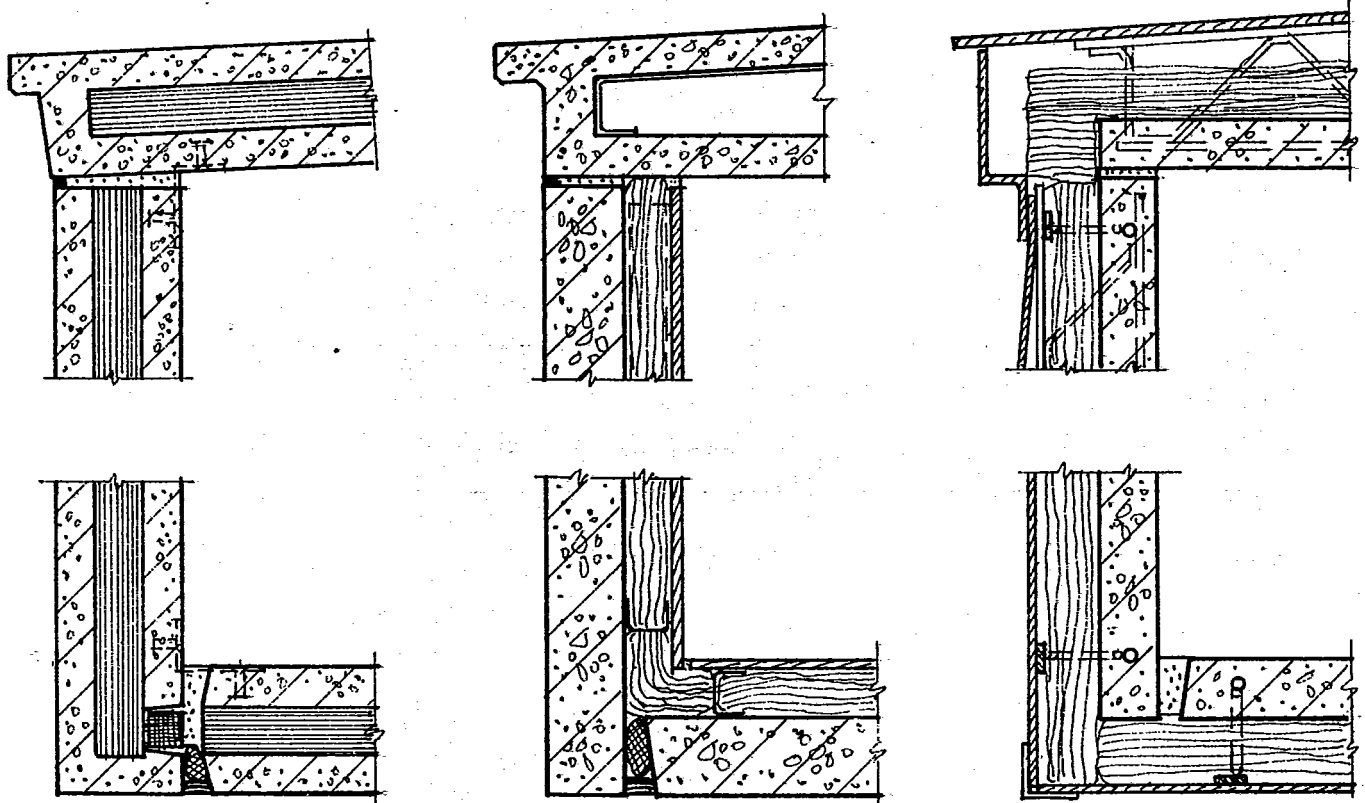


Forming Economical Concrete Buildings

Proceedings of The Third International Conference

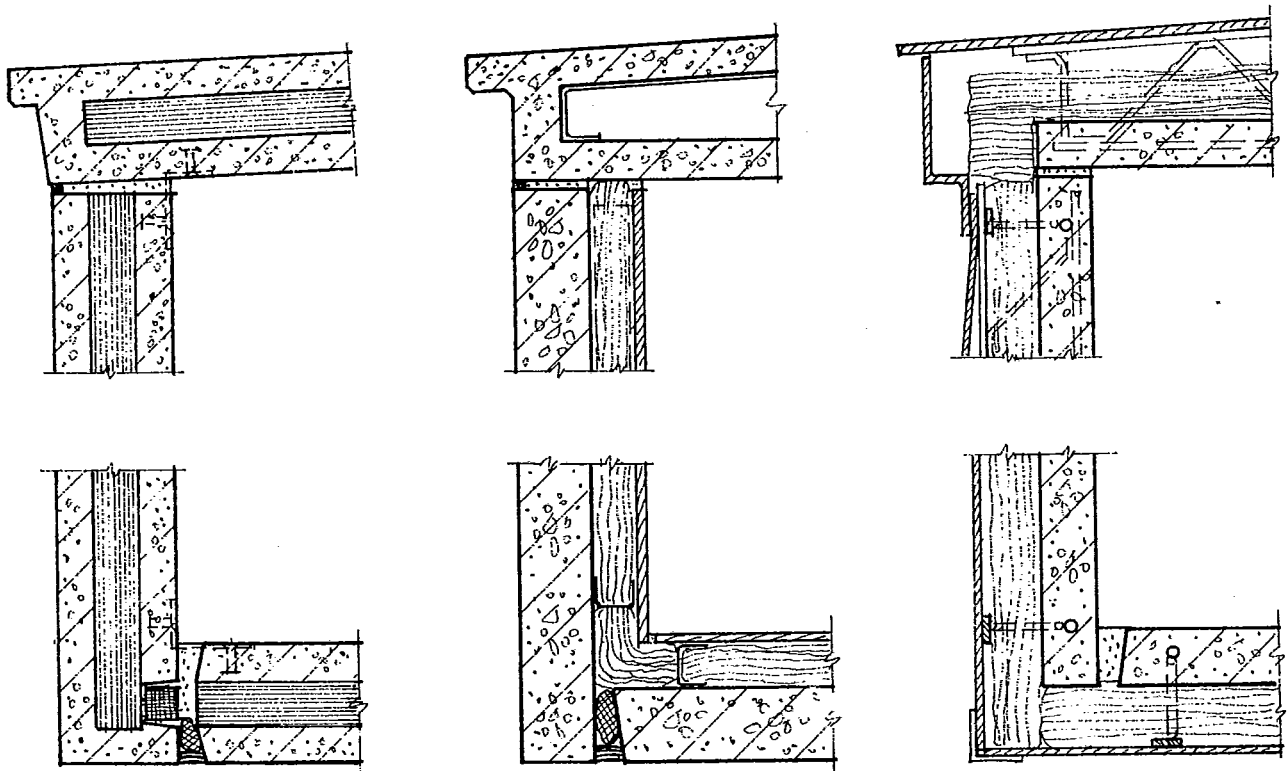


Ramon J. Cook
Editor

SP-107 **aci**
Documents
AVA Document Sharing Hub

Forming Economical Concrete Buildings

Proceedings of The Third International Conference



Ramon J. Cook
Editor

American Concrete Institute, Detroit

SP 107 
Documents
Document Sharing Hub

DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is February 1, 1989. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the July-August, 1989 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Copyright © 1988
 AMERICAN CONCRETE INSTITUTE
 P.O. Box 19150, Redford Station
 Detroit, Michigan 48219

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by any electronic or mechanical device, printed or written or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

Printed in the United States of America

Editorial production: Patricia J. Kost

LIBRARY OF CONGRESS CATALOG CARD NUMBER 88-70199

PREFACE

This volume is a collection of papers, most of which were presented at the Third International Conference on "Forming Economical Concrete Buildings" held November 19-21, 1986, at The Westin Hotel Galleria in Dallas, Texas. This conference was sponsored and planned by American Concrete Institute, Concrete Reinforcing Steel Institute, National Ready Mixed Concrete Association, and Portland Cement Association in cooperation with the following cosponsors: American Plywood Association, Architectural Record magazine, Building Design and Construction magazine, Building Economics magazine, Canadian Portland Cement Association, Cembureau (European Cement Association), Cement and Concrete Association of Australia, Cement and Concrete Association (England), Concrete Construction magazine, Engineering News-Record magazine, Instituto Colombiano de Productores de Cement (Colombia), Instituto Mexicano del Cemento y del Concreto, a.c. (Mexico).

The first of these biennial conferences took place November 8-10, 1982, at Marriott's Lincolnshire Resort, Lincolnshire, Illinois. Proceedings of that conference are available as publication SP026B from Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083. The second conference was held November 28-30, 1984 at the Drake Hotel in Chicago, Illinois. The proceedings of that conference are available from American Concrete Institute as publication SP-90, or from Portland Cement Association as publication SP036B.

The sponsors of these conferences chose the theme "Forming Economical Concrete Buildings" because formwork represents such a large segment of the cost of a concrete building. ACI, in its book Formwork for Concrete, states: "Economy is a major concern since formwork costs may range anywhere from 35 to 60 percent of the cost of the concrete structure." Formwork should be carefully considered when selecting building designs, layouts, structural member sizes, and construction methods. Substantial savings can be achieved by integrating the forming system into the total building process. All three conferences to date were organized with these thoughts in mind.

Eighteen synopses were received in response to an open call for papers of which 11 were accepted for development into papers for oral presentation or for publication in these proceedings. In addition, there were nine invited papers for a total of 20 of which 12 were reviewed in accordance with ACI policies for publication in these proceedings. Special thanks are extended to Ramon Cook of ACI Committee 347, Formwork for Concrete, and Committee 347 members who reviewed manuscripts.

The Fourth International Conference in this series is planned for December 7-9, 1988, at the New York Penta Hotel, in New York City.

William C. Panarese
Chairman
Program Planning Committee

CONFERENCE ORGANIZING COMMITTEES

Steering Committee

Richard A. Whitaker*	Portland Cement Association
Arthur J. Mullkoff	American Concrete Institute
Ramon J. Cook	ACI Committee 347, Formwork for Concrete
Jon I. Mullarky	National Ready Mixed Concrete Association
Peter Steiner	Concrete Reinforcing Steel Institute

Program Planning Committee

William C. Panarese*	Portland Cement Association
Arthur J. Mullkoff	American Concrete Institute
Ramon J. Cook	ACI Committee 347, Formwork for Concrete
Jon I. Mullarky	National Ready Mixed Concrete Association
James A. Rossberg	National Ready Mixed Concrete Association
Peter Steiner	Concrete Reinforcing Steel Institute

Arrangements and Publicity

Glen W. Simon*	Portland Cement Association
Bruce D. McIntosh	Portland Cement Association

Registration

Karen S. Gonzalez	Portland Cement Association
-------------------	-----------------------------

*Chairman

CONTENTS

PREFACE.....	iii
CONCRETE BUILDINGS — NEW FORMWORK PERSPECTIVES by W.R. Anthony.....	1
WIDE MODULE JOISTS FOR FLOOR AND ROOF DECKS by L.E. Svab and W.T. Scott.....	29
AIR FORMED CONCRETE DOME STRUCTURES by J. Zimmerman.....	41
LIFT SLAB CONSTRUCTION: ITS HISTORY, METHODOLOGY, ECONOMICS, AND APPLICATIONS by M.A. Russillo.....	59
MICHIGAN'S TALLEST CONCRETE FRAMED OFFICE BUILDING by W.R. Carr.....	69
ARCHITECTURAL CONCRETE — CONSTRUCTION REQUIREMENTS by J.M. Shilstone, Sr.....	79
CONFORMANCE AND PERFORMANCE FOR ECONOMY AND QUALITY by C.H. Murphree.....	103
PUMPING ARCHITECTURAL CONCRETE WALLS FROM THE BOTTOM UP by J. Bullock.....	121
THERMAL WALL SYSTEM by A.J. Cellucci.....	137
EVALUATING CONCRETE POTENTIAL AND PERFORMANCE by J.M. Shilstone, Jr.....	147
THE EFFECTS OF DRYING AND FORM AND SHORE REMOVAL ON FLEXURAL CRACKING IN BEAMS AND SLABS by K.C. Hover.....	169
FORMING SYSTEM FOR BUILDING SINGLE-STOREY HOUSES — A NEW CONCEPT by M. Linetsky.....	185
SI (Metric) TABLES.....	199
INDEX.....	201

SP 107-1

Concrete Buildings— New Formwork Perspectives

by W.R. Anthony

Synopsis: This text moves from a macro view of the entire building process toward a micro view of the specific details, in an effort to maximize the value of a site-cast concrete building frame.

It starts with an economic overview of the development process, including a budget analysis of a concrete framed building. A case is made for three basic principles that lead to constructability--allowing for efficiency during the construction of a site-cast concrete building from a formwork perspective.

The text focuses on both horizontal and vertical design strategies, then attempts to integrate these concepts into a total project strategy using a 10-step approach.

This paper stresses the need for teamwork. Teamwork being the key to achieving economy in the construction process and good communications among all parties facilitates the team effort.

The text is the product of a collaborative effort by the concrete construction division of The Ceko Corporation. Their findings and recommendations were organized and integrated by the author. Additional resources are noted at the end of the article.

Keywords: beams (supports); buildings; columns (supports); concrete construction; costs; economics; form removal; formwork (construction); frames; framing systems; structural design; walls

2 Anthony

Bill Anthony holds a B.S. degree in Architectural Engineering and is currently Director of Marketing for the Concrete Construction Division of The Ceco Corporation. Mr. Anthony was a contributing author to the Portland Cement Association's "Simplified Design" handbook, based on ACI 318-83.

DESIGNING A CONCRETE BUILDING FRAME: CAN LESS COST MORE?

During the value engineering process for concrete frames, the common approach--both in theory and in practice--is to search for ways to cut back on materials. In the pursuit of economy, each structural element is carefully examined to make sure that it is no heavier, wider or deeper than its load requires. Yet, for all the time and effort spent on reducing materials, total frame costs don't go down, but up.

To concentrate solely on permanent material reduction is to overlook the most important influence on concrete structural frame cost--formwork. While formwork is not even a tangible part of the finished structure, it can account for up to 50 percent of the cost of a site-cast concrete frame. It follows then, that any realistic effort to economize must integrate the construction process in its entirety: materials, plus time, labor and equipment.

Concrete frame economy begins in the design development stage. Often, two or more structural solutions will meet the design objective equally well. One may be significantly less expensive to build. To arrive at that optimal solution at the initial design stage--not later--requires a basic sense of formwork logic.

The following recommendations and practical suggestions are intended to help both designers and builders capitalize on the economic advantages of site-cast concrete.

CONCRETE BUILDINGS: AN ECONOMIC OVERVIEW

Reporting on a \$175 million project, the "Wall Street Journal" (Feb. 16, 1984), said: "If the project is completed only a month late, (the developers) will owe an additional \$3 million in construction loan interest and will lose up to \$6 million in rent."

Our focus in this discussion is on the potential construction economies that can be designed into a concrete building--savings in labor and materials. But as the example above makes clear, these potential economies are dwarfed by the cost variables relating to the initial choice of structural systems.

Concrete Formwork 3

Start-up time, construction time, finance cost and cash flow are real cost variables--just as real as the cost of materials and labor. When the designer takes the macroview by integrating all these variables, the low-cost building often is the cast-in-place concrete structure.

Start-Up Time

Concrete, reinforcing and skilled labor are locally available. Construction begins with a minimum waiting period for fabrication of materials. A cast-in-place structure can often be well under way before final plans are completed (Figure 1).

Start-To-Finish Time

With an automatic head-start over other systems, concrete pouring progresses upward while electrical, mechanical and plumbing systems, interior partitions and exterior finishing progress simultaneously on completed levels below--without waiting for the entire frame to be finished. For all but the tallest high-rise structures, no system moves faster than concrete from notice-to-proceed to final occupancy (Figure 2).

Construction Investment Costs

Concrete building materials are delivered to meet construction schedules. This spreads the cash outlay for materials into smaller increments over a known time frame. The shorter overall schedule and on-time record of concrete offer major interest and income advantages to the developer (Figure 3).

Exterior Cladding, Mechanical and Electrical Costs

The story height of a concrete building is up to 24" less per floor than other systems. This minimizes the exterior surface area to be enclosed, as well as vertical runs of mechanical and electrical systems and elevators (Figure 4).

Fireproofing/Fire Insurance Costs

Naturally fire-resistant, concrete needs no additional applied fireproofing to comply with local codes. This lowers risks for both building and occupant, and typically qualifies concrete structures for reduced insurance rates.

Marketable Space Cost

New high strength concrete and reinforcing design technologies allow longer spans with fewer, smaller columns. With more usable space, concrete buildings are highly marketable to both commercial and residential tenants (Figure 5).

4 Anthony

Structural Economy

Site-cast concrete is "monolithic." Structurally, this means that there is continuity among elements, allowing the loads to "flow" through the structure. This is accomplished because the walls, floors and columns all work together as a one-piece unit to transfer loads, without bolted, welded, pinned or grouted connections (Figure 6).

Since concrete structures are usually designed with continuous elements, the designer typically has greater flexibility in meeting a wide range of load and span requirements--doing so more economically than precast or structural steel which are typically designed as simply supported elements.

Maintenance Costs

Maintenance costs are extremely low for site-cast concrete buildings. Inherently resistant to weather, temperature and chemicals, concrete will retain its integrity and appearance indefinitely--with minimum upkeep.

HVAC Cost

High mass makes concrete a significant thermal reservoir, with the capacity to store large amounts of energy. In cold weather, floors and walls absorb and store interior heat during the day, then radiate warmth back into the conditioned space at night. Conversely, when outside temperatures are high, the same principle holds true for cooling. The inherent ability of concrete to maintain a steady interior temperature reduces peak demand on cooling equipment. This, combined with the reduced volume of concrete buildings, permits the installation of smaller, less costly HVAC equipment (Figure 7).

Long-Term Investment Attractiveness

Lower initial costs...lower life cycle ownership costs... cast-in-place concrete in the final analysis offers the most attractive long-term investment opportunity of all the alternative structural systems available.

CONCRETE FRAMES: A BUDGET ANALYSIS

Returning the focus to concrete frame costs, an analysis of typical budgets will help quantify the economic influence of design strategy. Formwork is the single largest cost component of a concrete building's structural frame. Fortunately, it is also the component that yields most readily to cost reduction strategy. As demonstrated in Figure 8, priority on formwork design can reduce total frame costs by almost 25%. This savings is not all direct (or hard) costs. Formwork efficiency has leverage effects--indirect (or soft) cost savings--which bring total concrete frame economies up to this level.

For example, formwork efficiencies accelerate the construction schedule, leading to savings in interest costs. The benefits of formwork efficiency are compounded throughout the project, from increased jobsite productivity to reduced opportunity for error. Conversely, looking for ways to economize in permanent materials alone, with little or no emphasis on formwork, can actually increase rather than decrease the total cost for the structure.

In Figure 8, Design "A" depicts a cost schedule for a hypothetical building in which the priority was permanent material economies. Permanent materials are considered to be the concrete and the reinforcement. The projected time required for construction of this project was 12 months. The total concrete structural frame cost to the owner was \$13.46/sq. ft.

In Figure 8, Design "B" depicts the same project, redesigned to accelerate the entire construction process. The emphasis shifted to constructability, rather than permanent materials savings. Constructability is a term which means simply "how easy is it to build?" The time frame has been halved to 6 months, with a resultant reduction of formwork, labor, general conditions, and especially, finance cost. Note in Design "B" that the cost of permanent materials has actually increased over Design "A." However, this has been more than offset by the impact of constructability on both hard and soft costs. The result is a 22% net reduction in costs/sq. ft. to the owner.

THREE BASIC PRINCIPLES FOR CONSTRUCTABILITY AND CONCRETE FRAME ECONOMY

Constructability, or making a structural frame faster, simpler and less costly to build (yet meeting all quality standards), can be a design objective. Constructability is a cost-justified objective as well.

Further, starting the design with constructability as an objective is more productive than modifying a design later to reduce costs.

Starting with the earliest freehand sketches, the designer can integrate constructability into a project by allowing three basic tenets of formwork logic to govern the work.

Design Repetition

Repeating the same layout from bay to bay of each floor, and from floor to floor to roof (Figure 9), permits a production line work flow and optimum labor productivity. The same equipment can be recycled quickly from one finished area to

6 Anthony

begin another floor. Conversely, constant changes in layout result in delays while plans are interpreted, equipment is modified, measurements are verified; all of which reduce jobsite labor productivity and increase total structure cost.

Dimensional Standards

The construction industry has standardized member sizes. Correspondingly, standard size forms are commonly available from suppliers like Ceco (Figure 10). Basing the design on readily-available standard form sizes is far less costly than specifying custom-built forms for the project. Unlike standard forms, the cost of non-standard forms usually is fully charged to the project for which they are developed.

Standard nominal lumber dimensions (Figure 11-A) are also important to cost control. The dimensions of site-cast structural members reflect the dimensions of material used to form it, as in Figure 11-B. Designs that depart from standard lumber dimensions require costly carpentry: sawing, piecing together, waste and time.

Dimensional Consistency

Expressing his preference for a crisp, uncluttered approach to architectural design, Mies van der Rohe said "Less is more."

As it applies to formwork cost, this concept has a much more practical meaning--consistency and simplicity yield savings, complexity increases cost, as depicted in Figure 12.

Specific examples of opportunities to simplify include:

- o maintaining constant depth of horizontal construction
- o maintaining constant spacing of beams and joists
- o maintaining constant column dimensions from floor to floor
- o maintaining constant story heights

Economies of scale may cost-justify some variations, but usually not. When work interruptions are taken into account, a trade-off may occur. The added cost of stop-and-start field work--slowdowns to interpret plans, to make and verify new measurements, to cut and piece lumber and other materials to form complex shapes--may more than offset any expected permanent material savings (Figure 13). In general, simplicity and design consistency will bring the project in at lower cost.

Repetitive depth of horizontal construction is a major cost consideration. By standardizing joist size and varying the width, not depth, of beams, most requirements can be met at lower cost because forms can be reused for all floors, including roofs. Going one step further, it is more cost-efficient to increase concrete strength or the amount of reinforcing material (to accommodate differing loads and spans) than to vary the size of the structural member.



Documents

Document Sharing Hub

Roofs are a good example of this principle. Despite the lighter load requirements typical of roofs, it is usually more cost-efficient to use the same joist sizes as those on the floors below. Changing joist depths, or beam and column sizes might achieve minor savings in materials, but it is likely that these will be more than offset by higher labor costs. Specifying a uniform depth will achieve major savings in forming costs, and hence, total building costs. Moreover, this will allow for future expansion at minimal cost. Additional levels can be built after completion, if the roof has the same structural capabilities as the floor below.

This approach does not ask the building designer to assume the role of a formwork planner, nor does it make the structural design a slave to formwork considerations. Its basic premise is merely that practical awareness of formwork costs may help the designer take advantage of less expensive structural solutions that are equally appropriate in terms of the aesthetics, quality, and function of the building. To use this pragmatic approach, the designer need only visualize the forms, visualize the field labor required to form various structural members and be aware of the direct proportion between complexity and cost.

HORIZONTAL DESIGN STRATEGY

Of all structural costs, floor framing is usually the largest component. Likewise, the majority of a structure's formwork cost is usually associated with the horizontal elements (Figure 14).

Consequently, the first priority in designing for economy is selecting the structural system that offers lowest overall cost while meeting load requirements.

Typical floor systems are shown in Figure 15. The relative total cost-intensity of these systems is a function of bay size and load condition (Figure 16).

The graphs (Figure 16) depict these shifting cost relationships for two variables: load and bay size.

Note: Beam-and-slab and wall-bearing systems are not depicted in the graphs because they are cost-effective only under special conditions.

For the design engineer who has established the bay size and load, the curves will indicate the most cost-effective floor system for those conditions. While absolute dollar-per-sq.-ft. costs will change over time, these relative values can be expected to remain fairly constant.

8 Anthony

If two or more floor systems are equally cost-effective for given conditions, then other considerations (architectural, aesthetic, electrical, plumbing, mechanical) may become the determining factors.

Horizontal Design Techniques

Once the most economical floor structural system has been selected, there are specific design techniques which help minimize overall costs.

Flat Floor/Roof Structural Systems

In general, any soffit offset or irregularity may cause a stop-and-start disruption of labor, requiring additional cutting and waste of materials.

Depressions for terazzo or tile (Figure 17) can be made at lower cost by varying the top slab surface only, rather than forming offsets in the bottom of the slab to economize on materials.

When drop panels at columns are used a 16'6" minimum spacing between drop panels will allow the use of standard 16' lumber without cutting (Figure 18). Dimensional consistency of drop panels in both plan and section reduces complexity and cost. Drop dimensions should consider nominal lumber dimensions as well.

Joist Floor/Roof Structural Systems

For maximum economy, spacing between joists should be consistent and based on standard form dimensions as illustrated in Figure 19. (Reference The Ceko Concrete Construction catalog for the variety of standard forms available.)

A consistent soffit elevation, with the depth of beam equal to the depth of the joist, is extremely cost-effective, because the bottom of the entire floor is on one horizontal plane (Figure 19). Added benefits of uniform soffit elevation are: reduced installation cost for HVAC, plumbing, electrical, interior partitioning and ceiling work.

Beam and Slab Floor/Roof Structural Systems

Standardization and repetition are of particular importance when using this relatively expensive system. Consistency in depth is the first priority; wide, flat beams are more economical to form than narrow deep beams. Figure 20 shows a system that may meet the same design objective as deep beams, but at lower cost.

If deep beams are necessary (Figure 21), they should be designed to nominal lumber dimensions. Width consistency ranks next in cost impact. The new skip-joist/wide module systems are an example of standardization and repetition for beam and slab construction. Rake-sided beams accelerate the process of stripping forms significantly.

Beam/Column Intersections

The intersections of beams and columns require consideration of both horizontal and vertical elements simultaneously. When the widths of beams and columns are the same (Figure 22-A), maximum cost efficiency is attained because beam framing can proceed along a continuous line. When beams are wider than columns, beam bottom forms must be notched to fit around column tops (Figure 22-B). Wide columns with narrow beams are by far the most expensive intersections for form: beam forms must be widened to column width at each intersection (Figure 22-C).

Beam Haunches

Beam haunches are expensive to form. Lower cost alternative designs (utilizing post-tensioning, for example) can usually eliminate the need for haunches. But if beam haunches are required, dimensional standardization is important. Further, standardizing beam haunches does not mean making the overall haunch + column + haunch dimension constant. As in Figure 23, standardizing dimensions "x," "y" and "z" allows changes in column width (if necessary) without requiring new forms to be built.

Spandrel Beams

Again, flat beams (same depth as floor construction) are less costly than deep beams. The deeper and narrower, the more costly to build. In addition, deep spandrel beams may limit the use of cost-effective flying form systems.

Forming a column supporting a deep, narrow spandrel (Figure 24-C) can cost twice as much as forming a column supporting a wider, flat beam. The reason is that the column collar (section above the construction joint) can require as many man-hours to form as the remainder of the column below the joint. Figure 24-A shows a far more economical solution.

If deep beams are required for tube or moment frame design, beam width equal to column width eliminates very costly beam/column intersections. Secondly, making the beam upturn (or partially so) reduces cost, as parapet walls (designed as beams) are less costly than deep beams to form (Figure 24-B).

10 Anthony

VERTICAL DESIGN STRATEGY

Vertical structural costs in concrete buildings--walls, columns, cores--are typically less than the horizontal. Only in the tallest highrises does the vertical component for gravity and lateral forces exceed the cost of the floor framing system.

Vertical costs are highly sensitive to design complexity and, conversely, to design simplicity and repetition. Elaborate designs can increase labor costs significantly. A design that incorporates practical construction techniques can be far less expensive to build, but no less satisfactory from all other structural and functional aspects.

Walls

Walls present an excellent opportunity for combining multiple structural functions into a single element. For example, a fire enclosure for stairs or elevator shafts, load bearing columns for vertical support, and horizontal bracing for lateral loads can all be incorporated into the same wall. As in Figures 25 and 26, for example, eliminating redundant structural elements also eliminates most other associated costs. Further, the structural necessity for concrete walls should be examined. In some cases lighter wall construction, drywall, for example, may be the most efficient.

Core Areas

Core areas for elevators and stairs are notoriously cost-intensive if forwork economies are neglected. In extreme cases, the core alone may require more labor than the rest of the floor, on a per-foot basis. Formwork economy here is achieved through a simplification strategy: eliminate as much complexity from the core configuration as possible.

The core will cost less to build, if the design follows the principles listed below and illustrated in Figure 27:

- o The shape is symmetrical, rectilinear, without acute angles.
- o The number of floor openings is minimized.
- o Floor and wall openings are constant in size and location within the core.
- o The core framing pattern for walls and floors is repeated on as many floors as possible.

Columns

The option to use modern, highly productive floor forming systems, such as flying forms or panelization, may be ruled out by certain column designs. Thus, column strategy has a serious impact not only on column cost, but on all formwork efficiency

and cost. Four aspects of column design are particularly important to high productivity:

- o Column sizes--The fewer changes in column size, the lower the column formwork cost. To accommodate an increase in load, increasing concrete strength and/or reinforcement is preferable to increasing column size (Figure 28). If column size change is mandatory, increasing one dimension at a time is most efficient for handset systems. For a gang system, changing both dimensions is most cost-effective.
- o Column orientation--Columns that depart from the established orientation cause major formwork disruptions at their intersections with the horizontal framing. Figure 29 is an example of a cost-intensive condition.
- o Column layout--A uniform, symmetrical column pattern facilitates the use of high productivity systems such as gang or flying forms for the floor structural system. Scattered and irregular positioning (Figure 30-B) may eliminate the possibility of using these cost effective systems. Even with conventional hand-set forming systems, a uniform column layout (Figure 30-A) accelerates construction measurably.
- o Column/slab intersections--Column capitals (Figure 31-C), especially if tapered, require additional labor and materials. The best approach is to avoid them altogether by increasing reinforcement (shearheads) within the floor slab (Figure 31-A).

If this is not feasible, rectangular drop panels (Figure 31-B) with drops equivalent to lumber dimensions located above columns serve the same structural purpose as capitals, but at far lower total costs.

VERTICAL DESIGN TECHNIQUES

Wall Thickness

Tradeoffs must be evaluated when designing wall thickness. Reasons to maintain constant wall thickness include repetitive use of standard forms, tie lengths and hardware. Reasons to change wall thickness include accumulating load. When wall thicknesses are changed, incremental steps of 2" or 4" are most efficient. Further, steps should be designed only on the wall face that intersects the horizontal framing (Figure 32). It is more efficient to step-in formwork toward an opening or building edge than to step formwork away from these conditions.

12 Anthony

Wall Corners, Intersections and Offsets

Compare diagrams 33-A, B, C, D and 33-E. Assume each represents the same lineal wall footage to be formed. There is a direct proportion between the number of changes in formwork direction (or plane) and cost. 33-A is the least expensive; 33-E the most costly.

Wall Brickledges

Following a grade contour closely with many small steps (Figure 34-B) is more costly than using fewer, larger steps (Figure 34-A). Large steps may use more bricks, but their added cost will be more than offset by formwork savings.

Brickledge thickness and height should be designed to standard lumber dimensions, approximating the dimensions of masonry to be applied.

Wall Openings

Each wall opening adds cost and time to form. Fewer, larger openings are more cost-effective than numerous smaller openings. Sizes and locations should be uniform for maximum re-use of formwork.

Wall Footings

Maintaining a constant elevation for the top of wall footings permits the use of efficient gang forming. As in Figure 35, when footing steps are required, fewer, larger steps, designed to standard lumber sizes, are more economical than many small steps.

Pilasters

The special forming required for pilasters sometimes can be eliminated by merging their function with that of the wall. By adding reinforcement, pilaster column loads can be transferred into the wall, to create a wall column or transfer beam action, as in Figure 36-A.

However, if pilasters are unavoidable, standardizing their dimensions and spacing them uniformly facilitate production-line forming. Further, a rake-sided pilaster configuration accelerates form removal (Figure 36-B).

DESIGNING WITH THE TOTAL BUILDING IN MIND

To enhance construction productivity and economy, horizontal and vertical elements can be isolated as separate design priorities. But viewing the building frame as a total project may reveal many additional opportunities to streamline the construction process, accelerate production and reduce costs.

Modular Dimensions

Virtually all construction materials, not just formwork but glass, HVAC, interior finishing materials and masonry as well, are sized in multiples of a nominal 4 inches. Concrete block and brick are typical examples, as in Figure 37. Consequently, designing according to this base module inevitably means less cutting, piecing and waste material.

Story Height

The capacity of temporary shoring decreases exponentially as the distance between levels increases. Minimizing story height permits use of fewer pieces of shoring material and less labor to erect and dismantle (Figure 38).

If spacing between floors is constant, the same vertical shoring materials can be recycled from one level to the next. If spacing varies, additional shoring must be procured and adjusted to fit. Likewise, all wall and column forms must be adjusted for variations in story spacing.

Form Removal Specifications

Typically, a building endures the greatest loads it will ever carry during construction, when fresh concrete elements have not fully cured and reached their design strength. Consequently, timing and removal of temporary shoring is a critical issue. For reasons so complex as to be beyond the scope of this manual, the designer's specifications for form and shoring removal can have a very significant impact on the speed of construction, shoring requirements, and as a result, cost. In the worst-case (Figure 39), the extreme-cost condition known as backshoring may be caused inadvertently by mis-timing form removal.

Where pour-strips are used (time-delayed pours to allow for shrinkage in long or post-tensioned structures) the backshoring condition may be avoided by designing the slabs adjacent to the pour strips as cantilevers. The pour-strip is designed as simple span, as in Figure 40.

In general, dual specifications facilitate the construction process: time specification for stripping vertical elements (e.g.: 12 hours after pouring) and a strength specification for stripping horizontal elements (e.g.: 75% of design strength) (See ACI 301, 4.5). This approach provides flexibility to the builder, without diminishing design control.

14 Anthony

Level Floor Soffits

Any drop below the soffit elevation of a framing system, whether for a deep beam (Figure 41) or a drop panel in a flat slab, is a discontinuity of the basic formwork framing. It interrupts production as crews stop one basic formwork framing system at that point, and piece-and-fit to start and finish another.

Permanent Slopes for Drainage

Four methods are available to design sloped surfaces (typically for drainage).

- a. Top-surface slope--Much preferred due to its considerably lower cost, this method maintains a constant soffit elevation and consequently, is faster to form. It is achieved either by varying slab thickness or with fills. This slope method and method (b) below may require a higher-quality roof membrane than other roof designs. But even with its added cost, the total cost of these methods is much less than methods (c) and (d) below.
- b. One-way slope--top and bottom surfaces (Figure 42)--To reduce deadload and save permanent materials, bottoms of slabs may be sloped to parallel the top. This is more costly than method (a). Positioning the deck at varying elevations is labor-intensive. (Beams should also be sloped to parallel the slab, to avoid variable beam depth.)
- c. Two-way slope--top and bottom surfaces (Figure 43)--This design is an extreme-cost option and almost always can be avoided. With ridges and valleys running in two directions, two-way sloping impedes formwork productivity, with stop-start disruption at each change of slope direction.
- d. Warps (Figure 44)--Of all slope designs, warps are the most extreme impediment to formwork productivity. Forming the curved surfaces requires intricate expensive carpentry and precision installation. If at all possible, alternative designs should be considered instead.

Camber To Offset Floor Deflection

Typically, cambered slabs are not structural necessities; sufficient stiffness can be designed into floor framing systems to keep deflection within tolerances. This also avoids forming costs associated with camber. If camber is a design imperative, it may be specified much like the sloped surfaces previously discussed: as one-way, two-way, or warped. Again like slopes, costs are progressively higher as complexity increases, with warps at the extreme.

Construction Joint Location

A concrete structure normally is built in progressive stages (Figure 45). However, to facilitate high-production recycling of equipment and manpower, some latitude in the precise location of construction joints (Figure 46) is desirable. The permissible locations for construction joints should be indicated on the construction drawings, to save time on the job and help ensure a quality structure. The contractor may then select the most efficient sequencing for the construction method to be used. The designer should approve all construction joint locations prior to commencement of the work. Once established, these locations should be communicated to all parties involved in formwork, concrete and reinforcement.

Floor Penetrations

Penetrations for electrical and plumbing require careful planning. Pipe sleeves, electrical boxes and other attachments to forms (Figure 47) can impede stripping of formwork. Double sleeving for block-outs (figure 48) speeds construction, especially for flying forms. Piping and conduit that turn up from the slab into a partition wall (Figure 49) are less expensive than those which turn downward, because a penetration of formwork is thus avoided.

Concrete Finish

The more rigid the specification for concrete finish, the higher its production cost, as in Figure 50. To achieve economy, the lowest acceptable level of quality should be specified. As-cast architectural concrete (ACI 347-78, Chapter 5) is the most expensive to form. When an exposed concrete finish is being considered, its cost should be weighted against surfacing alternatives ranging from sandblasting or spackling and painting to brick, ceiling tile, wall fabric or marble. This comparison may show exposed or architectural concrete to be cost-acceptable.

THE LOW-COST ANSWER: A 10-STEP APPROACH

There are endless ways to design a site-cast concrete building. Since few designers are accorded the luxury of unlimited time, an acceptable solution must often be found under severe time constraints.

Getting started--when the paper is blank--is the most difficult stage. And, at this point, it is the designer's challenge to reconcile all structural, economic, aesthetic and functional considerations.

16 Anthony

Value Engineering is a practical, 10-step process that helps integrate all these considerations, particularly the economic, right from the start:

1. Envision the structure as a whole.
2. With freehand sketches, compare all likely structural alternatives.
3. Make rough sketches of typical bays across the building.
4. Establish uniform column locations, with orientation and size constant where possible. Consult the "CRSI Design Handbook" or other design aids to establish preliminary sizes.
5. Evaluate the sketches and make rough cost comparisons. Consider consulting a Ceco office about economic variables relating to formwork, which in turn may influence the basic structural system. Ceco will assist in developing preliminary unit costs, even to the extent of providing a total per-square-foot estimate for the entire building frame.
6. Select the framing scheme which best seems to balance structural and aesthetic objectives with economic constraints.
7. Distribute prints of the selected framing scheme to all design and building team members to solicit suggestions that may reduce future changes.
8. Refine the design, placing emphasis on aspects with the greatest economic impact on structural frame cost.
9. Visualize the construction process and the resultant impact on cost.
10. Establish specifications that minimize construction cost and time by including items such as early stripping time and acceptable finish tolerance.

TEAMWORK: THE KEY TO CONSTRUCTION ECONOMY

Construction Consulting Services

Early in the design stage, communication between project designers, builders and formwork subcontractors is one of the best assurances of ultimate constructability, economy, and construction quality. Without question, it is in the owner/client's interest that these members of the building team consult each other to contribute suggestions and solutions derived from experience on comparable past projects.

Formwork subcontractors can contribute to formwork economy by consulting with all members of the design and building team during the planning stages. Representatives offer technical expertise, a valuable resource available at all times to designers and builders. As an experienced consultant, the Ceco representative can help analyze structural layout and suggest opportunities for greater construction efficiency. In most cases, a review of preliminary sketches or schematics is sufficient to make rough cost estimates and discuss the

variables related to building design, formwork economics, and the construction process.

Additional Resources

For more information on design concepts and standard detailing practices for reinforced concrete structures, the design engineer may wish to consult the following professional associations and organizations:

Concrete Reinforcing Steel Institute (CRSI)
933 N. Plum Grove Road
Schaumburg, IL 60195
(312) 490-1700

American Concrete Institute (ACI)
P.O. Box 4754, Redford Station
Detroit, MI 48219
(313) 532-2600

Portland Cement Association (PCA)
5420 Old Orchard Road
Skokie, IL 60077-4321
(312) 966-6200

Post-Tensioning Institute (PTI)
301 West Osborn, Suite 3500
Phoenix, AZ 85013
(602) 265-9158

Specific publications are available on the subject and are recommended for the reference libraries of design offices:

ACI 347 Recommended Practice for Concrete Formwork
ACI 318 Building Code Requirements for Reinforced Concrete with Commentary
ACI SP4 Formwork for Concrete
ACI 301 Specifications for Structural Concrete for Buildings
CRSI The Concrete Formwork Digest
CRSI Design Handbook
CRSI Manual of Standard Practice--Monolithic Reinforced Concrete
PCA Concrete Floor & Roof Systems Material & Cost Estimating Guide (PA136.03B)
PCA Economics of Long-Span Concrete Slab Systems for Office Buildings--A Survey (SP024.01B)
PCA Simplified Design - Reinforced Concrete Building of Moderate Size and Height (EB104.01D)
PCA Notes on ACI 318 (FB070.04D)
PTI Post-Tensioning Manual

18 Anthony

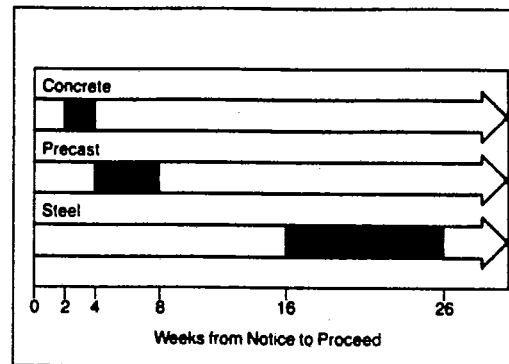


Fig. 1--Start-up time

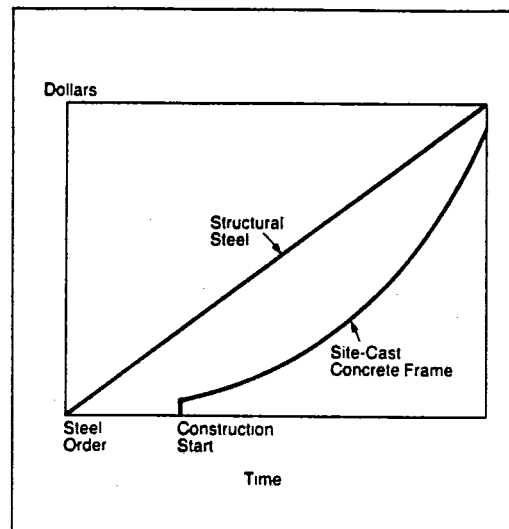


Fig. 3--Cash flow comparison

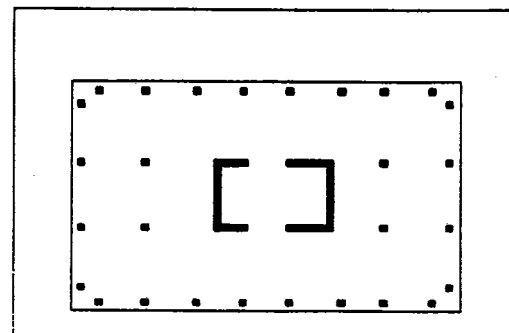
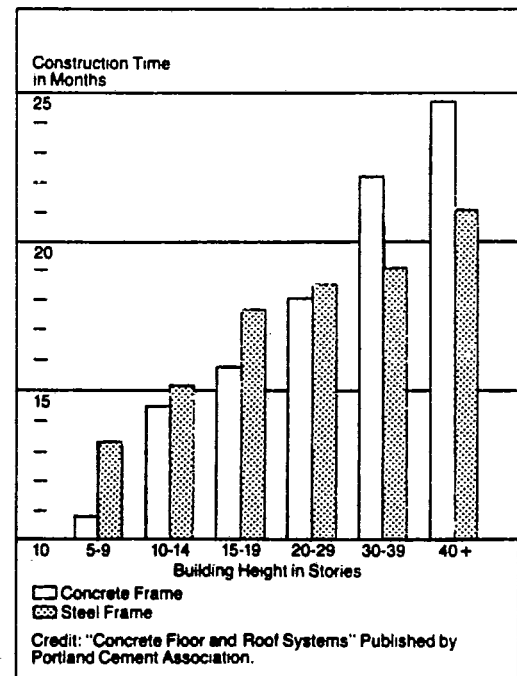
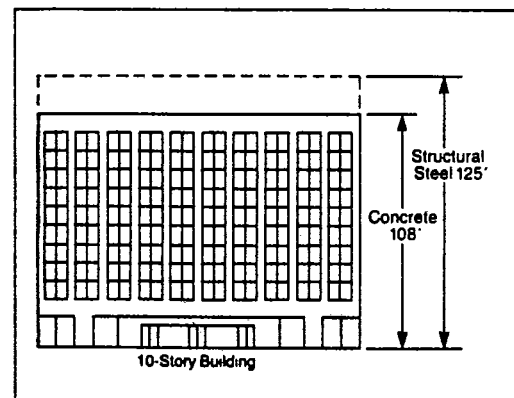


Fig. 5--Marketable space

Fig. 2--Start-to-finish time
(for office buildings)Fig. 4--Building volume of
concrete versus steel

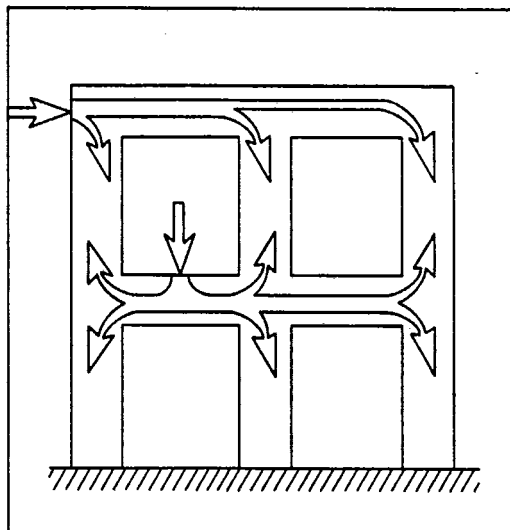


Fig. 6--Structural economy

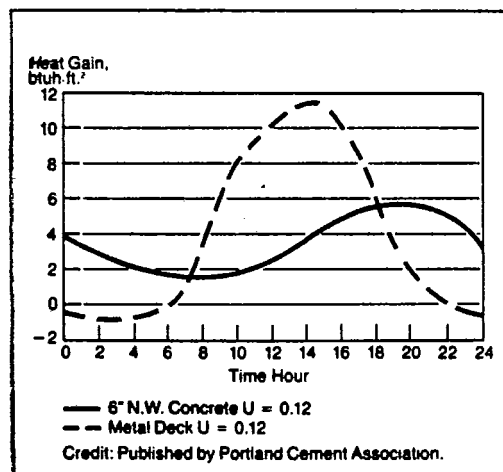


Fig. 7--Thermal reservoir comparison: concrete versus steel

(1985 Dollars)	DESIGN A	DESIGN B	PERCENT INCREASE (DECREASE)
FORMWORK Forming equipment and labor for installation and removal	\$ 5.25 39%	\$ 3.50 33%	(33%)
CONCRETE Permanent material and labor for placement and finishing	\$ 2.85 21%	\$ 3.00 29%	5%
REINFORCEMENT Materials, accessories and labor for installation	\$ 2.25 17%	\$ 2.50 24%	11%
GENERAL CONDITIONS Includes: performance bonds, insurance, utilities, site administration and material handling (cranes)	\$ 2.00 15%	\$ 1.00 10%	(50%)
SUB TOTAL—Direct (Hard) cost	\$12.35 92%	\$10.00 96%	(19%)
INTEREST Computed on straight line cash flow at 18% annual percentage rate (APR)	\$ 1.11 8%	\$ 0.45 4%	(59%)
TOTAL FRAME COST (\$/sq ft)	\$13.46 100%	\$10.45 100%	(22%)

Fig. 8--Owner's concrete structural frame cost per square ft. (These costs, in 1985 dollars are intended to be realistic, but may not reflect actual conditions in every region. The actual dollar values are not important. It is the principles involved and the relative values which are significant. These will remain constant.)

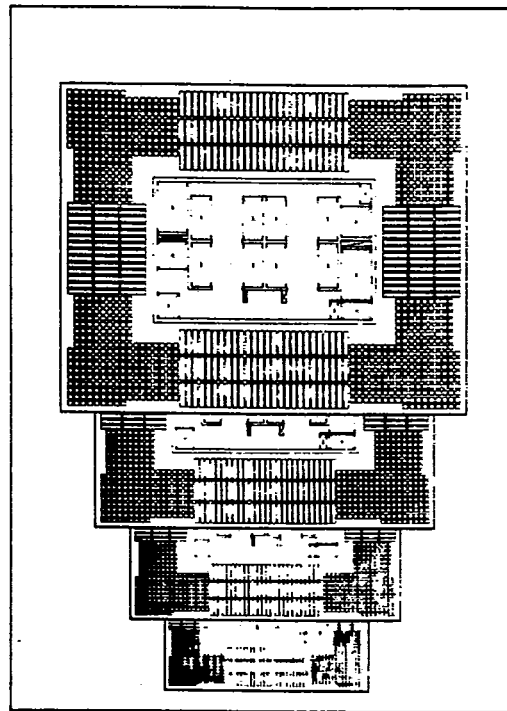


Fig. 9--Repetition

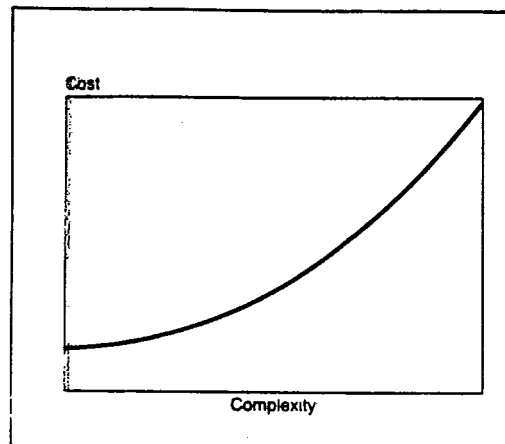


Fig. 12--Cost of complexity

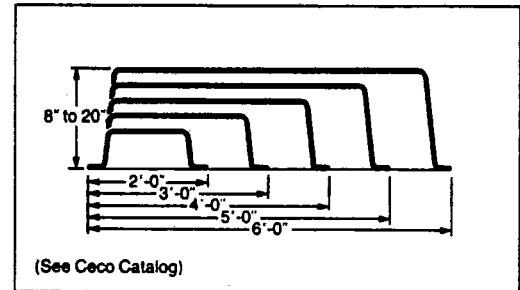


Fig. 10--Modules available

STANDARD NOMINAL LUMBER DIMENSIONS			
Nominal Size	Actual Size	Add for Plyform	Total Drop
2X	1 1/2"	3/4"	2 1/4"
4X	3 1/2"	3/4"	4 1/4"
6X	5 1/2"	3/4"	6 1/4"
8X	7 1/4"	3/4"	8"

11A

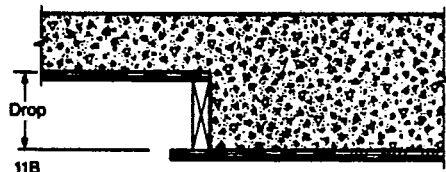


Fig. 11--Designing to nominal lumber dimensions

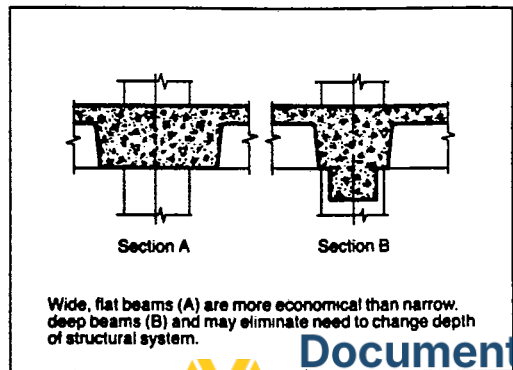


Fig. 13--Work interruptions

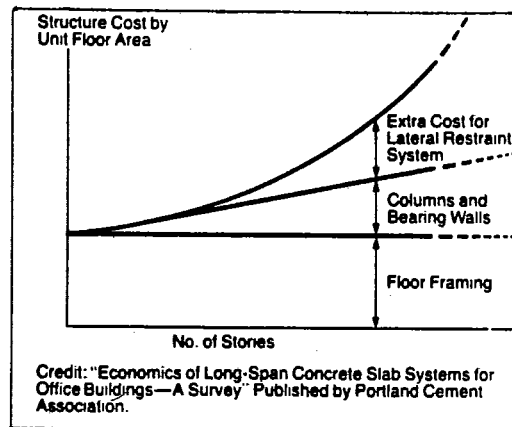


Fig. 14--Structural cost relationship of tall buildings

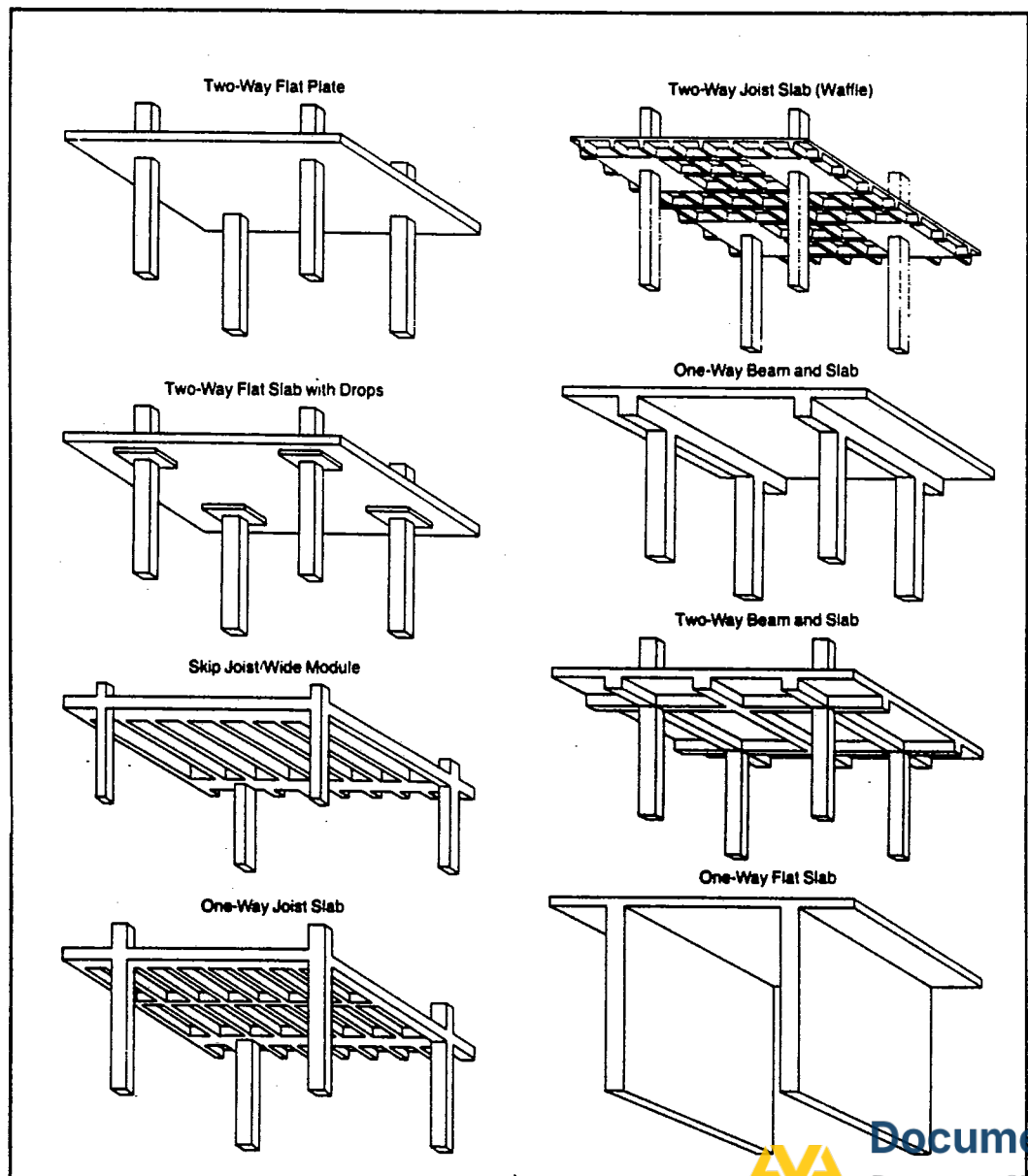


Fig. 15--Horizontal systems

22 Anthony

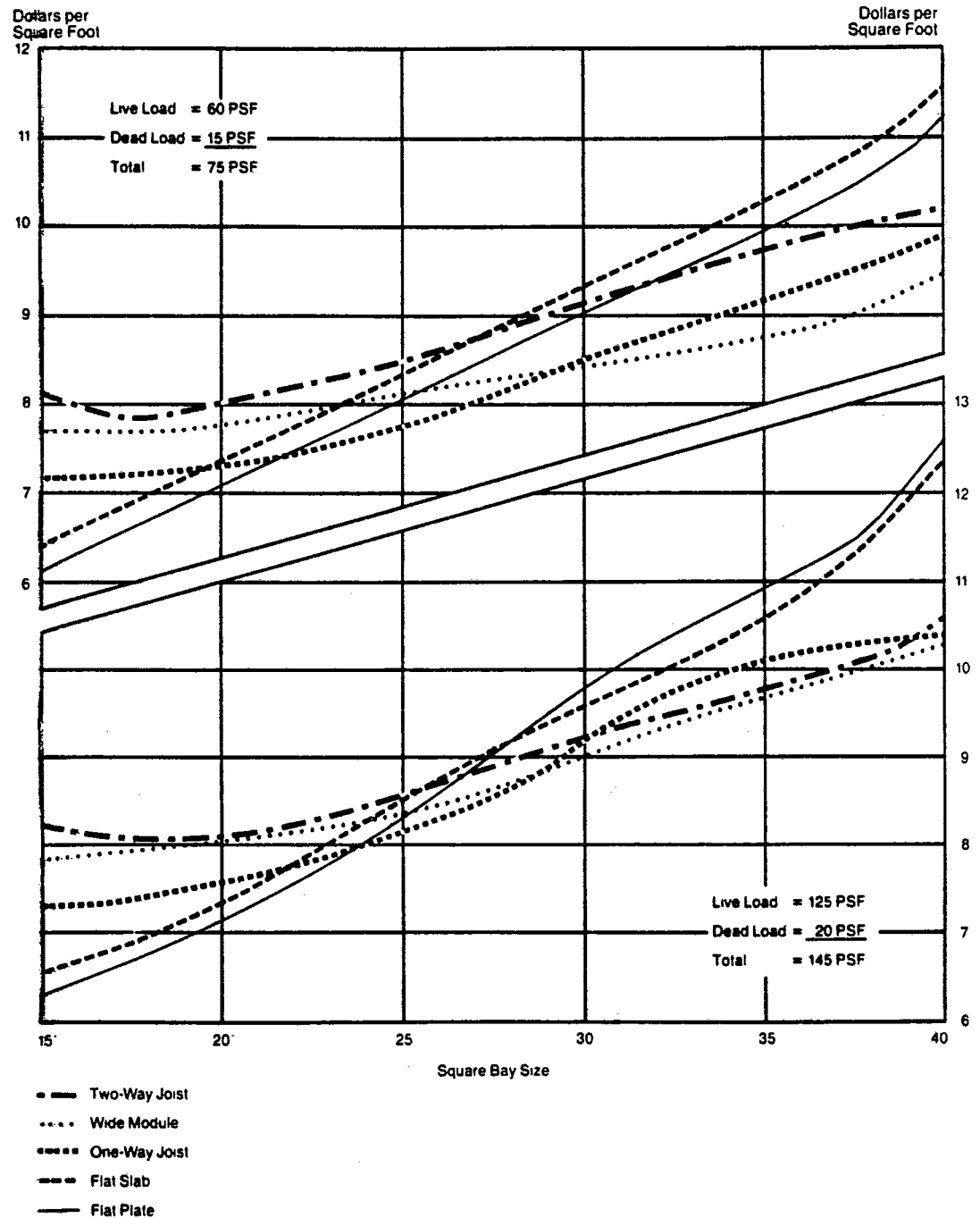


Fig. 16--Cost versus bay size and load

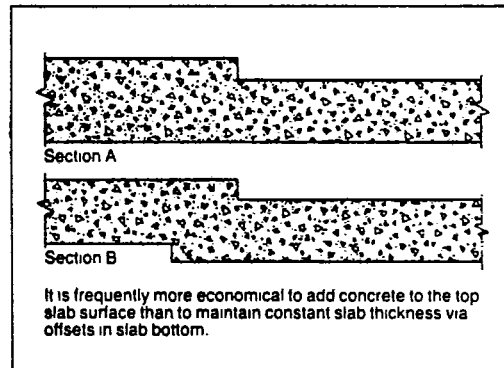


Fig. 17--Depressions

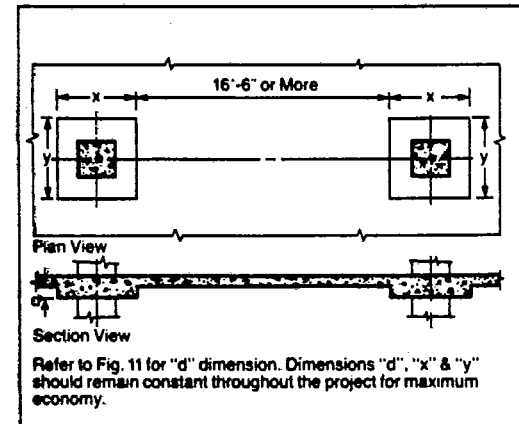


Fig. 18--Flat slab with drops

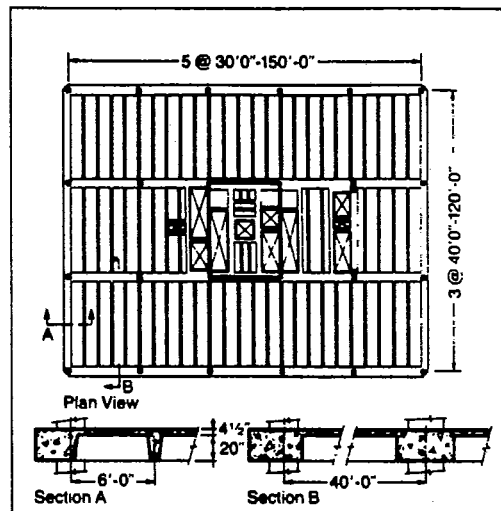


Fig. 19--Joist system

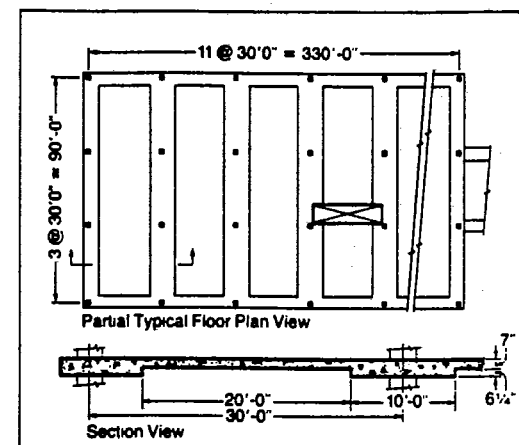


Fig. 20--Beam and slab system

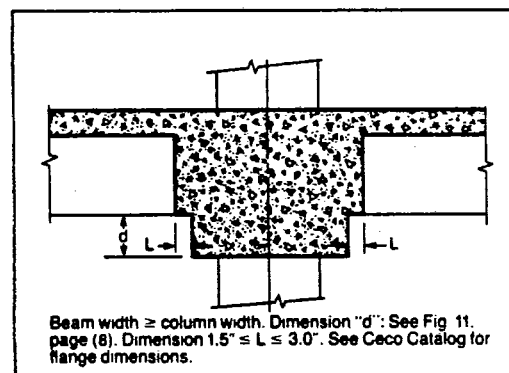


Fig. 21--Deep beam

24 Anthony

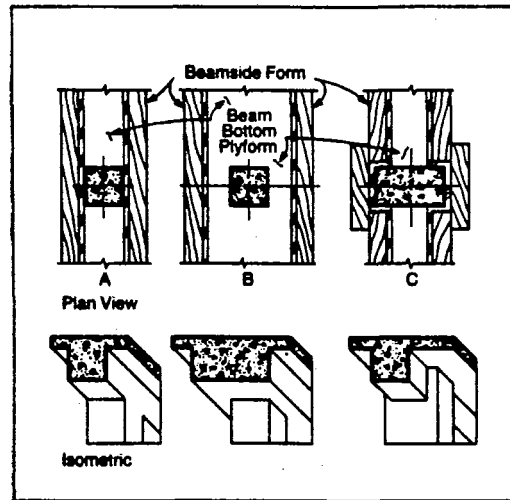


Fig. 22--Beam/column intersections

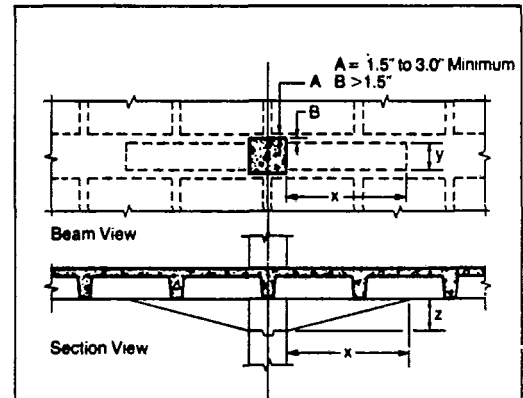


Fig. 23--Beam haunches

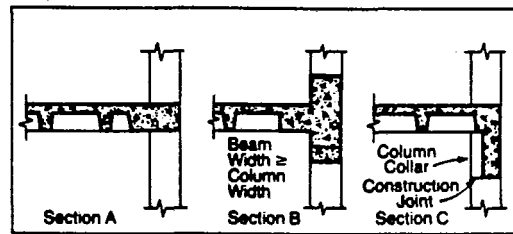


Fig. 24--Spandrel beams

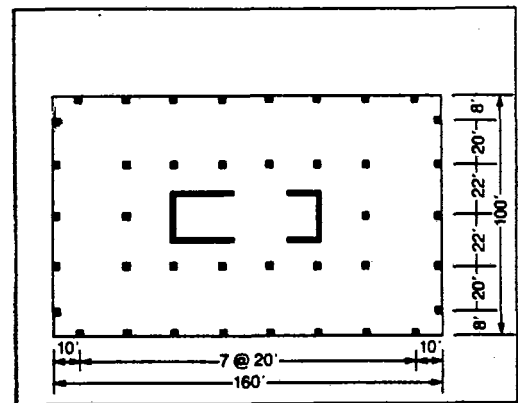


Fig. 25--Plan before structural functions were combined:
14 interior columns

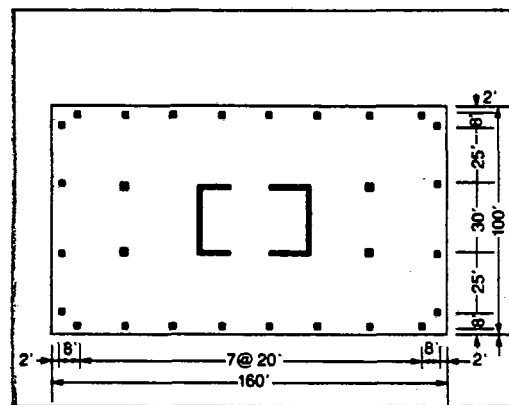


Fig. 26--Plan after redundant structural elements were combined:
4 interior columns

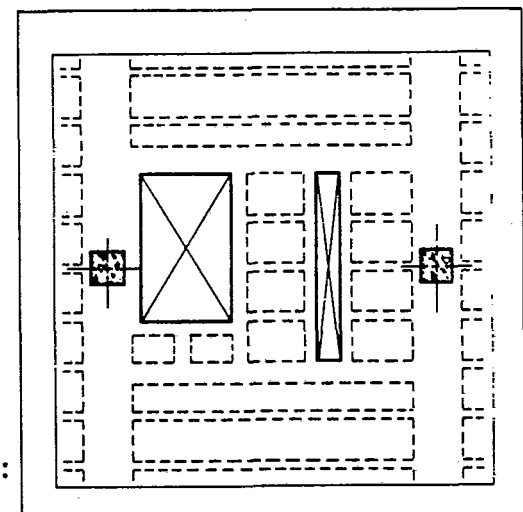


Fig. 27--Core areas

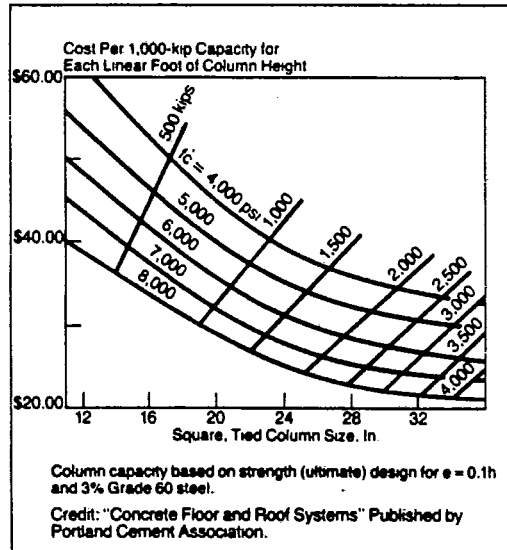


Fig. 28--Average cost versus column sizes

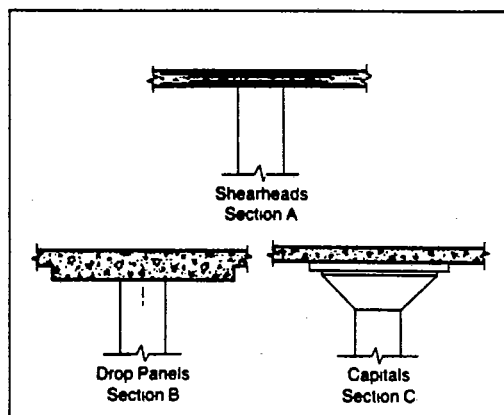


Fig. 31--Column/slab intersections

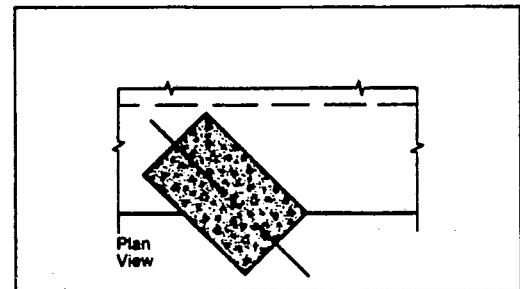


Fig. 29--Column orientation

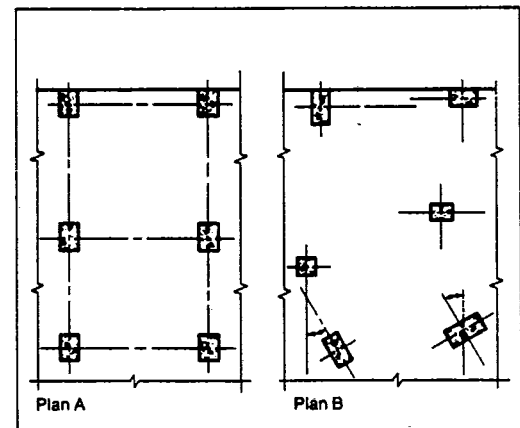


Fig. 30--Column layout

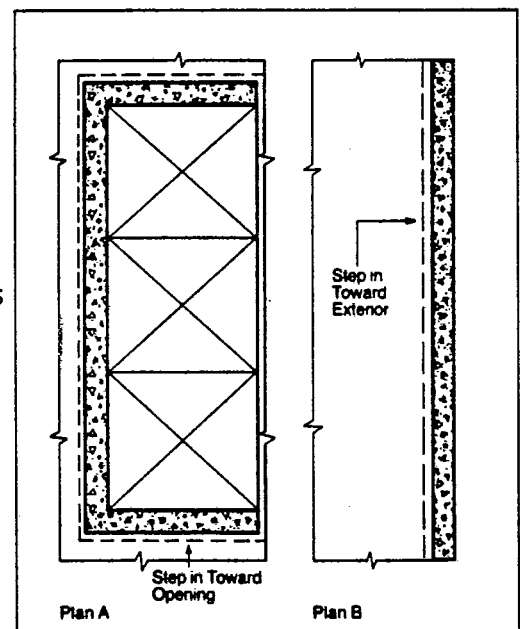


Fig. 32--Wall

26 Anthony

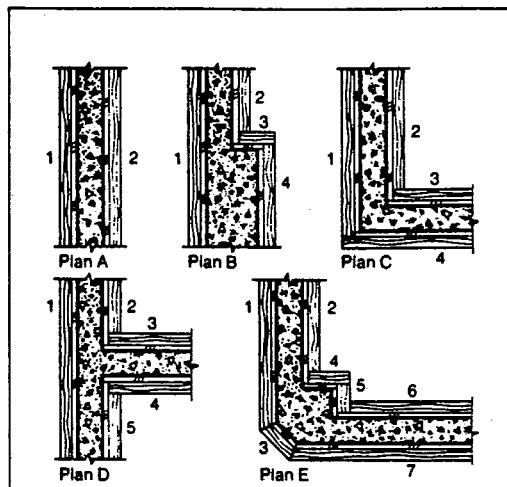


Fig. 33--Wall corners and intersections

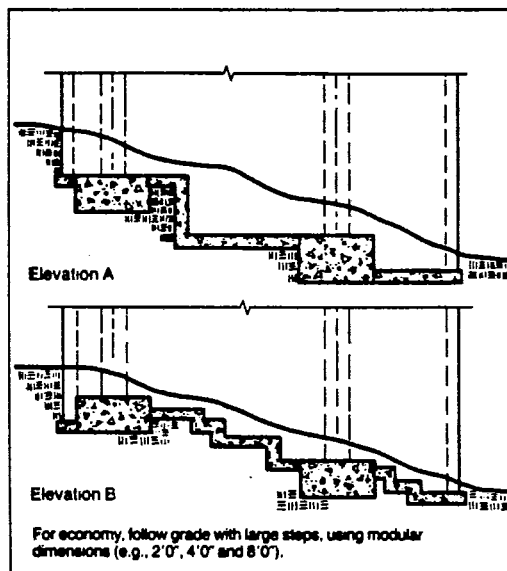


Fig. 35--Wall footings

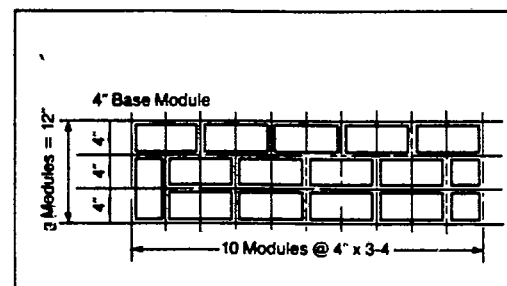


Fig. 37--Modular brick system

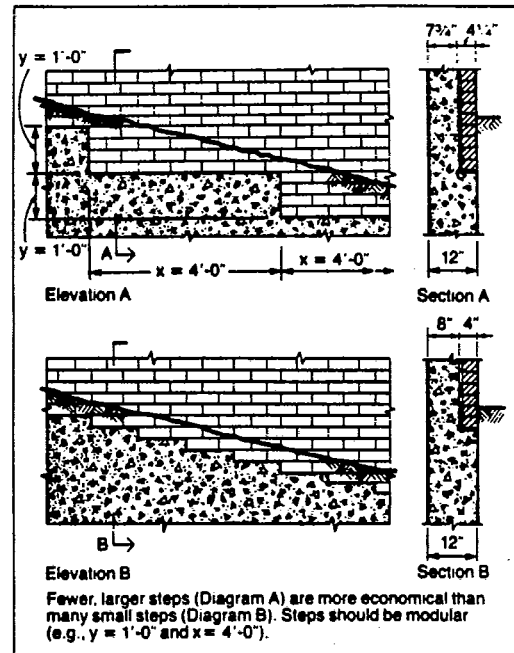


Fig. 34--Brick ledges

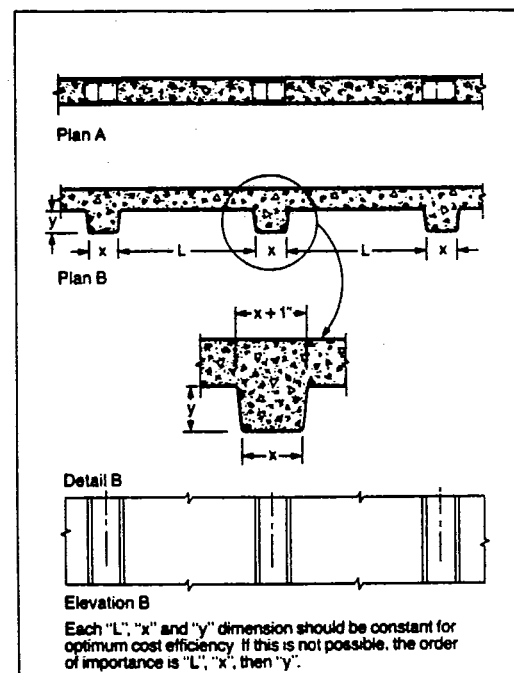


Fig. 36--Pilasters

28 Anthony

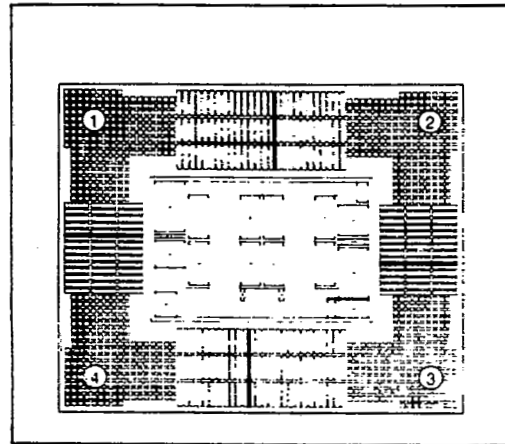


Fig. 45--Sequencing and recycling

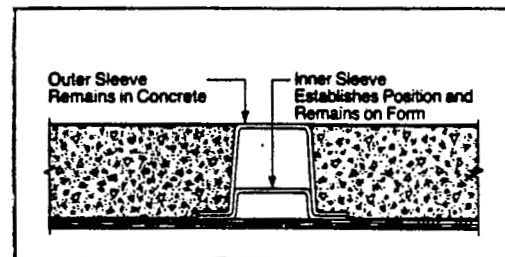


Fig. 48--Double sleeving for blockouts

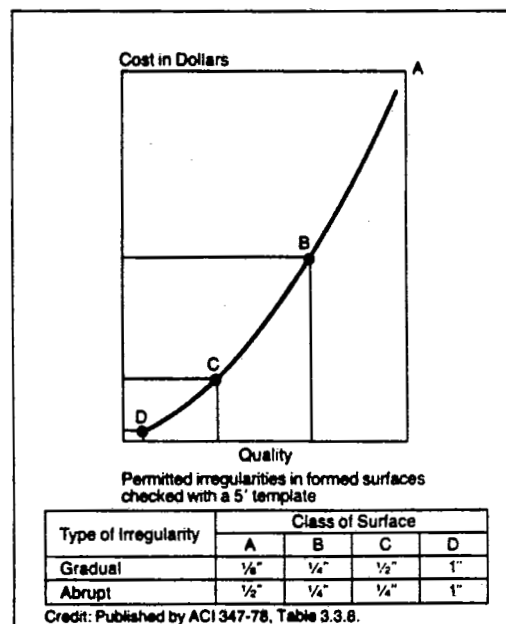


Fig. 50--Finish cost

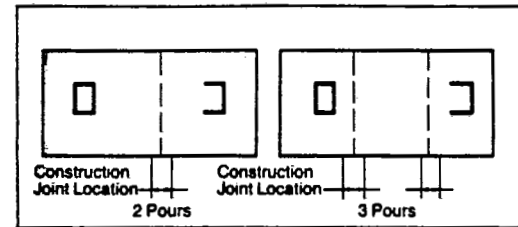


Fig. 46--Construction joint locations

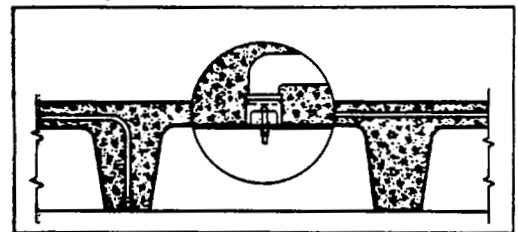


Fig. 47--Attachments to formwork

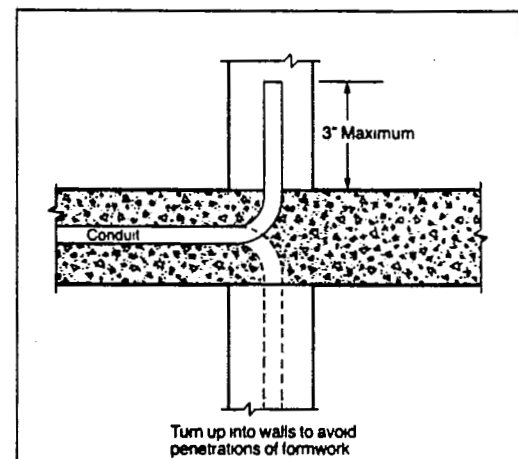


Fig. 49--Penetrations

SP 107-2

Wide Module Joists for Floor and Roof Decks

by L.E. Svab and W.T. Scott

Synopsis: Cast in place concrete one-way ribbed slab decks are undergoing an evolution. Slab thickness established by fire rating requirements and considerations of minimizing formwork labor and maximizing material economy have dictated a departure from the use of traditional 20 and 30 inch wide joist forms. Wider joist forms are being increasingly used to answer these considerations. Wide module joist systems generally have 6" to 8" wide ribs at 5' to 6' centers with 4 1/2" top slabs and are supported by wide beams. The ribs are designed as T-beams rather than joists. ACI 318-83 design requirements are not pin-pointed for the evolved slab/joist-beam system. Presented is an attempt to interpret and apply ACI 318-83 design requirements together with detailing and design considerations which are unique to this framing system.

Keywords: concrete construction; concrete slabs; detailing; floors; formwork (construction); framing systems; joists; one-way slabs; reinforced concrete; reinforcing steels; roofs; structural design; thickness

30 Svab and Scott

Laurence E. Svab holds BA and MS degrees in Architectural Engineering from the University of Illinois at Urbana, and is a Registered Structural Engineer. He is Senior Project Engineer, Construction Services, Ceko Industries. He has served on ACI Committees 215 & 348.

W. Thomas Scott holds a MS in Structural Engineering from the University of Nebraska at Omaha and is a Registered Professional Engineer. Since 1963 he has gained his construction experience with Ceko Industries and presently serves as Director of Engineering for the Concrete Construction Division. He is also active on ACI Committee 347.

INTRODUCTION

In reinforced concrete one-way joist decks, the thickness of the slab is quite often controlled by fire resistance requirements. Given the commonly required floor fire resistance rating of two hours, for example, the slab needs to be about 4 1/2 inches thick. When joist ribs are formed at only 20 or 30 in. clear spacings, the flexural capacity of the 4 1/2 in. slab is under-utilized. Increasing the joist rib spacing not only better utilizes the slab capacity, but also creates a system which has a more efficient structural weight to superimposed load ratio and coordinates well with a 5 or 6 foot modular layout.

DESIGN AND DETAILING CONSIDERATIONS

General Design Requirements

In wide module joist systems such as those shown in Fig. 1, the ribs are designed as T-beams rather than joists. (1) Minimum concrete cover for both flexural and shear reinforcement is 1 1/2 inches. Shear reinforcement is required when the factored shear force, V_u , exceeds one-half the concrete shear strength, ϕV_c . (2) The 10% increase in shear strength allowed for joist construction should not be applied. (3) For purposes of general identification, as opposed to design classification, this paper will continue to refer to the ribs as joists rather than beams.

Choice Of Joist Design Span

Proportioning the joists for shear, moment, and deflection involves, among other things, establishment of the joist span. Considering that, in this type of floor framing, the girder can easily be 48 inches wide, the difference between the joist center to center span ($L_{c/c}$) and the joist clear span (L_{clr}) can be significant (see Fig. 2).

With respect to proportioning the joist for shear due to a uniform loading, the maximum shear force in the joist can be taken at a distance "d" from the face of the joist support which, in this case, is the side of the girder. The most conservative approach of proportioning the joist for flexure and deflection would be to use $L_{c/c}$ as the joist span. If one is looking for maximum economy however, what span less than $L_{c/c}$ might be used?

If one were to use L_{clr} to check the joist deflection, he would be advised to recognize the contribution of girder rotation (in the plane of the joist span) to the joist deflection. Similarly, if one were to use L_{clr} to establish joist moments, he would have to recognize that the girder is an elastic support. Individuals have to weigh the benefits of such detailed calculations against the extra engineering time that it takes to make them. As a compromise, it is suggested that the joist effective span, L_{eff} , for flexure and deflection proportioning be taken as $(L_{c/c} \text{ less } h) > L_{clr}$. (see Fig. 2)

Joist Longitudinal Reinforcement

ACI 318-83 Section 10.6.6 sets forth the rules for location of flexural tension reinforcement in the flanges of T-beam construction. Assuming that a wide module joist configuration is a series of monolithic T-beams, compare the effective flange width as defined in ACI 318-83 Section 8.10 to the span/10 dimension from Section 10.6.6. Staying within the confines of a 4 1/2 in. slab with joists spaced 5 or 6 ft. apart, 16 times the slab thickness plus the joist rib width yields $(16 \times 4.5 + 7 = 79 \text{ in}) > 60 \text{ in}$ and $(16 \times 4.5 + 6 = 78 \text{ in}) > 72 \text{ in}$, so the effective T-beam flange width is equal to the joist spacing. The span/4 criteria allows one to use 5' and 6' effective widths for spans greater than 20 and 24 ft. respectively. For the commonplace wide module joist span range of 30 to 45 ft., one-tenth of these dimensions are 3.0 to 4.5 ft. ACI 318-83 Section 10.6.6 does not quantify how to split the reinforcement between the span/10 dimension and the effective T-beam flange width: equal spacing of the flexural tension reinforcement over the joist spacing is a straight-forward response to these code requirements. At least one (1) joist top bar must be placed over the rib to act as a stirrup support bar.

32 Svab and Scott

If uniform loading is anticipated for a specific wide module joist design, the "BEAM" section of the 1984 CRSI Handbook (6) presents recommendations for longitudinal bar cutoff points which could be followed (see Fig. 3)

Girder Design Implications

Usually, the most expeditious sequence of reinforcement placement in a wide module joist system is to set the girder longitudinal and stirrup reinforcement first, and then set the joist reinforcement. When this is done, the girder stirrup heights must be adjusted to allow the joist negative moment reinforcement to pass above the girder negative moment reinforcement while maintaining the proper cover dimension for the joist stirrups. Positioning of the girder bottom reinforcement need not be modified since the joist bottom reinforcement can be draped and will rest in the proper location. (see Fig. 4)

Joist Shear Design

Most designers find it more economical to develop shear strength by adding stirrups in the joist rib instead of increasing the rib width so that $1/2 \phi V_c$ exceeds V_u .

There are several configurations that joist stirrup reinforcement may take. Possible deformed bar stirrup configurations are single leg, simple U, or continuous "ladder" shapes. Alternatively, welded wire fabric can be modified to serve as stirrup reinforcement. (4) (see Fig. 5)

In order to function as stirrup reinforcement, the WWF sheets must be fabricated to meet specific vertical wire lengths and horizontal wire spacings (see Fig. 5a). Because of side cover and longitudinal bar clear spacing requirements, simple U stirrups may need to be skewed in joist ribs less than 8" wide (see Fig. 5c). Many rebar bending machines cannot make a U stirrup less than 4 1/2" wide. It is generally true that the greater material cost of the continuous or so-called ladder stirrup is offset by the labor saving realized in placing only one or two ladders per joist end rather than spacing out and tying many individual single leg or simple U stirrups. (see Figs. 5b & 5d)

Rib Width And Bar Size

The rib width required is determined by the maximum size bar required, the stirrup type and whether bars are bundled (see

Tbl. C). The six (6) inch rib, which is most economical, covers a wide range of spans but it is frequently necessary to use other widths.

Shear & Flexure In The 4 1/2 Inch Slab

ACI 318-83 Section 8.10.5 specifies reinforcement in slabs that are considered to be T-beam flanges. As discussed earlier in this paper, primary flexural reinforcement for the joist negative moment is set in the slab, spaced equally across the full joist width, in a direction parallel to the joists. Section 8.10.5 requires that transverse-to-joist-direction reinforcement be provided in the top of the slab. The stipulation that the transverse reinforcement be placed in the top of the slab is mirrored in Section 8.10.5.1, which states that the slab is assumed to act as a cantilever. Section 8.10.5.2 applies spacing limits for this transverse top reinforcement that are the same as those required for one-way slab temperature/shrinkage reinforcement. The code is silent regarding requirements for parallel-to-joist direction reinforcement in the slab in those areas between joist negative moment reinforcement. The top flange of the T-beam is in compression in this zone. It is common practice to omit longitudinal flange reinforcement in this zone. Figure 6 shows slab reinforcement and shows a method for supporting this reinforcement. Reinforcement is located to allow the use of continuous straight bars.

Calculations of transverse reinforcement for a 4 1/2 inch slab in a 6 foot module joist system were made. ACI 318-83 moment coefficients (5) for continuous spans were used to get slab reinforcement needed for three common loading conditions. The reinforcement amount needed to satisfy temperature/shrinkage criteria was also computed. Table A shows these slab reinforcement requirements. The reader should note that in all but one instance the temperature/shrinkage amount controlled. #3 @ 12" or #4 @ 18" provide sufficient reinforcement. The distribution of this reinforcement was found to meet the requirements of ACI 318-83 Section 10.6.4. It was also found that the 4 1/2 inch slab had adequate beam and punching shear capacity for the loadings that were used. Keeping in mind that ACI 318-83 only mentions the cantilever action of the slab as a T-beam flange, the reader should note from Table A that transverse reinforcement located as shown in Fig. 6 treats the top slab as a continuous slab and provides reinforcement needed for slab mid-span (positive) moment as well as support (negative) moment.

34 Svab and Scott

References:

- (1) Building Code Requirements For Reinforced Concrete; American Concrete Institute: Detroit, Michigan (ACI 318-83): Section 8.11.4
- (2) IBID Section 7.1.1
- (3) IBID Section 11.5.5.1
- (4) IBID Section 12.13.2.5
- (5) IBID Section 8.3.3
- (6) CRSI Handbook; Concrete Reinforcing Steel Institute Schaumburg, Illinois

TABLE A--COMPARISON OF 4½ INCH SLAB TRANSVERSE
DIRECTION REINFORCEMENT REQUIREMENTS

Loading Condition	Negative Moment Reinforcement (Sq. In. P.F.W.)	Positive Moment Reinforcement (Sq. In. P.F.W.)
50 psf L + 20 psf D (Uniform)	0.052	0.06
100 psf L + 10 psf D (Uniform)	0.071	0.08
2000 Lb Concentrated At Slab Mid-Span	0.08	0.11
Temperature/Shrinkage (ACI 318-83 Sec.7.12.2.1)	0.097	0.097

1. Self weight of 150 LB/CU.FT. Concrete is included.

2. Values are square inches per foot width.

$d = 2.75"$ for $- M$, $1.75"$ for $+ M$

3. # 3 @ 12 = 0.11 In²/FT.

4 @ 18 = 0.13 In²/FT.

36 Svab and Scott

TABLE B--WIDE MODULE JOIST SPAN CAPABILITIES
FOR TWO COMMON UNIFORM LOADINGS

Joist Size	Superimposed 50L + 20D = 678 LB/FT u	Loading 80L + 20D = 984 LB/FT u
14 + 4 1/2 - 6 + 66	28'	25'
14 + 4 1/2 - 7 + 66	34'	31'
14 + 4 1/2 - 8 + 66	37'	33'
16 + 4 /12 - 6 + 66	30'	27'
16 + 4 1/2 - 7 + 66	39'	35'
16 + 4 1/2 - 8 + 66	41'	37'
20 + 4 1/2 - 6 + 66	35'	32'
20 + 4 1/2 - 7 + 66	42'	38'
20 + 4 1/2 - 8 + 66	47'	43'

1. Material properties used in preparation of table: normal wgt. concrete w; $f'_c = 4000$ psi; reinf. ASTM A615 Grade 60.
2. Span determination was based on the following conditions:
 - a. interior span ACI 318 moment coefficients.
 - b. no reduction in live load magnitude.
 - c. stirrups included so that unreinforced concrete shear would not control.
 - d. rib bottom bar sizes:
6" rib / 2-#6; 7" rib / 2-#8; 8" rib / 2-#9
3. Greater spans or loads are possible when using larger bar sizes for positive moment reinforcement. See Table C for maximum bar sizes.

TABLE C--LARGEST POSSIBLE LONGITUDINAL BARS
IN JOIST RIB CONSIDERING STIRRUP FIT

Stir.	Rib Width	6" Rib	7" Rib	8" Rib
Ladder Or "J" Stirrup (Fig. A, B)		#6	#9	#11
"U" STIR. (Fig. "C")		#4 SPCD. or #8 BUN	#8 SPCD. or #11 BUN	#10 SPCD or #11 BUN

BUN = BUNDLED SPCD = SPACED

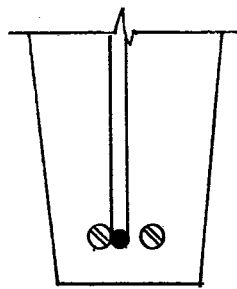
Table C: Largest Possible Longitudinal Bars In Joist Rib
Considering Stirrup Fit

Figure A

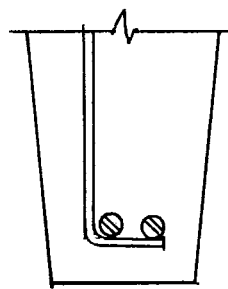


Figure B

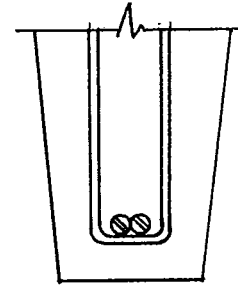


Figure C

38 Svab and Scott

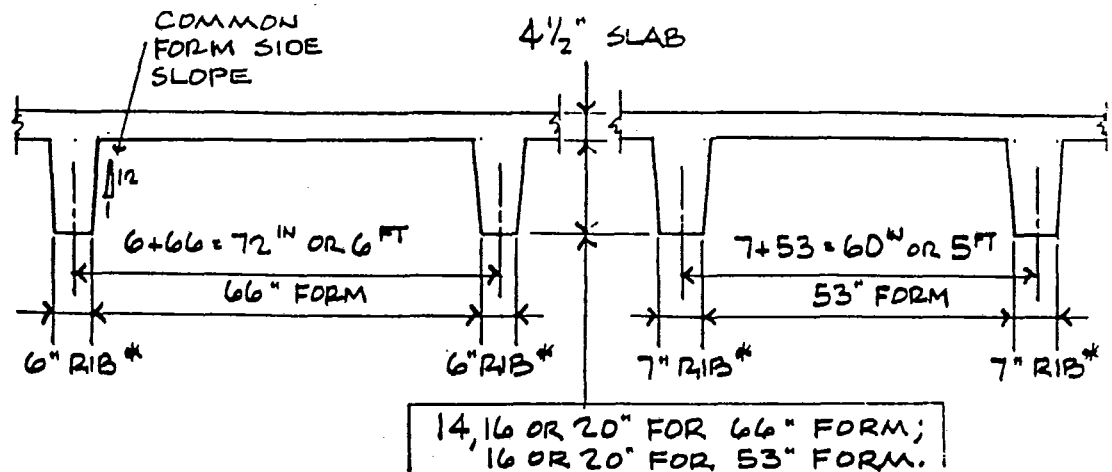


Fig. 1--Representative wide module joist configurations
 * Rib width must be checked against bottom bar side cover and minimum spacing requirements

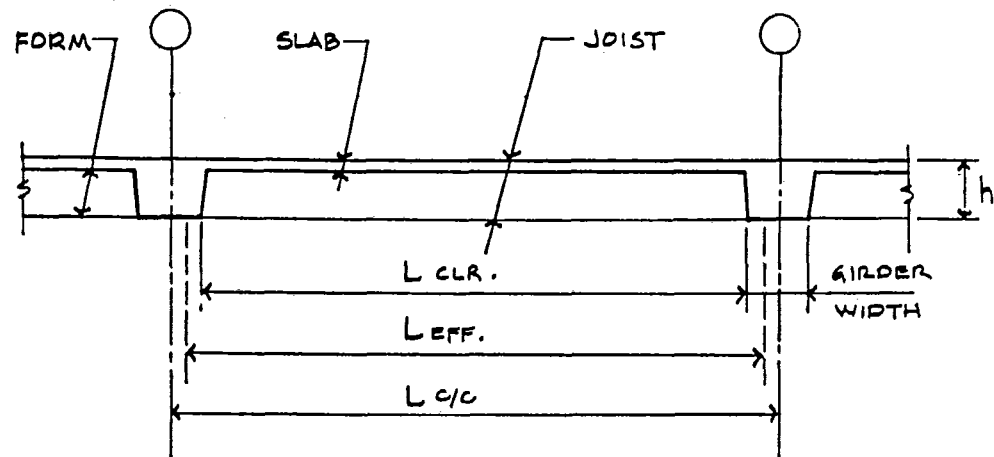


Fig. 2--Wide module joist span conditions

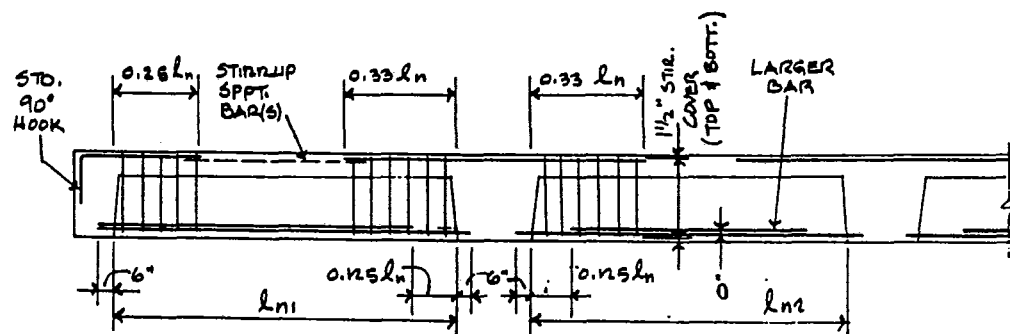


Fig. 3--Recommended bar detailing for wide module joists
 (slab and girder reinforcing not shown)

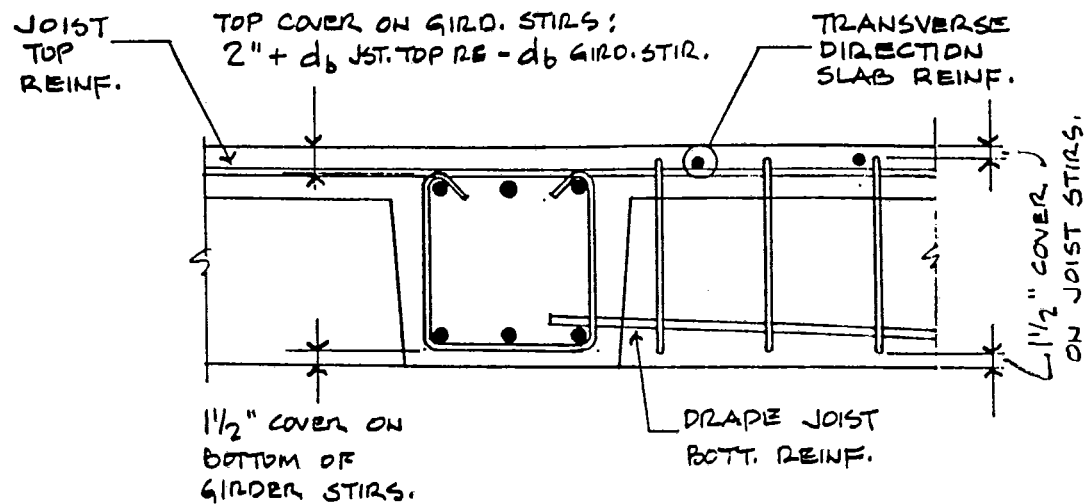


Fig. 4--Reinforcement detailing at joist-girder intersection

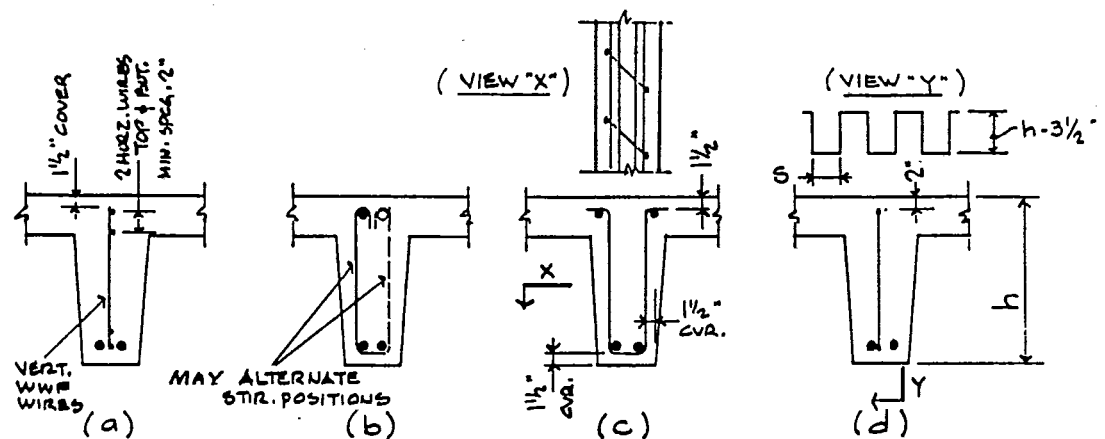


Fig. 5--Alternative wide module joist stirrup arrangements

40 Svab and Scott

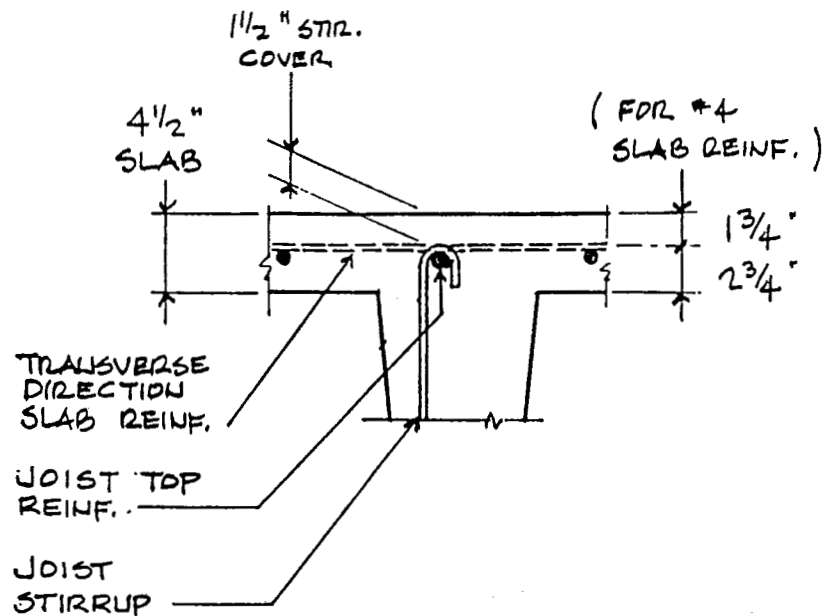


Fig. 6--Transverse-to-joist-direction slab reinforcement

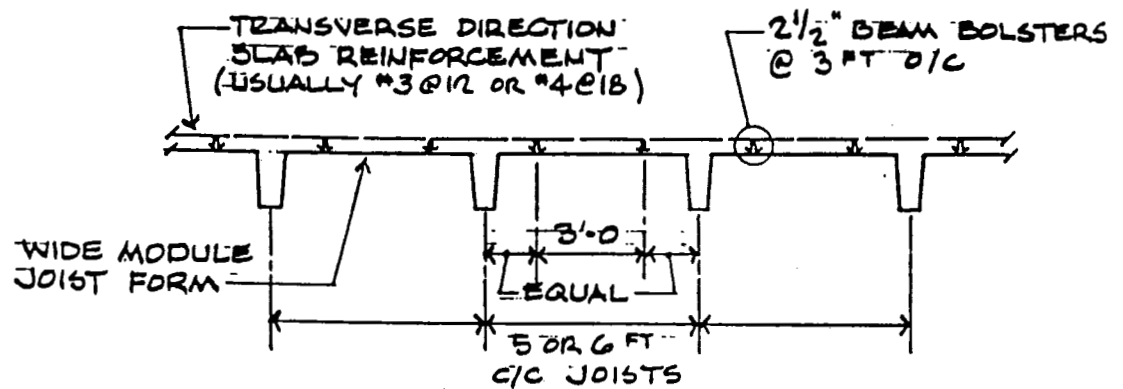


Fig. 7--Suggested method for supporting transverse direction slab reinforcement

SP 107-3

Air Formed Concrete Dome Structures

by J. Zimmerman

Synopsis: Air supported forming represents a rapid and cost-effective technique for building long span, thin shell, monolithic concrete structures. This construction method consists of inflating an air form, designed to the required building size and shape, after attachment to a foundation ring. Once inflated, the inside skin of the air form is sprayed with polyurethane foam. Steel reinforcement is fastened to the inside surface of the foam. Concrete is sprayed over the steel reinforcement, again from the inside. Steel is not placed, and concrete is not sprayed where shell openings are required. The air form can be color coated and textured, or removed for reuse when protective coatings are applied over the exposed foam. This technology is appropriate for free-span architectural applications, bulk storage of granulated solids, and liquids.

Keywords: domes (structural forms); energy conservation; forming techniques; formwork (construction); inflatable structures; reinforcing steels; shells (structural forms); shotcrete

42 Zimmerman

Jonathan Zimmerman, AIA, is an architect with McCarty Engineering in Longmont, Colorado. He has been involved in airforming technology for fifteen years. His most recent project was published in International Design and Construction by ACI.

INTRODUCTION

Concrete dome structures have been a part of the construction industry for many years. The use of earthforming and bolted together forms constitutes the two most popular methods of building curvilinear concrete structures. Earthforming entails the mounding of earth to the appropriate building shape and the placing of concrete and steel reinforcing over the mound. The sculpting of the earthform itself is a time consuming and labor intensive process. It is difficult to achieve a uniform geometric shape which meets both design and engineering specifications. Once the concrete has cured, the earthform must be excavated, leaving a free-standing structural concrete shell. The earth removal process is also labor intensive and expensive.

The use of prefabricated forms, which are bolted together on site, represents a significant improvement over the earthforming process in both speed and precision. For domes and dome-like shapes, however, the fabrication of such forms, as a series of doubly curved pieces, incurs expensive forming costs. The expected cost for these forms alone can be in the range of \$8.00 to \$10.00 per square foot of surface area. With either method of construction, the result is an uninsulated thin shell concrete structure. Without insulation, the structure is susceptible to heat loss as well as thermal shock due to temperature differences between the opposite sides of the structure in sun and shade.

Air Forming

The use of air supported forming systems, or air forming, provides a major advancement in the ability to economically form and construct large span, column free, thin shell concrete structures. This patented process of air forming consists of the following basic steps: build a foundation

weight ring; inflate a balloon attached to the ring; spray polyurethane foam on the inside surface of the balloon; place steel reinforcing on the inside surface of the foam; spray concrete over the steel, again from the inside; finish shell openings; and apply a cosmetic coating over the balloon, or remove the balloon for subsequent reuse and apply the appropriate foam coatings.

Foundation System - (See Figure 4)

The process starts with construction of the weight ring. As with any foundation system, the dead and live loads of the planned structure are balanced with the soil bearing characteristics of the project site. In addition, the use of air pressure to inflate the balloon air form provides uplift forces upon the foundation. The appropriate inflation pressure selected for the construction process creates an uplift force which is applied to the weight ring. This force must be calculated and compared to the weight of the ring in terms of pounds per lineal foot of circumference. Air pressures, creating uplift forces in excess of the weight of the foundation, can literally cause the ring to lift out of the ground and depressurize the air form. In addition, the inflated air form must be seen as an aerodynamic shape. Wind, passing over the form, creates positive pressures on the windward side and negative pressures on the leeward side, causing uplift forces. The foundation must also weigh enough to compensate for these forces during the initial stages of the construction process, before enough concrete is sprayed to provide the necessary dead load.

Air Form - (See Figure 5)

The air form is fastened to the weight ring prior to inflation. The tie-down system must be engineered to accommodate the uplift forces which are to be transferred to the weight ring. The balloon is manufactured with a hem at the bottom through which a heavy rope is threaded. Horizontal steel banding, placed above the hem and fastened to anchor bolts cast into the foundation, provides a positive connection between the air form and the weight ring.

The balloon is fabricated from a fiberglass reinforced nylon fabric which is capable of sustaining the appropriate skin stresses. Skin stresses in the balloon fabric are proportional to the radius of curvature of the overall shape. The

44 Zimmerman

larger the shell to be constructed, the greater the fabric stresses. Fabrics are selected as a function of strength, cost, durability, and appearance.

Air Form Advantages

The use of an air form provides four distinct advantages. These advantages are: construction cost, speed, working environment, and design flexibility. Firstly, balloon fabrication costs range from \$1.10 to \$1.25 per square foot of surface area. This represents a significant cost reduction when compared to conventional forming costs. The air form can be reused as many as ten times. This has been done with projects requiring on-site mass production of repetitive structures. Multiple reuse of air forms can reduce the cost of the form to almost negligible proportions.

It can be argued, however, that since the concrete is not sprayed directly onto the inside surface of the balloon, that forming costs should include the cost of the polyurethane foam. In-place costs for foam can be estimated at \$1 per board foot (one square foot, one inch thick). Should an estimator choose to include the cost of the foam as a forming cost, the structure can then be considered to have been insulated for free.

Secondly, erection speed is a matter of activating the inflation fan system once the air form is properly fastened to the weight ring. Dual centrifugal fans, operated by at least two separate power supplies, can inflate a 120-foot diameter by 44-foot high balloon in 50 minutes. Thus, balloon inflation is much faster than conventional methods.

Thirdly, the inflated form provides an enclosed environment in which all further construction takes place. Concerns with weather and temperature are mitigated by being able to work within a controllable environment. In cold weather, for example, an in-line heater can be located within the inflation system, or space heaters can be placed anywhere within the construction space.

Fourthly, the use of a balloon as a construction form provides a degree of design flexibility unmatched by conventional systems. Unlike pure geodesic systems, balloons can be fabricated in spherical, ellipsoidal, and parabolic shapes. These shapes can be combined to produce compound forms. Although simplicity is a property to be pursued as