Concrete Formwork: Constructability & Difficulties

Saving on formwork labor costs which are the leading costs in concrete construction should be a design objective.

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THE IMPACT of formwork on the cost of a concrete structure cannot be overemphasized. Under current practice, formwork that is designed and built by the contractor is by far the most expensive item in a typical concrete building. The cost of formwork sometimes exceeds the cost of the concrete and reinforcement for the structure. The most important cost item in formwork is labor, which sometimes accounts for more than 30 percent of the total concrete cost, especially when the forms are custom-built. Formwork labor, therefore, has the highest potential for cost saving in a typical concrete job and is thus the prime target for value engineering analysis. Unfortunately, most value engineering endeavors focus on cutting the costs of concrete without giving formwork the attention that it deserves.[1]

Concrete formwork is one of the more difficult items of a construction contract to estimate. Labor productivity (square feet of form contact area constructed per hour) is usually difficult to assess. Most of the formwork is constructed in open air, thus leaving the construction process susceptible to inclement weather. Project location, labor availability and management conditions all affect formwork construction productivity. Formwork configuration — *i.e.*, the geometrical characteristics of the structure — is another major factor that complicates the estimator's task in establishing productivity rates for various formwork components such as beam, column or slab.

The traditional method of construction contracting minimizes the interaction between designer and constructor before construction initiation. All too frequently, construction contracts are bid on in a great hurry, leaving the estimator little time to visualize and consider all the difficulties that may arise during the construction phase. A lack of communication between designer and builder frequently results in designs that are unnecessarily difficult and expensive to build. Unless the estimator is highly experienced and proficient, budget overrun will occur, especially in labor-intensive areas such as formwork construction. Any deviation from the most simple and repetitive pattern in forming — *e.g.*, wall openings, windows, peculiar beam-slab intersections, bulkheads, blockouts, *etc.* — will result in lower productivity rates and higher costs, since the estimator would have a difficult time considering all these factors and allowing for them in the estimate. If some quantitative factors can be calculated to allow for each type of irregularity (or difficulty), then the estimator increases the chances of estimating the formwork costs more accurately, thus precluding faulty and underbudget estimates.

There are means available to quantify such "difficulty factors" for formwork estimating. These factors can alert less experienced estimators to determine whether there will be formwork difficulties, to account for these difficulties and arrive at more accurate formwork estimates quickly. Because of the nature of construction practice, these factors depend on the individual company and its own method of managing the job. In other words, universal factors cannot be developed to be used by all contractors because of various elements affecting the productivity rates in different companies.

Formwork Economy

Formwork costs account for between 40 to 60 percent of the total concrete costs.[1,2,3,4] Since formwork labor typically averages 2 to 3 times the formwork material cost, it accounts for about 30 percent of the total concrete cost and thus is the most important cost item in reinforced concrete projects.[5] These data apply to forming systems such as flying forms or gang forms. If custom-built forms are used, this percentage can go higher. The high cost of formwork has spurred a great deal of innovation and technological development by formwork systems' manufacturers in the past two decades. Today's trend is toward the prefabrication of forms, assembly and erection by mechanical equipment and their reuse.[5] Obviously, forming systems are justified only if enough reuse can be realized. Therefore, these systems are particularly efficient on large jobs with modular or repetitive designs.

Given the current cost breakdown for a concrete structure with formwork costs so high, trying to reduce the size of structural members in the hope of economizing the design is often a futile pursuit and usually results in more expensive structures. Generally, the more slender and delicate a member, the more time it takes to form — the cost of formwork becomes higher than the cost of concrete and reinforcement.

Computing productivity rates in the construction industry is much more complicated than in the manufacturing industries. So many variable factors affect productivity in construction that average productivity rates can be seriously misleading when applied to specific jobs. The more important factors that affect formwork productivity can be divided into two major groups.

The first group consists of factors that do not depend on the type and shape of the structure. Weather, project location, type of labor (union *vs.* open shop), management and contractor's experience are among the more important factors in this group. The effect of some of these factors is so profound that computing average productivity rates without categorizing the type of project would have little benefit to the estimator. Research on methods for quantifying the effects of these factors on construction productivity has been conducted.[6,7]

The second group consists of factors that depend on the formwork requirements and the geometrical shape of the structural members. These factors are at least as important as the factors mentioned in the previous group. Most of the extra costs are a result of these factors and can be eliminated by carefully designing the structure, thus resulting in substantial cost savings. The designing of deep and narrow spandrel beams; changing column cross-section (*e.g.*, from circle to square or rectangle); reducing the column dimensions every few floors; and the placement of wall openings and windows of different sizes, blockouts and pilasters and many other peculiarities in the structure all contribute to the already high cost of forming the structure.

The topic of constructability has received much publicity recently in discussions on ways to improve construction productivity and quality in the United States. O'Connor and Tatum present detailed treatments of this important subject.[8,9] With regard to constructability as related to formwork and concrete structures, in order to make a concrete building easier to form and cheaper to build (yet meeting all the quality standards), three design steps should be taken:[1]

1. The design should consist of as many as possible similar modules. Using similar plans for the building floors and repeating the same layout in various building components will enable the contractor to use the same forms several times and allow the workers to become familiar with the work, thus improving the productivity rate because of learning curve effects.[10]

2. Since manufacturers' prefabricated forms are readily available in standard sizes, designs should conform to these standard sizes, thus enabling the contractor the opportunity to employ them. Even in the case of custom-built forms, the member dimensions should be selected with the standard lumber sizes in mind, thus saving a lot of time in carpentry and reducing waste.

3. Structural members should be designed with the least amount of variation in dimensions. Using the same depth for beams and girders, the same height for floors, identical cross-sections for columns from floor to floor will all facilitate and reduce the cost of formwork construction.

This design for constructability philosophy is summarized in *New Formwork Perspectives* as follows:

"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 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."

Difficulty Factors

Difficulty factors or complicating factors are defined as factors that quantify the effect of irregularities in formwork productivity.[11] For example, Richardson suggests that a factor of 4.5 be multiplied by average formwork productivity (manhours/square foot) for walls to arrive at the productivity rate (manhours/linear foot) for forming the intersection shown in Figure 1.[11] Or, according to Walker's, the cost of forming the face and sides of pilasters runs from 25 to 50 percent more than plain wall forms both for material and labor (p. 8.25).[12]

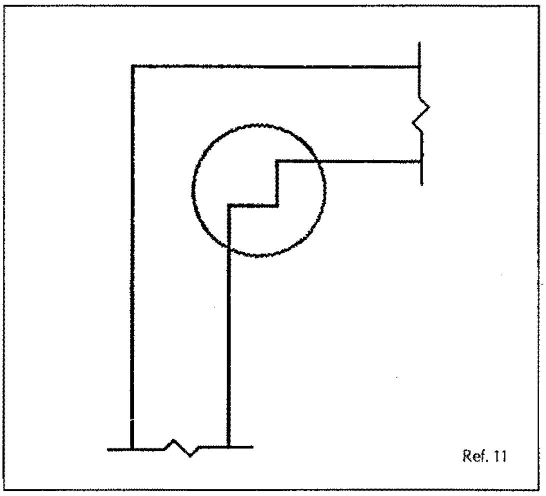


FIGURE 1. Plan view of wall intersection.

Good data on difficulty factors are hard to find. Not only is it difficult to accumulate this type of data, but the competitive nature of the business discourages its dissemination. The following sources of information on this type of data on difficulty factors are available:

1. *Construction estimating reference books.* Well-known estimating reference books usually provide limited information regarding formwork difficulty factors. Richardson covers some of the situations in an independent section.[11] Walker's and Means treat the subject while covering various formwork costs and productivity rates.[12,13] For example, the wall formwork difficulty factors mentioned in Walker's cover wall pilasters, radial wall forms, forming openings in walls, and forming setbacks and haunches on walls (pp. 8.25-8.27).[12]

Since these reference books provide average data, they should be used with care.

Many contractors do not use these references because they believe that their work and conditions are very different from the average values that are presented for cost and productivity in these references.

2. *The estimator's own knowledge and experience.* This type of knowledge is the most common source used during the estimating phase. Experienced estimators who have been working with a certain contractor for a number of years have a thorough knowledge of the organization's efficiency and capability and can determine the effect of formwork difficulty factors rather quickly. The most successful estimators are those who pay a great deal of attention to detail. Estimators should routinely count the number of corners, openings, blockouts, *etc.*, in estimating the formwork and allow for the cost increase in their estimates.

Unfortunately, the short period of time that is usually available for estimating and preparing a bid on a proposal limits this approach to only the most experienced and competent estimators. Such individuals are vital to the contractor's success. Their knowledge is largely intuitive and not documented, or easily documentable, for use by others.

3. *The contractor's historical data.* Few smaller construction companies maintain an extensive database of construction costs and productivity rates. The larger construction companies, however, with in-house computer capabilities, maintain detailed data from previous and current jobs. With the widespread use of personal computers, their simplicity and declining prices, it is quite conceivable that data collection and reduction will become more affordable for even the smallest construction firms. The level of detail in data collection and reduction varies from firm to firm. One of the more detailed systems used for data collection consists of weekly reports of progress on the different items of formwork for each floor (*e.g.*, formwork for spandrel beams, slabs, columns, *etc.*) and the comparison of these data with the pre-estimated measures of productivity to compute budget overrun/underrun. The general procedure is that the project engineer assigns values for the quantities of work performed under the various categories of beam, column, *etc.* Data pertaining to spandrel beams that had been collected in this process were found in many instances to be assigned quantities of progress in different categories without a high degree of accuracy. In these cases, the resulting data can be hard to categorize. For example, forming the beam-column intersection, especially in complicated configurations (*e.g.*, round columns) takes considerable time. It is not clear that this time should be assigned to beam formwork or column formwork. In order to clarify these ambiguities, footnotes and extra information should be included in the progress reports. For this reason, useful reporting on even moderate sized jobs requires a greater commitment than most contractors are prepared to make. Still, the importance of accurate and detailed productivity and cost reporting cannot be overemphasized for the serious contractor. These data, if carefully collected, can be invaluable in developing accurate estimates, winning contracts and operating at a profit in today's extremely competitive building market. This competitive edge is extremely important. For example, a few projects involving building correctional facilities on the west coast last year were bid upon and the low bidder was not more than 0.1 percent apart from the second lowest bidder.[14]

If a rather detailed cost and progress reporting system exists at a construction company that is based on the collected data from specific projects and the estimators' knowledge, experience and estimating references, the values of difficulty factors can be determined for various formwork categories. These difficulty factors can then be used for estimating future projects with speed and accuracy.

Methodology

An example can be used in demonstrating the general methodology that can be applied to estimating. Assume that the concrete frame of a multi-story building has been recently completed and the contractor wishes to estimate the difficulty factors in formwork so that they can be used in future biddings. In this case, only spandrel beams are considered. The productivity data (or total manhours) per floor have been compiled by the contractor. There are 10 bays of 20-foot and 6 bays of 25-foot spandrel beams in each floor (see Figure 2). Four types of beam cross-sections are used as shown in Figure 3. Depending on the number of floor and architectural considerations, different beam types are used on different floors. Therefore, each floor consists of a combination of different beam types with different lengths, some with blockout and some without.

Some components of these beams are more difficult to form. For example, forming the bulkhead for construction joints is much more time consuming than forming the beam sides. The bulkhead should allow for all the longitudinal rebars to pass through it, causing a lot of problems. Forming beam soffit can take much longer than beam sides because of the time involved in constructing the support system beneath the beam. Beam-slab intersection can also be relatively slow. One suggested method is to key a form into the beam face and punch it to permit the slab rebars to pass through. Building beam blockouts present another challenge that usually takes more time than routine forming. The objective is to find out the productivity rates for forming beam sides, beam soffit, bulkheads, blockouts and the beam-slab intersection. The following general equation can be developed for each floor:

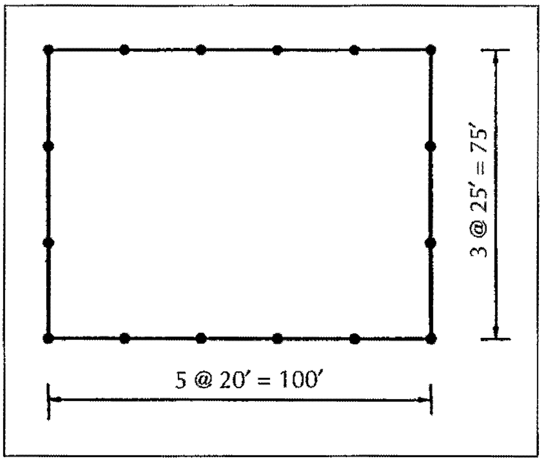


FIGURE 2. Plan view of the building.

$$\sum_{i=1}^{n} A_{ij}X_i = Y_j \qquad (1)$$

where:

n = total number of unknown productivity rates, and
j = floor number.

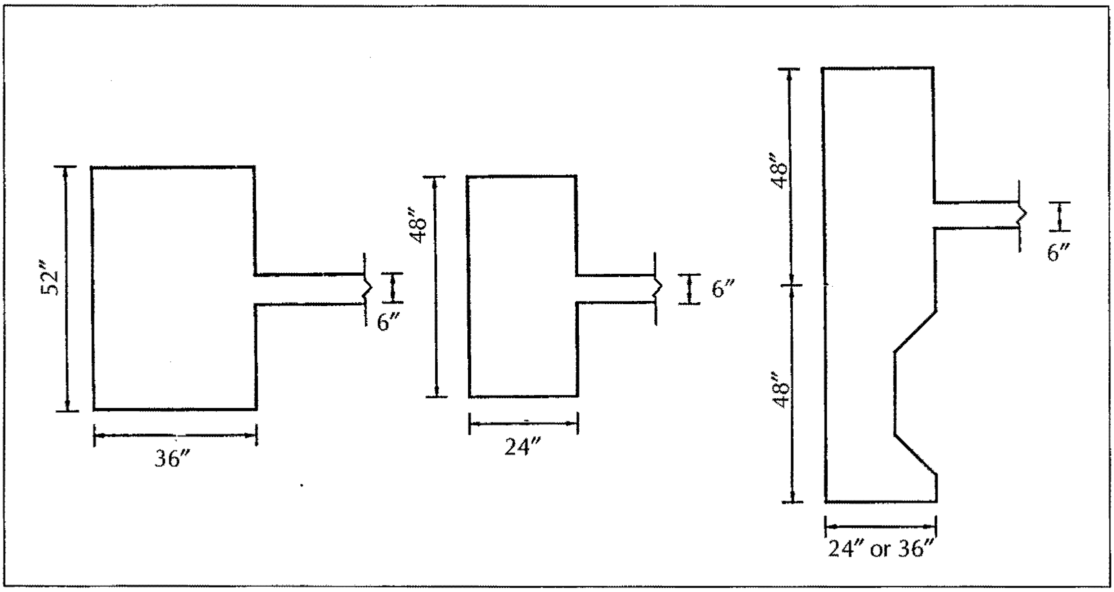


FIGURE 3. Beam cross-sections.

Table 1
Sample Spreadsheet for Regression Analysis of Hypothetical Problem in Figure 2

Floor No.	Sides ($ft.^2$)	Soffit ($ft.^2$)	Bulkhead ($ft.^2$)	Beam-Slab (linear ft.)	Blockout ($ft.^2$)	Total Actual (manhours)
1	A_{11}	A_{21}	A_{31}	A_{41}	A_{51}	Y_1
2	A_{12}	A_{22}	A_{32}	A_{42}	A_{52}	Y_2
3	...	...	...	...	...	...
...	...	...	...	...	...	...
...	...	...	...	...	...	...
n	A_{1n}	A_{2n}	A_{3n}	A_{4n}	A_{5n}	Y_n

For example, for Floor 1 there is:

$$A_{11}X_1+A_{21}X_2+A_{31}X_3+A_{41}X_4+A_{51}X_5=Y_1 \qquad (2)$$

where:

A_{11} = area of beam side ($ft.^2$) Floor 1
A_{21} = area of beam soffit ($ft.^2$) Floor 1
A_{31} = area of beam bulkhead ($ft.^2$) Floor 1
A_{41} = length of beam-slab intersection (linear feet) Floor 1
A_{51} = area of beam blockout ($ft.^2$) Floor 1
X_1 = productivity rate for beam side (manhours/$ft.^2$)
X_2 = productivity rate for beam soffit (manhours/$ft.^2$)
X_3 = productivity rate for beam bulkhead (manhours/$ft.^2$)
X_4 = productivity rate for beam-slab intersection (manhours/ft.)
X_5 = productivity rate for beam blockout (manhours/$ft.^2$)
Y_1 = total manhours spent in Floor 1 on spandrel beams

Similar equations can be constructed for each floor. The values for Y_j can be taken from the final progress reports. The values of the A_{ij}'s can be computed from the building drawings. The unknown components are the productivity rates, X_i's, that need to be quantified. The less the number of variations in each floor, the more similar these equations should be from one floor to another. In the case of similar floors, the effect of repetition will cause the total manhours spent on each floor, Y_j, to decline on the higher floors. This effect can be analyzed by the theory of learning curves.[10] If the floors are not identical, the effect of learning curves are less profound and probably can be disregarded in the first trial. If it could be assumed that productivity rates were consistent from floor to floor, then it would be possible to use any five sets of equations to solve for five X_i's. The computed values of X_i's then should fit into the rest of the equations as well. However, for several reasons as cited above, it is difficult to imagine a situation where productivity rates remain "absolutely" constant for every floor. The

Table 2
Regression Matrix for the Hypothetical Problem of Figure 2

$$\begin{pmatrix} A_{11} & A_{21} & A_{31} & A_{41} & A_{51} \\ A_{12} & A_{22} & A_{32} & A_{42} & A_{52} \\ A_{13} & A_{23} & A_{33} & A_{43} & A_{53} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{1n} & A_{2n} & A_{3n} & A_{4n} & A_{5n} \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ \cdots \\ \cdots \\ X_5 \end{pmatrix} = \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \cdots \\ \cdots \\ Y_n \end{pmatrix}$$

analyst should remain content with a moderate amount of variation in the values of X_i's. Therefore, the general problem is reduced to finding values for X_i's that fit into all the developed equations (one per floor) as closely as possible. It is suggested that a multiple regression analysis be performed on the data. The most simple way is, of course, to start with linear regression. Performing regression analyses on five variables requires a rather large number of equations. In the case where there are less than ten equations, for example, it can be very difficult to find meaningful values for the variables. It is possible that negative values are found for some of the X_i's. In such a case, one or two variables should be estimated using estimating reference books or the company's historical data. After reducing the number of variables, the regression should be performed on the rest of the variables. One efficient way to do this is to use the regression routine available on some of the available commercial microcomputer-based spreadsheets. Several analyses can be done efficiently and in a short period of time. The regression matrix should appear similar to the matrices presented in Tables 1 and 2.

After the values of X_i's are computed, the results should be compared to the results of analyses performed on other similar projects. If the results are consistently similar across a few projects, then those productivity rates can be used in estimating future jobs. Also, the values of computed X_i's for a completed job can be compared with those assumed productivity rates in estimating the job when it was bid so that reasons for any significant differences can be determined.

Case Study

This proposed method for costs analyses was applied to estimating the formwork costs for a 20-story building. In the design of this 600,000 square-foot correctional facility, 59 different types of spandrel beams were used. The cross-section of beams varied from floor to floor and within each floor. The contractor had a difficult time forming all these different configurations. When the job was finished, it was decided to investigate the effect of these radical variations in beam configuration on the cost of concrete formwork. Major reasons for variations, apart from various beam dimensions, were:[15]

- Slab tied into the beam at different levels of beam at various floors.
- Beam blockout configuration changed.
- Column pilaster changed (in some floors the column cross-section changed from square to circle)
- Difficult bulkheads due to the amount of longitudinal rebars

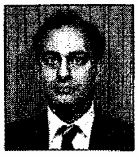
Based on the above observations, a number of difficulty factors were considered. Regression analysis was not successful on the first nine floors because there were so many variations on these floors that 15 difficulty factors had to be accounted for. The analysis was performed on Floors 9 to 18 by considering four difficulty factors. Beam configurations in these floors were much more consistent. The results of regression analysis, augmented by the estimator's viewpoints, quantified some of the more important difficulty factors. For example, it took twice as long to form the beam soffits as compared to beam sides. One major cause for delay and expense was the beam-slab intersections. A form was keyed into the beam face at the intersection location and drilled to accommodate protruding slab dowel bars. On average, forming this intersection required ten times as much labor as forming the beam sides.[4] Interested readers in the project and methodology should refer to Qabbani.[15]

Conclusions

Formwork labor is the most expensive item in a typical concrete job. Trying to save on formwork labor, therefore, should be the designer's objective rather than saving on concrete material. Repetition, consistency and standardization are three key issues in coming up with economical formwork construction.

The concept of formwork "difficulty factors" was discussed and a methodology proposed for quantifying these "difficulty factors." The nature of competitive bidding in construction allows very little time to the estimator to consider all details. However, if the estimator has access to a set of appropriate difficulty factors, then the estimate can be more accurate. Due to the large number of factors affecting productivity rates in construction, every contractor should develop their own set of difficulty factors.

The brief case study presented above demonstrates the application of a suggested method for applying difficulty factors to a specific construction project. It revealed that forming beam-slab intersections takes about ten times as long as forming beam sides. This huge difference points out the importance of considering the effect of formwork irregularities and difficulties when bidding on complex jobs.



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