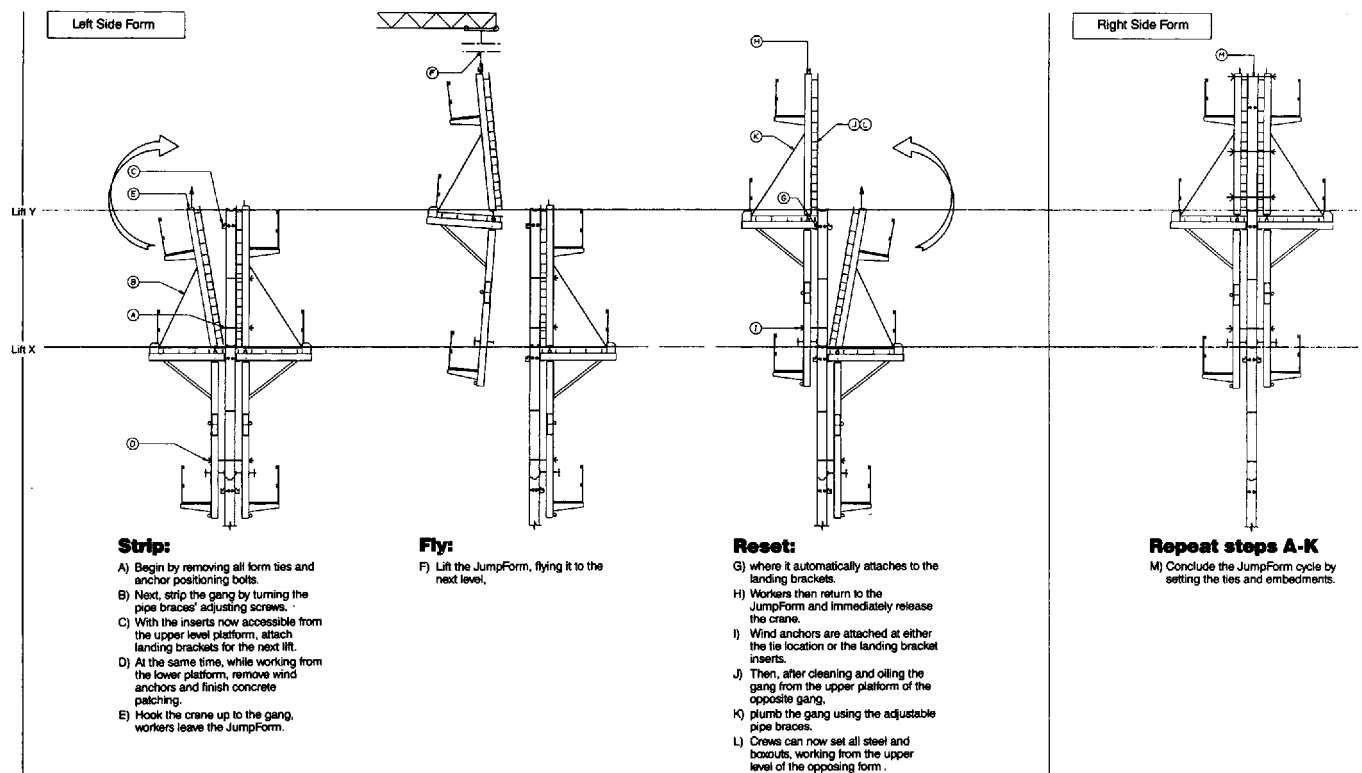


Fig. 4 — Typical jump form cycle.

Concrete is placed into the form from a working platform that is attached to and slides up with the inner form. Concrete is usually placed continuously, often 24 hours a day while the forms are moved upwards, until the structure is complete.⁴

Jump forms

Jump forms are used where no floor is available on which to support the wall formwork, or the wall and column proceed ahead of the floor. Jump forms consist of a framed panel attached to two or more strongbacks. They can be one floor high, supported on inserts set in the lift below. Two sets, each one floor high, that alternately jump past each other can also be used. Figure 4 shows a typical jump form cycle, which consists of three basic operations: strip, fly, and reset.⁵

Self-raising forms

This system consists of upper form(s) and lower lifters (self-raisers). The lifters are attached to the wall already cast below the form. Figure 5 is a schematic representation of a typical self-raising form cycle.^{6,7}

Factors affecting selection of formwork systems

Selecting the formwork system for cast-in-place reinforced concrete buildings is a critical decision affecting cost, safety, quality, and speed of construction. Many factors must be considered for the proper selection of the vertical formwork system.

Vertical and lateral support^{8,9}

Typically, columns and walls are utilized to support the vertical loads resulting from the dead loads and live loads. In high rise buildings, another vertical support system is needed to withstand the loads from winds and earthquakes.

Rigid frame. A rigid frame system consists of rectangles of vertical columns and horizontal beams connected together in the same plane. A bearing wall is a special case of the rigid frame system (Fig. 6a).

Shear walls. A shear wall formation is a thin slender beam cantilevered vertically to resist lateral forces (Fig. 6b). It can take the

form of a rectangular or box-shaped core, which can contain vertical transportation and energy distribution systems (e.g., stairs, elevators, toilets, mechanical shafts).

Framed shear wall. This system consists of a combination of frames which utilize beams and columns with the shear wall designed to resist lateral loads (Fig. 6c).

Framed tube. This is a structural system in which the perimeter of the building, consisting of vertical, closely-spaced supports, connected by beams or bracing members, acts as a giant vertical internally stiffened tube (Fig. 6d).

Table 1 — Structural systems and building height^{8,9}

Structural system	Optimum height
Rigid frame	Up to 20 stories
Shear wall	Up to 35 stories
Framed shear wall	Up to 50 stories
Framed tube	Up to 55 stories
Tube-in-tube	Up to 60 stories

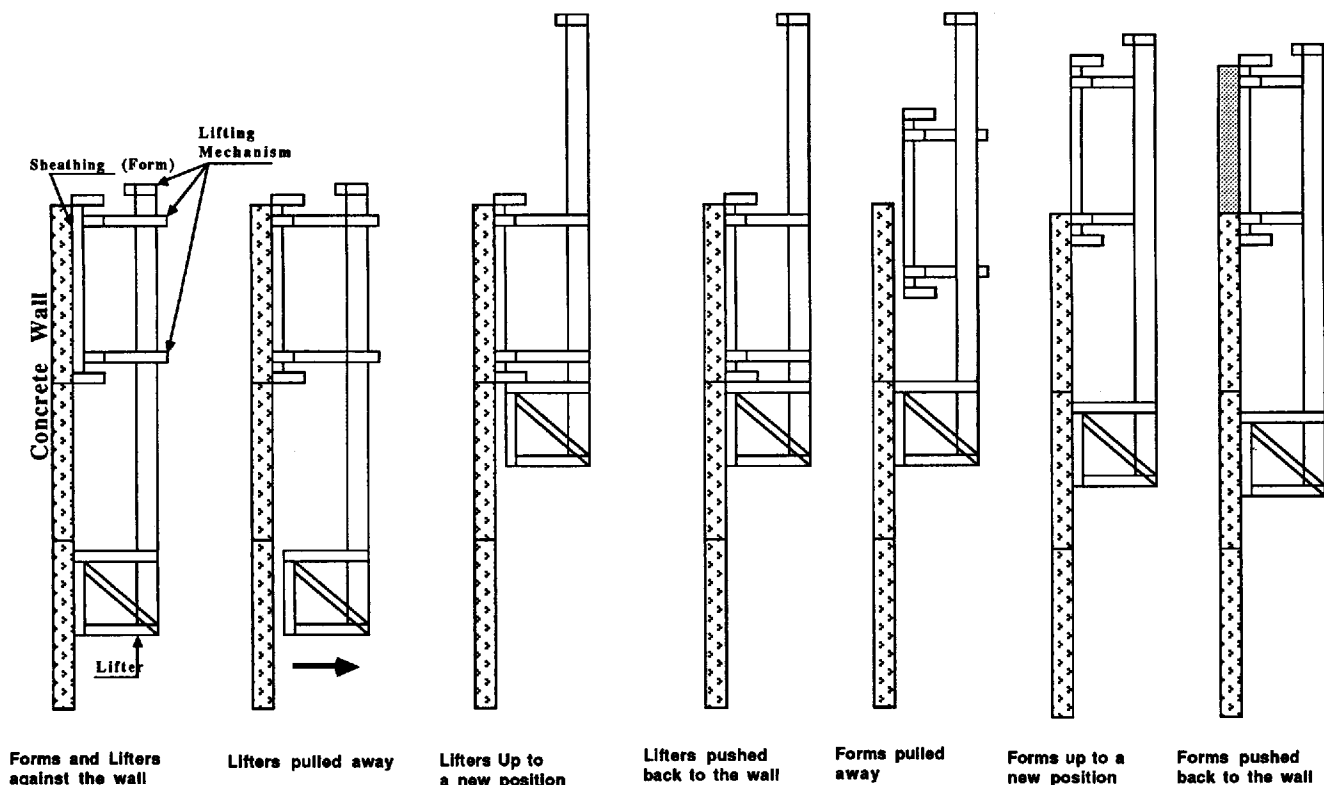


Fig. 5 — Typical self-raising form cycle.

Tube-in-tube. This system is a combination of the framed-shear wall, which acts as an interior tube, and the framed tube, which acts as an exterior tube. The floor structure ties the interior and exterior tubes together to allow them to act as a unit to resist lateral loads (Fig. 6E).

Table 1^{8,9} indicates the optimum height of each lateral support system and serves as a rough guide for determining the suitable lateral supporting system for each building height. Judgment, experience, and the personal preference of the designer are all-important factors in choosing the proper lateral support system.

Concrete finish

Surface quality and appearance is always referred to as the concrete finish. Concrete surfaces can be classified as rough finish as-cast surface, smooth exposed, or covered (with a special cladding material or painted), and textured (with an architectural surface texture and treatment).

As-cast concrete finish typically shows some irregularity and may contain concrete surface defects. An

as-cast finish is usually found in concrete buildings where appearance is not important, such as warehouses.

Exposed concrete finish is characterized by a smooth regular concrete surface and regular positioning of form ties. Exposed concrete surfaces are typically found in columns and bearing walls.

Architectural concrete is favored in vertical concrete elements (columns and walls). As a result, concrete finish must be considered as one of the major factors in the selection of a formwork system. Architectural concrete requires careful selection of a formwork system that includes stiffer form liners, tighter joints, smoother finishes, and more care in implementing chamfers and rustications.

Site characteristics

The building site may influence the selection of a suitable formwork system, because of site limitations and accessibility for construction operations. The feasibility of using ganged forms, for instance, is influenced by site characteristics such as accessibility, availability of a make-up area, and surrounding area re-

strictions such as property lines, adjacent buildings, power lines, and busy streets. In open and unrestricted suburban sites, all formwork systems are usable and some other considerations should be evaluated to determine the most efficient and cost effective system. In downtown restricted sites, the choice may be limited to slipforms and self-raising forms.

Hoisting equipment (cranes)

Some formwork systems require special handling techniques including adequate crane service. The ganged formwork system is a good example of crane influence on the selected system. The size of the ganged modules may be limited by the crane carrying capacity and its maximum and minimum lift radii.

Another important factor that influences the selection of the formwork system is the available crane time. In one case study,⁶ the limited crane time available for formwork erection to meet the project completion date was the major factor that led the formwork designer to choose the self-raising form alternative (which requires no crane time).

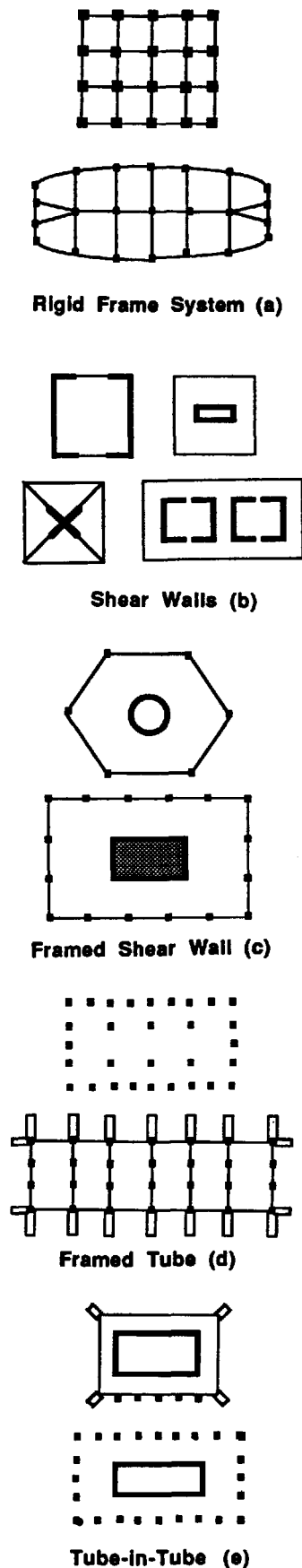


Fig. 6 — Lateral support systems.

The WALLFORM vertical formwork selection system

WALLFORM is an expert system developed to assist the formwork engineer select a vertical formwork system. Expert systems are an effective tool for archiving the expert's knowledge on selecting the appropriate vertical formwork system for buildings. Expert systems are interactive computer programs incorporating judgement, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks.¹⁰

WALLFORM knowledge base

Knowledge for WALLFORM was acquired through literature review and unstructured and structured interviews. Twelve structured interview sessions were conducted with experts working for formwork subcontractors and manufacturers. The knowledge acquired was arranged in a tabular format. Table 2 shows the influence of various factors on the selected formwork systems for vertical concrete work. The information in the table represents the condensed form of the formwork selection knowledge base.

Knowledge representation for WALLFORM

Production rules chosen to represent the WALLFORM knowledge base were directly extracted from the tabular knowledge base. The tables were also used to create subgoals. For example, in developing the expert system for the vertical formwork system, there was a subgoal called "adequacy of hoisting equipment." This subgoal is a synthesis of availability of crane and crane time involvement, existence of adjacent buildings and other obstructions, and adequacy of crane carrying capacity.

Explanation facility

The WALLFORM explanation facility is designed to respond to two types of questions:

- During the consultation, the user may wonder why the system needs to know the information it is requesting. If the user types WHY, the system will respond by displaying the rule(s) for which it is trying to determine validity. The rules contain a textual note that clarifies their

purpose and the terminology associated with each rule. It also contains a reference telling the user where the information for the rule was obtained.

- At the end of the consultation session, the user may desire an explanation of a certain conclusion output. If the user types the line number of the choice or statement, the system will respond by displaying all of the rules used to determine the value of that choice or statement (line of reasoning).

Output of WALLFORM

WALLFORM contains 5 possible solutions (formwork systems) to the problem among which the expert system will decide. The goal of an expert system is achieved by selection of the most likely choice based on the data input, or by a list of all possible choices arranged in order of likelihood.

At the end of each run, the system will display the selected types of formwork followed by "probability =" or "confidence =" and a number. The number indicates the confidence that the choice is correct. The system utilizes a zero to 10 rating system. In this system, zero indicates definitely NO, and 10 indicates definitely YES. Values between 1 and 9 are degrees of certainty between the extremes. Values scored above 6 are strong candidates for selection, and the final selection may be based on system availability and area practices. In this mode, the final confidence factors are simply the averages of the fired (evaluated) rules which contain choices in their consequents. An assignment of zero or 10 to a choice by any rule, however, excludes all other confidence factors from consideration.

In a pure production system, rule ordering is not important. Therefore, addition and deletion of rules is quite simple. The only concern is the effect of the changes (addition or deletion) on the structure of the subgoals.

System features

The system was developed using a commercially available expert system shell. The shell has the capabilities of utilizing both forward and backward chaining techniques. However, the problem addressed by

Table 2 — Factors affecting selection of vertical formwork systems

Formwork systems							
Influence factor		Conventional forms	Ganged forms	Jump forms	Slipforms	Self-raising forms	
Building design	Lateral support	Lateral support system	Most suited for frames and retaining walls	Shear walls Bearing walls Retaining walls	Shear walls Frames & framed shear walls	Shear walls Shear walls Tube systems Tube-in-tube	
		Building height	Up to 120 ft	Up to 350 ft	Up to 350 ft	Average 400 ft Min. recorded = 60 ft Max. recorded = 600 ft	At least 300 ft No maximum
	Building shape	Column/wall size and location	System can handle variation of column/wall size and location		System can handle moderate variation of columns/walls size and location	Walls should be of the same location Wall size variation can be accommodated	System can handle reasonably modular design
		Openings/inserts	System can handle openings/inserts of different size and location	Variation in opening size and location can be accommodated at additional cost		Openings/inserts should be regularly occurring from floor to floor	Should be minimum Too many openings/inserts make this system impractical
Job specification	Speed of construction	Concrete finish	As-cast concrete finish	Produces smooth exposed concrete finish Tie pattern and number should be designed Form liners can be used for architectural concrete		System produces rough concrete finish No ties	Smooth concrete finish. Form liners can be used
		Construction sequence	Slabs and walls are placed concurrently	Slabs and walls are placed concurrently Walls can be placed ahead of the floor slab	System is used when no floor slab is available	Typically walls are placed entirely or at least several stories ahead of the floor	Walls are ahead of the floor. Other method is used for the first to 3 stories
		Cycle time	1 Floor/week	1 Floor every 3 to 4 days	1 Floor every 2 to 3 days	1 Floor every day. Rate of placing = 8 to 20 in./hour	1 Floor every 2 to 3 days
Supporting organization	Cost	Stripping	Hand strip High stripping cost	Crane is used to strip the system High stripping cost	Forms are equipped with mechanism for stripping Min. stripping cost	Forms are stripped at the end of the project Min. stripping cost	Forms are equipped with mechanism for stripping Min. stripping cost
		Reuse	Less than 10	Between 40 and 50 reuses horizontally or vertically	Between 15 and 30	Between 50 and 100 (i.e. between 200 ft and 400 ft high)	At least 30 reuses should be available vertically
	Hoisting equipment	Location of adjacent building and obstruction	Generally not a factor	A major factor; system must have a free space to be moved from floor to floor		Minimum free space should be available for crane movement	Not a major factor; system can be used in restricted areas
		Crane time	Not a factor; system can be hand set	Crane-dependent system Sufficient crane time is a must	System substantially reduces crane time Average crane time pick = 20 minutes	Crane is used only for materials delivery and concrete placing	Crane-independent system
		Operating system	Hand set system Crane increases system efficiency and reduces cost	Crane set system Crane serves two functions: lifting and supporting the forms	Crane is used only to lift the forms Crane is not used for form dismantling	Locomotion is provided by electric, pneumatic, or hydraulic jacks climbing on smooth steel rods	System is lifted by hydraulic, electric, or pneumatic lifters
	Safety	No special safety features required	Special care for handling the large ganged units by crane	Safety features Safe guarded platform No one need be on form during crane handling	For hydraulic systems, special safety precautions must be taken to prevent fire several hundred feet above the ground		
	Supporting yard facility, supplier or make-up area	Not a major factor, but system is more efficient if a local yard facility is available	A major factor; system must have an adequate make-up area of close-by supplier	System is rented or purchased	Continuous materials delivery is a must. Uninterrupted concrete placement must be assured.	System preassembled; make-up area is not a factor. Local supplier must be available	
Local conditions	Area practice	More efficient in areas of high quality, low cost labor force	Work best in areas of high cost, low quality labor force	System is easy to learn and adapt Short learning curve	System can be learned in 2 to 3 weeks	System requires high quality supervision	
	Weather	Generally not a major factor	A major factor; walls should have sufficient strength before stripping which is largely influenced by weather conditions High winds limit the crane movement		Hot or cold weather affect the concrete rate of setting which slow the rate of rise	In cold weather, forms should be protected and concrete should be heated	
	Site characteristics	Access to site	Geneally not a factor for loose forms	Can be a major factor if the system is pre-assembled in a local yard facility	Site must be accessible, forms can be up to 16 ft high and 44 ft wide	System must have a limited access for material delivery	Min. site access is required for concrete placing and rebar delivery
Site size		Not a factor	Can be a major factor if the forms have to be built on site	Not a major factor; forms are pre-assembled and unloaded directly	Not a major factor; system can be used in restricted small sites		

WALLFORM is a design problem characterized by a limited number of solutions (goal state), which warrants the use of backward chaining.

It is a rule-based expert system, designed to assist formwork designers and planners to select the optimum formwork system. WALLFORM selects the vertical formwork system and tie type, and recommends some formwork manufacturer's products.

The primary users of these systems are general contractors and formwork subcontractors. The system assumes that the user has some knowledge about formwork. The user would be at the early phase in the development of the project, with some information available about building shape, site conditions, and resources.

In multi-purpose high-rise buildings, each set of floors has certain functions and features which may result in the use of different formwork systems for each section. In this situation, the user is advised to run the system more than one time to determine the optimum system for each part of the building.

Expert's evaluation

To assure the validity and credibility of the implemented expert system, the tabular knowledge base was sent to a well known expert in formwork who reacted favorably to the tabular knowledge base. It should be noted that this expert was not a major source of knowledge for the research, and thus the expert's views were considered unbiased.

The second attempt at validation was provided an expert who acted as a major source of knowledge. The expert used the expert system to select a formwork system for one of his current projects. The system provided the answer he was expecting. The expert then changed some parameters and reran the system. It again provided him with the expected answer.

Acknowledgements

The authors wish to acknowledge the Consortium for the Advancement of Building Sciences (CABS) at Pennsylvania State University for providing the expertise and the financial support for this research. The authors also extend their thanks to Mr. T. Gallis, Manager,

Forming Products, Patent Scaffolding Co., and to M.K. Hurd, author of *Formwork for Concrete*,² who provided valuable information and suggestions.

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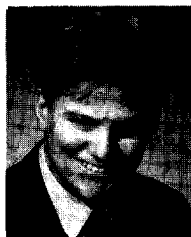
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Selected for reader interest by the editors.

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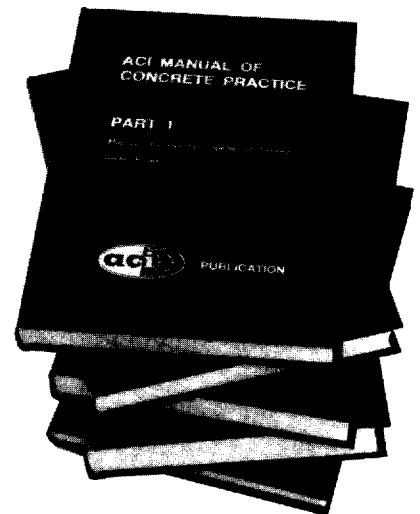
SLABFORM, an expert system for selecting horizontal formwork, will be the subject of a *Concrete International* article later this year. Information on obtaining software for WALLFORM and SLABFORM will be provided at that time.

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ACI COMPILATION

Automatic Adjustment of Concrete Mixtures

by K.W. Day

There surely can be no dispute that the objective in concrete production should be to produce a concrete having constant properties. The major properties to be held constant would include:

- Strength
- Slump/workability
- Sandiness/cohesion
- Entrained air content
- Setting time

The factors that may cause variation in the above would include:

- Aggregate grading, cleanliness, moisture content and specific gravity (SG)
- Cement quality
- Concrete temperature
- Batch proportions
- Admixture dosage

The task of controlling concrete quality is to vary the batch proportions and admixture dosage so as to avoid, or at least reduce as far as possible, variation of items in the first group. There are two alternative philosophies on which control may be based:

Quality Assurance (QA) is to pre-test the first three items in the second group and vary the last two items accordingly.

Reactive Quality Control (QC) is to closely monitor the items in the first group along with selected items from the second group (including actual batch proportions) so as to rapidly identify the cause of, and to correct, any variation occurring in the first group.

On paper the QA approach is clearly superior, but it does involve being able to accurately predict the quantitative effects and necessary adjustments.

The reactive QC approach may

sound risky, but if the variations are small and they are rapidly detected and rectified it can produce lower variability than QA (e.g., a cement content adjustment based on a laboratory cement test can be more immediate than an adjustment based on early age strength of production concrete, but it is not likely to be as accurate).

The task of the controller is not to select one of these alternatives but to blend both together to produce an acceptable degree of control at a minimum cost. In effect this means operating reactive QC to establish which items merit the QA approach, whether the adjustments made by the QA system are accurate, and whether any new factor has emerged to affect the concrete quality.

In February 1989 the author installed a system in a large commercial ready-mix plant which, when fed with normal concrete and aggregate test data, integrates this with actual batch proportion data to show the interaction of all the factors discussed above. The system has the basic ability to automatically compensate for all variations advised or detected, but has so far been used only to assist and advise a human operator to make such adjustments.

Automatic adjustments

Strength

Automatic strength compensation requires great care if it is not to make the situation worse. First, it is necessary to be reasonably sure that a change to a new stable level has occurred. Second, it is necessary to

establish this very quickly. An analysis of 30 test results, running or not, is not a sufficiently current basis. Cusum analysis¹ is the only suitable basis yet known to the author. It is possible to automatically assess cusum data, but to date the author has preferred to do this manually.

Very accurate adjustment is possible. A 7-day strength cusum (of fairly low variability concrete) will very clearly show to within 10 lb/yd³ (6 kg/m³) what cement change has been made or is needed. Cement efficiency will certainly be between 5 and 15 lb per 100 psi (3.3 and 9.9 kg per MPa), and for a particular concrete will be known to within ± 11 lb per 100 psi (± 0.66 kg per MPa). It is therefore possible to "tune" the mean strength of concrete to about ± 50 psi (345 kPa). This is a far greater accuracy than is possible in the best laboratory trial mix, and in any case laboratory test results are not accurately transferable to field conditions. It would therefore be quite ridiculous to require a laboratory trial as a basis for amending a current production mix.

Slump/workability

It is true that slump does not accurately indicate the relative workability of different mixes. In fact about the only thing that slump does well is to indicate the relative water content of otherwise identical concrete mixes. However since this is precisely what is required in the current situation, the slump test is a satisfactory basis. Of course there may be major inaccuracies in individual slump tests, but we are talking here about adjusting water content at the batch plant based on a

succession of readings (or opinions) on a succession of truckloads. Final discretion may or may not be given to the truck driver to adjust slump, but in any case the slump at the batch plant should be as uniform as possible.

Sandiness/cohesion

The author's *specific surface*² (which is not true specific surface, but a figure especially designed to represent water demand) can be used to maintain sandiness/cohesion/water demand constant as sand grading varies. This works over a wide range of sand percentages (from 25 to 50 percent of total aggregates is a reliable area; 20 to 55 percent may give satisfactory results depending on such items as coarse aggregate grading and shape, cement content, and required workability).

In the author's mix design/batching control system, the proportions of all mixes simply change automatically when the revised specific surface figure is input.

Entrained air content

Admixture dosage must be varied as necessary to maintain desired air content, rather than maintaining a constant dosage. There should not be much need for adjustment unless the sand/silt or fly ash/carbon contents vary substantially.

Whilst it may be desirable to regularly monitor air percent directly (using a pressure meter or alternative device), reasonably adequate control is obtained by monitoring cylinder density and only carrying out direct testing when cylinder density changes.

Setting time

It is desirable to have a table relating concrete temperature to admixture dosage (and type), but this would be over-ridden by field observations and requests. Again, the intention should clearly be to provide a concrete with consistent properties rather than to maintain a fixed admixture dosage/type regardless of concrete performance.

Aggregate variations

Grading has been dealt with above. In the (fairly rare) event of variation in SG, a fixed volume rather than a fixed weight of the aggregate in question must be maintained.

Properly adjusted for, neither grading nor SG variation should cause a change in water or cement requirement. Silt content is a different matter. Silt/clay will increase water requirement just as surely as a finer grading, but it does not justify a change in sand content. The same applies to a more angular particle shape, as may be experienced when using crusher fines in the absence of natural sand. In both these cases a higher water requirement must be accepted (unless compensated for by additional water reducing admixture), requiring consequent small adjustments to cement and aggregate batch quantities to maintain strength and correct yield.

Cement quality

In controlling over a million cubic metres of concrete in many different countries, the author has never found it necessary to carry out regular cement testing but does not deny that it may be worthwhile in some areas or circumstances. Two pre-conditions must be met to justify omitting cement testing: a very effective early age concrete strength monitoring system must be in place, and strength variations must be small enough not to cause concern over structural adequacy in the period between detection of a downturn and its rectification.

Where regular cement testing is not undertaken, it is a useful precaution to take a small airtight container of cement from each delivery. The sample is kept until satisfactory concrete strengths are obtained at 28 days, and then discarded. If the cement does come under suspicion, the sample is available to test.

Concrete temperature

Although denied by some authorities, the author's control graphs almost invariably show a strength downturn (due to a water increase) when concrete temperature rises.

The effect is not great enough to make a day to day cement content adjustment essential, but certainly makes a seasonal adjustment necessary in Australia and countries with similar climatic variations. Although not essential, a small automatic adjustment that would even take place between a cold morning and a hot afternoon would improve strength uniformity.

Batch proportions

There are two aspects to batch proportion variations: intentional variations as dealt with above, and the extent of unintentional variation being experienced.

The author's batch plant control system records the actual and intended batch weights for every batch produced and provides automatic computer analysis of this data, including integration with actual concrete test results. Such a system might be considered essential before permission was granted to allow the batching computer to initiate automatic adjustments to the mixes in use. With such a system it can readily be seen what adjustments the computer "decided" to make and how accurately it was able to execute its own intentions. Further, it could clearly be seen how typical of the overall production were the batches actually sampled for testing.

The system could also single out the weakest (highest w/c) batch of any grade and predict what strength it would have. The amount of error involved in such a prediction would be clearly established by the normal operation of the control system. This functions in part by predicting the strength of every batch tested (from its batch proportions and material properties) and analysing the accuracy of such predictions.

Admixture dosage

Again, variations would include intentional and unintentional variations. These are both monitored by the batching control system in exactly the same way as other batch proportions (except that metering is by volume rather than weight).

Conclusion

This article was written because it was realized that some (many?) specifying authorities actually prevent the production of uniform concrete, or at least ensure very slow reaction to variations in conditions and materials.

Nothing in this world is totally uniform and consistent, and concrete materials are certainly not the exception. To require batch proportions to remain rigidly unchanged is to ensure that no attempt can be made to compensate for whatever variations in materials or conditions occur.

It may be true that many concrete producers have neither the technical knowledge nor the physi-

cal facilities (or even the interest?) to make effective use of permission to continuously adjust mixes, but this does not excuse the inhibition of desirable technical advances.

Where a new mix or new materials are introduced, a preliminary laboratory trial may be desirable (although the author usually prefers to go directly from a computer mix design to a trial truck of concrete supplied to a non-critical location since trial mixes are rarely more accurate than the computer design). However, to suggest that a laboratory trial is more accurate than a calculated small adjustment of a mix in production, and to hold up a desirable adjustment until the results of such a trial are available, is quite unrealistic.

The future progress of the concrete industry depends upon the origination of new techniques and new equipment for both the production and the control of con-

crete. Such developments will be hindered if they are not matched by improved methods of specifying concrete, establishing a climate in which it pays to do a better and more scientific job of producing concrete.

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Selected for reader interest by the editors.

Keywords: admixtures; aggregate gradation; air entrainment; batching; concretes; mix proportioning; moisture content; quality control; setting (hardening); workability.



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Interactive Horizontal Formwork Selection System

by Awad S. Hanna and Victor E. Sanvido

In multistorey reinforced concrete building construction, selection of formwork to shape and support freshly cast concrete is largely based on the experience of the person selecting the system. There are typically one or two such experts in a company who make these decisions. This may often result in the selection of a particular system that is not the optimum. Also, the expert "Knowledge Czar" is not always available and an outside consultant is expensive to hire. This fact imposes some limitations especially for small and medium size contractors.

This article describes a computer system the authors developed to help the contractor select a horizontal formwork system. The expertise of several formwork engineer/planners was used to produce a body of decision rules and knowledge represented as an expert system.¹

Horizontal formwork systems

Horizontal formwork systems are those used to form the horizontal concrete work (slabs or floors). There are seven horizontal formwork systems that can be used to support slabs and roofs. Two of the systems — joist-slab and dome forms — are usually placed above the plywood sheathing. They are therefore considered special cases, because they can be used in conjunction with any of the five basic systems described below.^{1,2}

Conventional wood systems

Conventional wood systems consist of wood shores supporting wood stringers and joists, with the deck

surface made of plywood (Fig. 1). The deck may also be made of large panels tied or ganged together and supported by scaffold-type shoring.^{3,4}

Conventional metal systems

Conventional metal systems usually consist of wood or aluminum shores supporting aluminum stringers and joists, with the sheathing made of plywood (Fig. 2). The same type of deck forms can be made up of large panels tied or ganged together and supported by steel scaffold-type shoring.^{2,5}

Flying truss systems

Flying truss forms usually consist of large sheathing supported by steel or aluminum trusses (beams) that rest on screw jacks that allow the forms to be adjusted to the right level (Fig. 3). For stripping, after the concrete has gained enough strength, the system can be lowered away from the slab by turning down the jacks. The truss-mounted forms are then moved by crane from one casting position to the next.⁶

Column-mounted shoring systems

Formwork under cast-in-place slabs has typically been supported by shores resting on the floor or ground below. Another way to cast the slab without using the shoring system is to use long span form panels supported by up-and-down adjustable brackets attached to the bearing walls or columns of the building itself. The system consists of plywood decking that can be assembled on the ground or in place once the form has been flown and set on the columns (Fig. 4). The plywood decking is supported by

joists (headers) attached to the stringers (steel beams). For stripping, jacks are lowered until the framing beam of the deck rests on the rollers attached to the bracket and the entire form assembly is rolled out and carried by crane to the next floor.⁸

Tunnel formwork systems

Tunnel forms (also known as tunnels) are U-shaped or inverted L-shaped prefabricated steel forms that allow slab and supporting walls to be cast simultaneously (Fig. 5). After the concrete has gained enough strength the tunnels are removed and moved to the next level (Fig. 6). Half tunnels are used for spanning wide rooms, full tunnels for spanning narrow rooms. Standard modular panels offer a wide range of flexibility in room size. Forms range in width from 13 ft to 24 ft, in height from 7.5 ft to 10 ft, and in length up to 40 ft.^{9,10}

Joist-slab formwork systems

A one-way joist slab is a monolithic combination of regularly spaced joists arranged in one direction and a thin slab cast in place to form an integral unit with the beams and columns. One-way joist slabs have frequently been formed with standard steel pans. Any spacing between pans more than 30 in. is referred to as a wide-modular or skip-joist system.^{3,12}

Dome formwork systems

Standard size domes are usually used for waffle slab construction. They are based on two, three, four, and five foot modules.³ The two foot modules utilize 19 x 19 in. domes with 5 in. ribs between

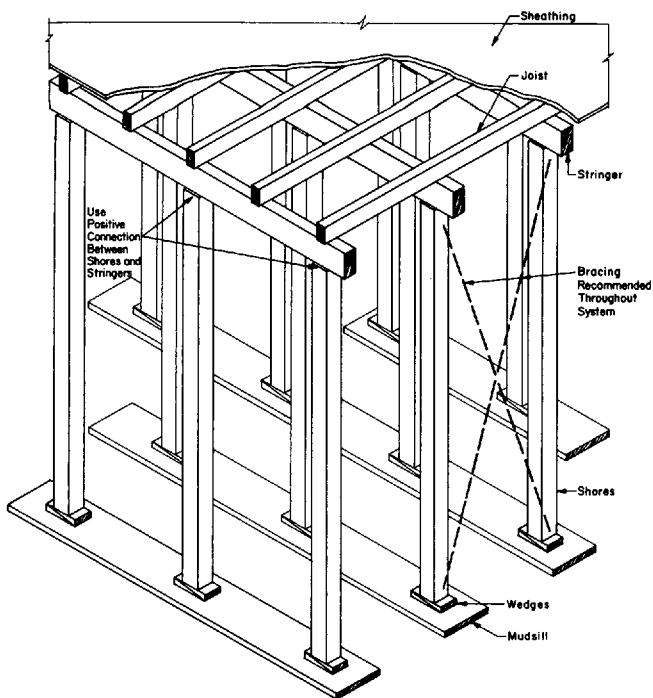


Fig. 1 — (above) Conventional wood formwork system.

Fig. 2 — (right) Conventional metal formwork system.

Fig. 3 — (below right) Flying truss formwork system.

Fig. 4 — (below) Column-mounted shoring system.⁷

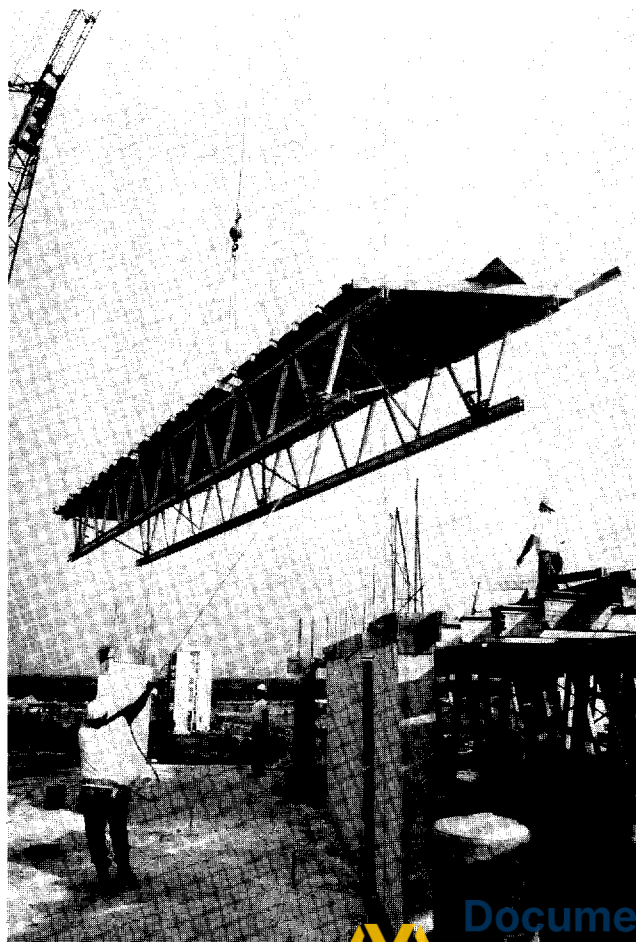
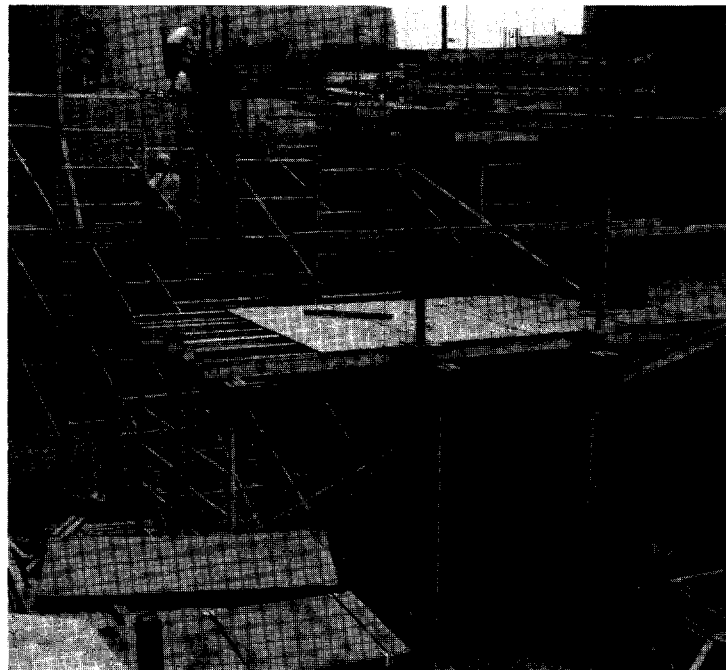
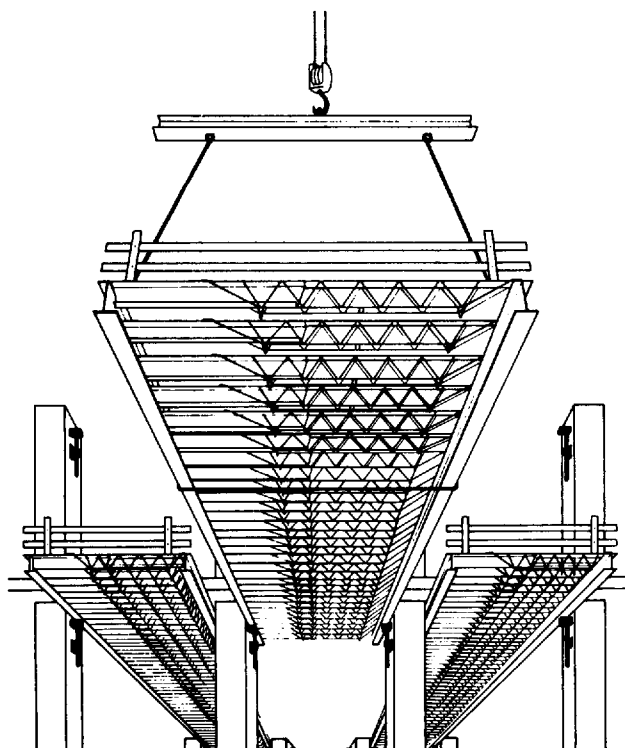


Illustration courtesy of Patent Scaffolding Co., a division of Harco Corporation.



them. The three foot modules can be formed with 30 x 30 in. domes and 6 in. ribs.

The preceding sections presented five different horizontal formwork systems and two special ones, joist and waffle slab forming systems. Two of these systems — the conventional wood system and the conventional aluminum system — are classified as hand-set systems. The remaining systems are classified as crane-set systems. Joist-form and dome forms can be handled by hand or attached to the surface deck of the flying form and flown as a unit.

Factors affecting selection of formwork systems

There are several ways to form any given concrete building. One of them will typically be the lowest cost method. Selecting the lowest cost method of formwork requires searching through a maze of formwork systems and their attributes.

The construction cost of slabs is often more than half the cost of structural framing systems, except in extremely tall buildings.⁴ Selection of the floor formwork system therefore deserves considerable attention to minimize cost.

Types of slabs

The selection of a formwork system should be made on the basis of the selected floor system that satisfies the structural loading conditions. Floor slabs in concrete buildings are classified into two basic types, based on the load distribution applied on the slab:

- Two-way slabs, in which the rectangularity ratio (slab length/width) is between 1 and 2, and the slab load is transferred to the supporting beams in two directions. Two-way slabs include flat plates, flat slabs, waffle slabs, and two-way slabs supported by drop beams.
- One-way slabs, in which the rectangularity ratio (slab length/width) is more than 2, and the slab load is transferred to the supporting beams in one direction. One-way slabs include solid slabs on beams or walls,

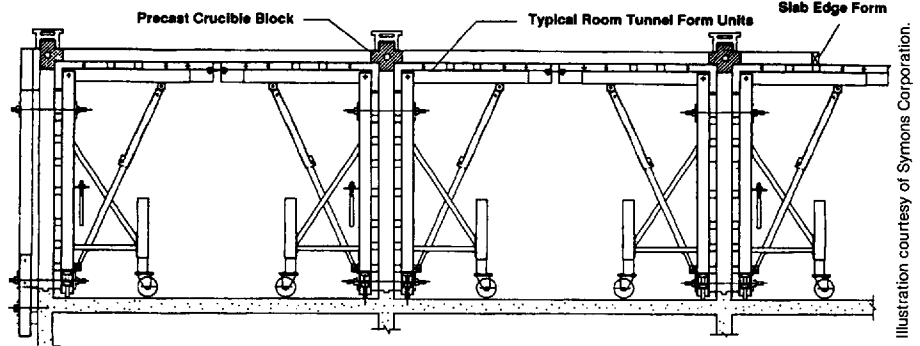


Fig. 5 — Tunnel formwork system.¹¹

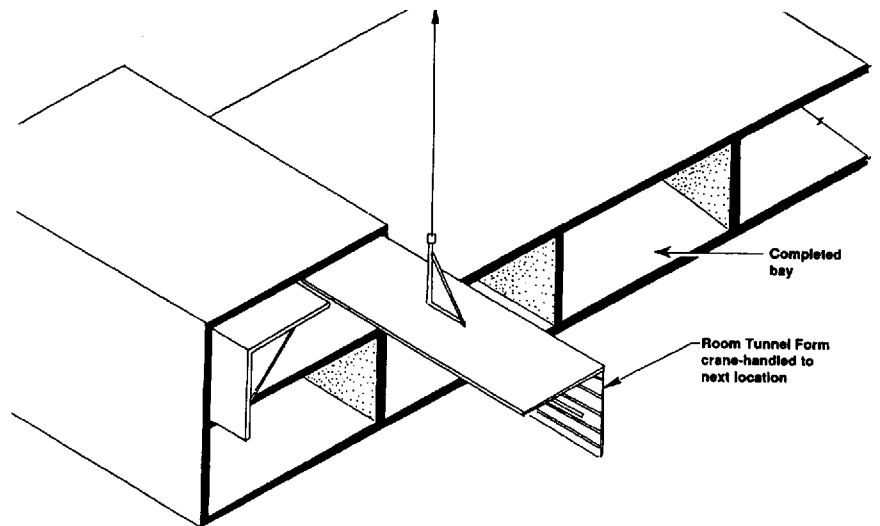


Fig. 6 — Stripping of tunnel form.¹¹

and one-way joist (ribbed) slabs supported by beams or bearing walls.

Two-way flat plate. A flat plate is defined as a structural floor system consisting of a concrete slab of constant thickness throughout, without beams or drop panels at the columns (Fig. 7a). The supporting columns for flat plates are usually equally spaced to facilitate the design and construction of such slabs. Flat plates can be constructed in minimum time because they utilize the simplest possible formwork.

Two-way flat slab. A flat slab is defined as a structural system consisting of a constant thickness concrete slab with drop panels at the columns (Fig. 7b). In earlier years, column capitals were used along with drop panels, but because of the higher form cost, column capitals are less favoured in today's construction practices.¹³

Waffle slab. Waffle slab construction (Fig. 7e) consists of rows of concrete joists at right angles with solid heads at the columns. Waffle slabs can be used for spans up to about 50 ft., and are used to obtain an attractive ceiling.

Two-way slab supported by beams. This system consists of a solid slab designed to span in two directions to either concrete beams or walls (Fig. 7g). The primary advantage of the system is the saving in reinforcing steel and slab section as a result of being able to take advantage of the two-way action. Formwork for the two-way system is complicated and usually outweighs the cost advantages associated with the saving in reinforcing steel and slab thickness.

One-way slab, beam, and girder. This system consists of a solid slab spanning to concrete beams uniformly spaced apart. Girders at

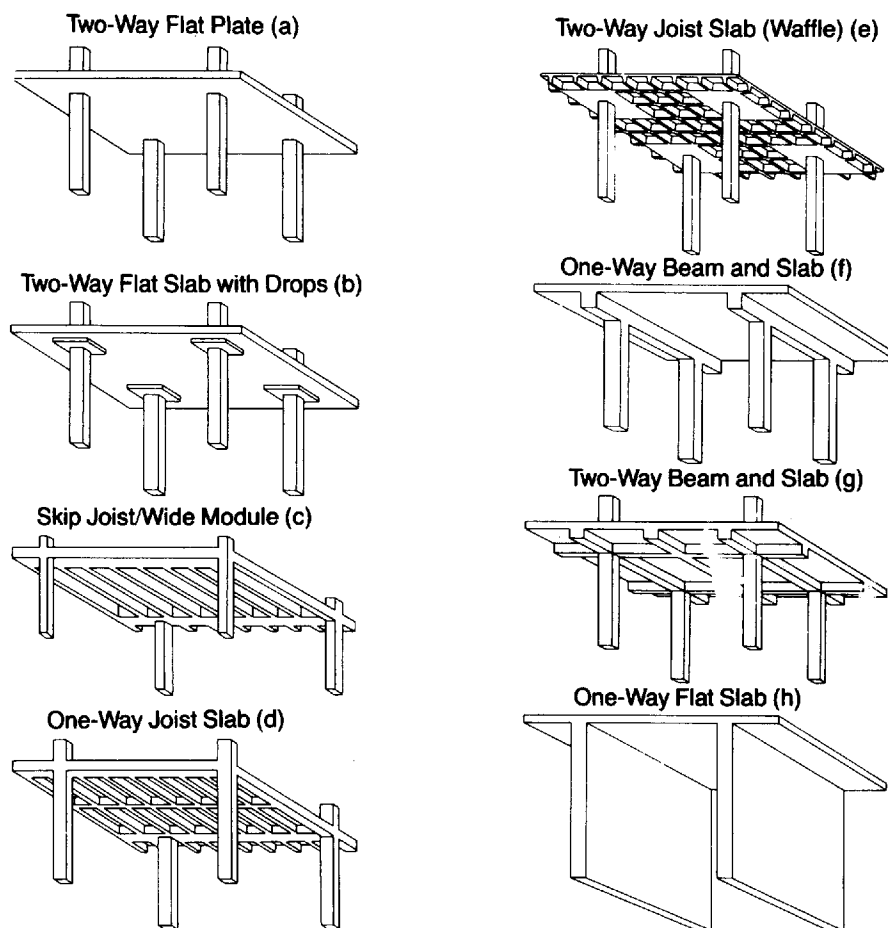


Fig. 7 — Slab systems.

right angles to the beams transfer the loads to the columns. This system generally affords the opportunity to span longer distances than two-way slabs by designing deeper beams and girders.

One-way slab supported by beams or bearing walls. This modification of the slab, beam, and girder system eliminates the secondary beams (Fig. 7h). Reinforcing steel is relatively simple, and the existence of openings is generally not a critical concern.

One-way joist (ribbed) slabs. One-way joist slabs are a monolithic combination of uniformly spaced beams or joists and a thin cast-in-place slab to form an integral unit. When the joists are parallel, this is referred to as one-way joist construction (Fig. 7d). Joists are very attractive to architectural layout and mechanical requirements.

Building design: building shape

Special buildings such as industrial buildings and power plants usually have extensive electrical and mechanical requirements that do not lend themselves to any formwork system. As a result, they should be constructed using the traditional formwork method (stick forms).

The feasibility of using a formwork system or traditional formwork methods is influenced by several design features such as variation of size, shape, and location for various structural elements (columns, walls, beams, cantilevers), existence of blockouts and openings for windows and doors, and HVAC requirements.

A building's structural layout is either uniform modular or irregular. Uniform modular design is characterized by regular spacing between columns and walls, equal story heights, and regular spacing of

cantilevers and openings. Irregular design is characterized by irregular positions of the different structural elements and broken lines or irregular curves in architectural plans.

Speed of construction

The most important advantage of using a formwork system is the speed of construction. The speed of construction affects cost because it determines the time when the building will be available for use and also influences the financing charges. In recent years, casting two floors per week in high-rise buildings has been achieved, especially in metropolitan areas.¹⁵ This fast floor cycle can only be achieved by using sophisticated formwork techniques such as flying forms, which are capable of forming one story every two days.

Area practice

In areas where the labor force is expensive and unskilled, the use of formwork systems can substantially reduce the cost. In areas where the labor force is inexpensive and skilled, a conventional formwork system is an economical alternative even if the building features lend themselves to a formwork system. As a result, preassembled formwork systems are used in some areas because of the lack of inexpensive skilled labor.

Site characteristics

The building site influences the selection of a suitable formwork system, because of site limitations and accessibility for construction operations. The feasibility of using flying forms, for instance, is influenced by site characteristics such as accessibility, existence of surrounding area restrictions, and availability of a make-up area to the site.

In open and unrestricted suburban sites, all formwork systems are viable and some other considerations should be evaluated to determine the most efficient and cost effective system. In downtown restricted sites, the only possible system may be ganged units that can be transferred from floor to floor.

Table 1 — Factors affecting the selection of horizontal formwork systems.

Formwork system			Conventional wood system		Conventional metal system		Flying truss system		Column-mounted shoring system		Tunnel form		
Influence factor													
Building design	Slab type	Slab type	All slab systems Most suited for two-way slab supported by beams or one-way slab, beam, girder				Two-way: flat plat and flat slab One-way: slab supported by beams or walls and joist slab (standard or skip-joist)				One-way slab supported by walls		
	Lateral support	Compatibility with lateral load supporting system	Compatible with all lateral load supporting systems				Generally not suitable for framed tube and tube-in-tube because of the close distance between columns characteristic of tube systems				Bearing wall		
	Building shape	Horizontal uniformity/irregularity	System can handle variations in size, shape, and location of beams and cantilevers				Beams and cantilevers should be of the same size and location or within 10% difference from floor to floor				Beams and cantilevers should be of the same size and location		
		Vertical uniformity/irregularity	System can handle variations of column/wall size and location System can handle variations in story height within one floor or from floor to floor				Column/wall should be of the same size and location or within 10% difference from floor to floor Can handle limited variation (10%) in story height				Walls should be of the same size, location, and height from floor to floor		
	Miscellaneous	High stories (> 14 ft high)	Not suitable for high stories		More suitable for high stories		Limited by truss depth (up to 20 ft)		Height independent system		Limited-height system (up to 10 ft)		
		HVAC	Can accommodate extensive HVAC		Cannot accommodate extensive HVAC		HVAC should be minimal and identical from floor to floor						
		Dimension limitations	Used for small building size (less than 100,000 sq. ft.)		Used for medium building size (100,000 to 200,000 sq. ft.)		Used for large size buildings (more than 200,000 sq. ft.)						
Job specification	Speed of construction	Floor cycle (number of floors/day)	Typically floor every 5 working days Faster cycle can be accommodated at additional cost (more stories to be shored and reshored)					Floor every 3-4 days			Floor every 1-2 days		
		Rate of placement	Generally not a major factor in horizontal concrete work; average rate between 25-30 cy/hr										
		Construction sequence	Pouring columns, then beams and slabs Slab on grade need not be in place, but cost can be reduced if slab on grade is in place					Pouring columns, then beams and slabs Slab on grade needed for form to be used in first floor		Pouring columns, then beams and slabs Slab on grade need not be in place		Pouring slabs and walls together 3 in. starter wall is necessary	
Supporting organizations	Available capital	Initial make-up cost	Average cost range from \$1 to \$3 per sq. ft. of contact area				Average cost range from \$10 to \$15 per sq. ft. of contact area				Average cost ranges from \$20 to \$50 per sq. ft. of contact area		
		Potential reuse	Up to 15 reuses		Up to 20 reuses		Minimum of 12-15 reuses should be available		Minimum of 15-20 reuses should be available		Minimum of 50 reuses should be available		
		Stripping cost	High stripping cost (approximately 1/2 of the makeup cost)					Low stripping cost (approximately 1/2 of the hand set systems)				Low stripping cost	
		Average labor productivity	12 sq. ft. per contact area		18 sq. ft. per contact area		36 sq. ft. per contact area		45 sq. ft. per contact area		50 sq. ft. per contact area		
	Hoisting equipment	Availability of crane and crane time	Can be hand-set Less expensive if crane is available		Can be hand-set Crane is necessary if made into panels		Adequate hoisting equipment must be available						
		Adjacent building, traffic, and other constructions	Generally not a factor		Generally not a factor May be a factor if system panelized		A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building						
		Adequate crane capacity	Generally not a factor		May be a factor if system panelized		Crane should have adequate carrying capacity at maximum and minimum radii						
	Home office support	Safety	Normal safety precautions are required					Special safety in dealing with crane operation.					
		Supervision Trouble shooting experience	Minimum engineering supervision		Requires skilled crew Requires moderate engineering supervision		Requires high engineering supervision					Requires high degree of engineering supervision	
		Supporting yard facility	Minimum yard is required		Requires local yard if made into panels		Requires enough supporting local or regional yard facility					System should be available nearby No yard is required	
Local conditions	Area practice		Work best in areas of high quality, low cost labor force		Work best in areas of high quality, high cost labor force		Generally work in areas of high cost, low quality labor force						
	Site characteristics	Available storage and make-up area	Require minimum storage and make-up area		Small make-up area is required if system is panelized		Site must have adequate storage and make-up area					System preassembled Minimum storage area is required.	
		Access to site	Generally not a factor for hand-set systems					Job must be accessible for large form units May not be a factor if forms are assembled on site					Job must be accessible for large preassembled systems

Total building size is

1. small - less than 100,000 sq. ft.
2. medium - between 100,000 and 200,000 sq. ft.
3. large - more than 200,000 sq. ft.

Enter the number(s) of the value(s), WHY to display rule being used, Quit to save data, <H> for Help

Fig. 8 — Input format.

Supporting organization

Most of the ganged formwork systems (flying forms, column-mounted shoring forms, and tunnel forms) require high initial investment and intensive crane involvement. The major resource requirements that should be carefully evaluated when selecting a formwork system are discussed below.

Available capital (cost)

The cost of concrete formwork is influenced by three factors:¹⁵

- Initial or make-up cost, which includes cost of transportation, materials, assembly, and erection.
- Potential reuse, which decreases the final total cost per square foot of contact area.
- Stripping cost, which also includes the cost of cleaning and repair. This item tends to remain constant for each reuse up to a certain point, at which the total cost of repairing and cleaning start rising rapidly.

In deciding to use a specific formwork system, the initial cost should be evaluated versus the available capital allocated for formwork cost. Some systems tend to have a high initial cost, but through repetitive reuse, they become economical. For example, tunnel forms have a high initial cost, but the average potential reuse (usually over 100) reduces the final cost per unit of contact area of this alternative. In the case of rented formwork systems, the period of time in which the formwork is in use has a great effect on the cost of formwork.

Hoisting equipment (cranes)

Some formwork systems require special handling techniques including good crane service. The flying truss system is a good example of crane influence on the selected system. The size of the flying modules may be limited by the crane carrying capacity and its maximum and minimum lift radii.

Supporting yard facility

The feasibility of using preassembled forms for floors or walls is largely influenced by the availability of a local or central (regional) yard facility. When a local or central yard facility is available, the

standard formwork elements can be manufactured and assembled under efficient working conditions. However, the cost of transporting form sections to the site may influence the economy of the selected system.

The SLABFORM horizontal formwork selection system

SLABFORM is a rule-based expert system, designed to help the designer/planner select the optimum horizontal formwork system. The system selects a horizontal formwork system and provides advice on a variety of issues. The system requires the user to answer questions in multiple choice format. The questions cover a variety of items, including building shape, site characteristics, and available resources. To gain the largest benefit, SLABFORM should be run before preparing the project cost estimate. The system could be used for the whole building or part of the building that has repetitive features. When the analysis is complete, SLABFORM will provide a list of formwork systems with numeric ratings reflecting the suitability of the desired system.

SLABFORM knowledge base

The basis of the success and valid knowledge included in any expert system depends upon the interaction of an expert or experts in the process of system development. In developing SLABFORM, periodical interviews were conducted with two experts in formwork selection/design. The two experts were selected by an intensive literature review, referral by others, and their years of experience. They provided the basis from which SLABFORM was developed. Short interviews with other experts were conducted to ac-

quire specific knowledge or to resolve conflict among the principal experts. Table 1 shows the effect of some of the above influence factors on the selected formwork system for concrete slabs. The information in the table represents the condensed form of the formwork selection knowledge base.¹⁷

Input of SLABFORM

During the consultation session, SLABFORM asks the user questions by displaying a list of all the possible options to the question. The user answers the question by typing the number of the desired response. Multiple answers are allowed and are achieved by typing all the desired answers separated by commas. Fig. 9 shows examples of some questions presented to the user. A user who wants to know why the system needs to know the information can type WHY, and the system will respond by displaying the rules for which it is trying to determine the validity.

Output of SLABFORM

At the end of each consultation session, the system provides the user with the optimum horizontal formwork selection. Each formwork system is followed by number from 0 to 10. A value of 10 denotes absolute suitability for the building, while 0 means absolutely wrong selection. Numbers in between represent various degrees of suitability. Any score above 6 indicates a reasonably economic system. Fig. 10 shows output from the program. The system also gives advice about a variety of issues including the selection of the shoring and reshoring system, and the type of sheathing used for the expected number of reuses.

System features

SLABFORM was developed using a commercially available expert system development shell. Knowledge is loaded into the shell directly in the form of if-then rules. SLABFORM is similar to WALLFORM, the interactive vertical formwork selection system developed by the authors.¹⁶ SLABFORM uses a backward chaining mechanism through its knowledge base to make influences.

Expert's evaluation

The fact that the construction of an expert system is an iterative process led to an early development of a prototype system. A working system prototype was developed early in the process to provide a starting point for more adjustments. This prototype system was then refined and expanded to produce decisions acceptable to the expert. The prototype system was then tested on a series of sample problems. Running the prototype system on these sample problems led to the detection of some inconsistencies in the knowledge base. These problems were corrected and more rules were added.

Once the writers were satisfied that the expert system was fully developed and performing with consistency and reliability, it was applied to some test cases. The diskette was given to a formwork designer/planner, who ran the system using information from a current concrete building. The run was so successful that he decided to use the system as a training tool for his company.

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Values based on 0 - 10 system	VALUE
Flying truss system	8
Column-mounted shoring system	7
Conventional wood system	4
Conventional metal system	4

- The total number of levels below floor being cast that must be interconnected is THREE levels of reshores plus one level of form.

- Supplier X (Formwork contractor/manufacturer) offers three standard truss heights of 4, 5, and 6 ft. truss.

The 5 ft. truss is supported every 10 ft.; the load carrying capacity of this truss is 3300 lbs./liner ft.

- Sanded B-B forming grade plywood class 1 is suggested for sheathing, the cost per square foot ranges from \$0.52 to \$0.84 (1988 prices).

Fig. 9 — Sample output.

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Selected for reader interest by the editors.

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The software for SLABFORM and WALLFORM, and the referenced technical report, are available upon request from Dr. Awad S. Hanna, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5.

Computer Aided Equipment Selection for Concrete Placing

By Sabah Alkass and Apraham Aronian

A prototype integrated computer system has been developed to assist in planning and controlling concrete placing operations. Developing the system has illustrated the complex managerial decisions that must be made during the process. The system has considerable value in assisting less experienced personnel in reaching such decisions.

Concreting operations in any construction project are major bid items, with planning and estimating accuracy being of considerable importance in winning a job and maximizing profit. Quality control and careful selection of equipment are essential in the process.

The required quality of concrete materials used is usually well defined in the specifications. However, concrete production procedures are often left unspecified; consequently the resulting concrete quality may suffer from the lack of standard production procedures.¹ This increases the risk of reworking the unsatisfactory concreting operations, thus affecting productivity and increasing costs.

Contractors generally want to minimize costs and maximize profits within the constraints of a specification. This requires prior knowledge of the cost of mixing, transporting, placing, and finishing a unit of mixed concrete in its final placing zone. The total cost combines the cost of material, labor,

and equipment. As a consequence, the equipment resources would, by implication, have already been decided. Inexperienced personnel are clearly unable to reach this decision.

To reduce the complexity of the problem, Artificial Intelligence and Expert System techniques have been applied. These are based on combining heuristic and mathematical techniques to select the equipment required for the task. The approach relies on well-founded principles requiring the amount of placed concrete to be carefully evaluated after which the appropriate equipment selections are made using rules of thumb, i.e. types of knowledge acquired from the domain experts and stored in an expert system. Data base information and algorithms for making routine calculations are also linked to the system.

There have been very few attempts to develop computer systems for concreting operations. Celik, Thorpe, and McCaffer¹ developed a prototype expert system which provides expert advice relative to concrete batching and mixing operations. Phelan, Radji, Hass, and Hendrickson² developed a computerized method for concrete placement optimization which considers both material costs and time delay penalties to minimize the total cost of placing concrete. Unfortunately, these systems failed to consider the importance of equip-

ment selection and its cost effect on concreting operations. The authors' experience in concreting operations and other areas of construction³ proved that equipment selection process plays a vital role in the project's planning, execution, and costs.

This paper describes the development of a prototype integrated expert system designed to assist the construction management team control concrete placing operations and equipment selection. Knowledge and experience possessed by planning engineers and equipment specialists has been captured and interpreted in a form suitable for manipulation by computer programs.

Expert systems

Expert systems are computer programs that incorporate human expertise to provide advice on a wide range of topics. They are developed by creating knowledge bases which contain information collected from all possible sources, mainly with the help of an expert practitioner in the domain. These systems function as consultants in the given area of knowledge and can provide explanations of reasoning. They can simulate a consultation as though the computer was the tutor and the user a pupil.^{1,4,5}

Because of their ability to combine factual knowledge with judgment, handle incomplete information,

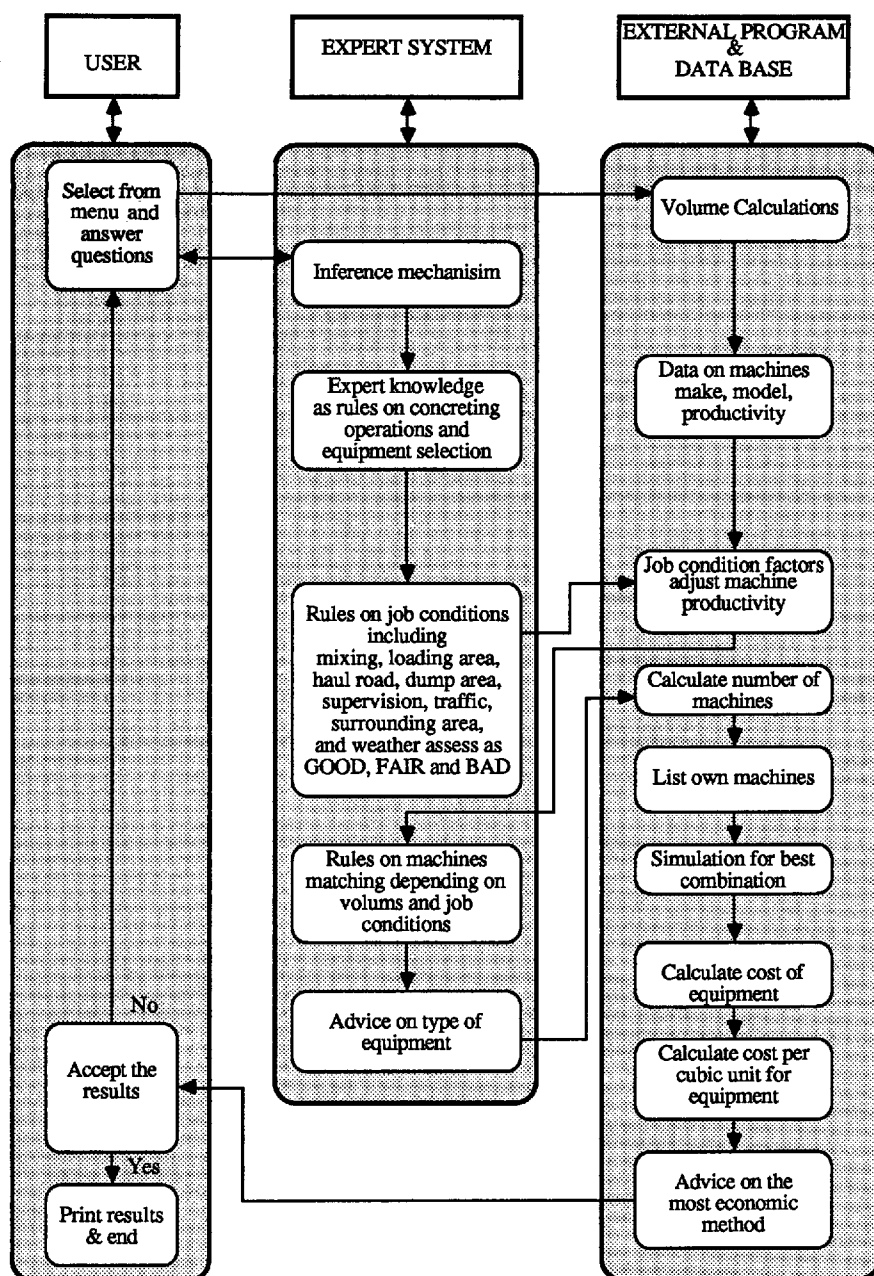


Fig. 1 — System's integration process.

tain data, and communicate with the users in a natural language like English, such systems have a special appeal to the construction profession. However, expert systems are not a total substitute for experts. They help to conserve expertise and are used to make expertise more widely, easily, and quickly available to assist the decision making process. Expert systems and their applications have been extensively described in literature.^{3,6,7}

Aims of the system

The objectives in developing the expert system were:

- To obtain a precise understanding of the methods of analysis and decision making used by those personnel involved in concreting operations on construction sites and equipment rental companies.
- To arrange the knowledge gained into a form capable of advising the inexperienced on the most appropriate methods of concreting and equipment selection for different job conditions. The potential of the system lies in using the computer to behave as the expert would.
- To link external programs to the system capable of calculating the cost of utilizing these resources in

order to arrive at the most economic combination.

Concrete placing

Concrete placing takes place between the stages of mixing and hardening. This is only possible when the concrete is still plastic and workable. During concrete placing, two operations must be carefully controlled even if the fresh concrete is of desired quality: concrete haulage and concrete consolidation.

Concrete haulage involves transporting concrete from the mixer to the placing position. Transportation of the concrete has a significant contribution to the cost of concrete operations and is essential in making a realistic cost estimate.

Many ways for transporting concrete exist, each with different characteristics. The choice is wide and difficult, and only by proper evaluation involving experience and judgement can the correct approach for a particular set of circumstances be chosen. Any evaluation of the means of transporting concrete has to consider the following factors:

- Vehicle capacity
- Vehicle output
- Site characteristics
- Weather conditions
- Operator efficiency
- Hiring costs
- Purchase and maintenance costs
- Depreciation
- Other possible uses
- Temporary haul roads

Concrete consolidation, or compaction, is the removal of entrapped air from fresh concrete. In order to achieve the required specifications and produce good concrete quality, efficient concrete consolidation equipment and workmanship must always be present during placing operations. Generally, vibrators are used in concrete consolidation and they should be applied systematically at short distance intervals in order that all areas of concrete overlap without omission.

Vibration should be continued until all fills and voids are thoroughly filled and consolidated. It is usually best to apply more vibration than less vibration for this will not drastically affect a properly proportioned mixture. However, on construction sites, the use of over