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 Ceco 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

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 proces 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.

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).

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 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.

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.

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 Ceco Concrete Construction catalog for the variety of standard forms avilable.)

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 addiiton, 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).

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:
- The shape is symmetrical, rectilinear, without acute angles.
- The number of floor openings is minimized.
- Floor and wall openings are constant in size and location within the core.
- 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