Classic Papers from AISC's
Engineering Journal

The AISC *Engineering Journal* is a practical journal designed to present papers with information that is useful and relevant. Many of the questions received by the AISC Steel Solutions Center can be answered by referencing one of the papers published in the journal. *EJ* is available to all by subscription and is available to members through free electronic access using AISC's ePubs feature at **www.aisc.org/epubs**.

While all papers in the AISC *Engineering Journal* make a contribution to the state of knowledge of steel design and construction, some papers rise above the rest and stand as seminal in their importance. This regular feature in *Modern Steel Construction* magazine will highlight those most notable of works in the AISC *Engineering Journal*.

Ponding of Concrete Deck Floors

By John L. Ruddy
From the 3rd Quarter 1986 issue

The following highlights can be examined in greater detail by reading the full paper, available at **www.aisc.org/epubs**.

Floor construction consisting of concrete over metal decking and supported by steel beams and girders is a frequently employed structural system. When temporary shoring is not used, the steel framing and decking deflects during placement of the concrete floor slab. If the concrete were placed to the specified uniform thickness, the result would be a floor surface defined by the deflected shape of the supporting members. To create an acceptable level surface, one of the following options is normally employed:

1. The floor system is shored during concrete placement;
2. The floor beams are cambered to compensate for anticipated concrete placement deflections;
3. The concrete volume is increased resulting in a varying slab thickness to compensate for placement deflections.

The third option, placing a varying slab thickness, is probably the most commonly employed alternative. The success of the approach is often left to the control of the contractor, and seldom is considered in the design process.

[When attempting to predict] concrete volumes required to produce an acceptably level slab that is placed over a flexible substrate [it must be recognized that, as] concrete is placed, the supporting system deflects. As more concrete is placed to compensate for the deflection, additional displacements occur. The situation may be considered analogous to the rainwater ponding phenomenon of roof systems. However, there are notable differences between the rainwater ponding phenomenon and the concrete placement operation. Concrete is plastic, not liquid, consequently it does not seek a constant level. Also, the concrete placement process is controlled by man and rainwater deposition is not.

Analysis

Despite the shortcomings, a ponding analogy offers a convenient analytic approach to predicting a maximum concrete volume as a function of beam and girder stiffnesses. The objective of the rainwater ponding investigations has been to assure that the equilibrium position of the system is reached before the elastic limit of the structural elements is exceeded. The structural element stresses occurring during concrete placement are normally well below the elastic limit of the materials and attainment of the equilibrium position within the elastic material limitations is not normally a concern.

[The] structural system shown in Fig. 1 represents an interior bay of a floor system and consists of equally spaced beams supported by girders. The perimeter members of the bay are supported by columns and identical framing systems are assumed to occur on all sides of the bay being investigated. The investigation will be made assuming the deck contribution to the system deflection is negligible, and therefore the inertia of the members may be considered distributed uniformly over the bay. It is also assumed concrete placement will occur over a sufficiently large area so the load contributed to the perimeter members by placement of concrete within the bay being considered is equaled by placement of concrete in adjacent bays. The load transfer from the floor beams to the girders is assumed to be distributed, rather than as load concentrations. The equilibrium position deflections are determined by considering the deflected position of both the beams and girders to vary as the ordinates of a half sine wave as illustrated in Fig. 2.

[The full paper provides detailed

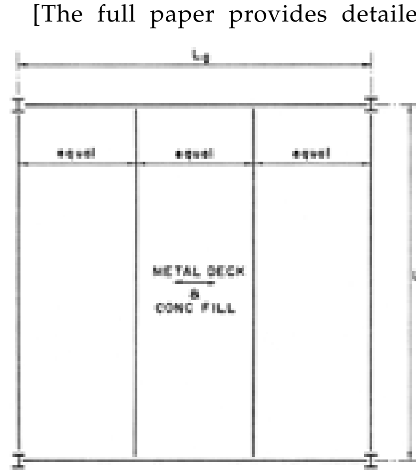

Figure 1.

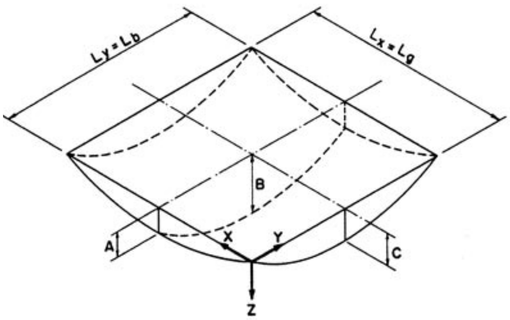

Figure 2.

calculations and example problems of ponding flexibility coefficients and system deflections. It also provides for the determination of the] total volume of additional concrete required to compensate for the initial deflected position, as well as the deflection induced by the placement of the additional concrete, [which] can be determined by using the deflection magnitude at three locations over the surface of the bay.

Construction Procedures

A concrete placement operation involves a repeated sequence of deposition, screed, darby float, and final finish. The quantity of concrete placed in a continuous operation is determined as that quantity which can be placed, leveled, and finished in a normal working day. Generally, 200 to 275 cu. yds. of concrete are scheduled for a single crew for each day of placement. That quantity would require finishing of 10,000 to 15,000 sq. ft of slab surface for a nominal 6″ slab thickness. The number of repetitions of the placement sequence (i.e. deposit, screed, float, and finish) is determined by the length of the screed board, which is typically a 16′-long 2×6. Consequently, once concrete is deposited over an area of approximately 200 sq. ft (± 14′ × 14′) the concrete is struck to a plane surface with the screed board and the floating operation started. The levelness of the slab is monitored for each placement sequence.

Consider the four 28′ × 28′ bays in Fig. 5. This partial plan represents the northwest corner of an elevated floor system. The sequence: Place, screed, float, and finish occurs in a rotation over ± 200-sq. ft areas within a bay and, subsequently, in a sequence over the floor. The contractor responsible for concrete placement is normally free to select a sequence. It will become apparent from the description of a specific sequence that both the final surface profile and the volume of concrete required are affected by this selection.

One placement sequence typically used is shown graphically in Fig. 5 and is described in the following:

- Top of finished slab elevations are marked on columns as control points prior to concrete placement. Concrete is deposited over quadrant 1 until completely covered. A control point is set at mid-bay (Location **e**) by mounding the concrete to the desired surface elevation. This control point is set to the finished slab elevation referencing a remote fixed point using an optic level or laser. A wet screed is formed by striking off the concrete in a straight line between the control point (Location **e**) and the top of the north slab edge angle (Location **b**). The concrete in the quadrant is then screeded using wet screed line (Location **b** to Location **e**) and the west slab edge angle (Location **a** to Location **d**). Immediately following the screed operation, the concrete is float finished.
- Concrete is deposited over quadrant 2 as the floating operation is accomplished over quadrant 1. A control point is set by mounding concrete at Location **h** referencing a remote fixed point. The concrete is struck in a straight line between Locations **h** and **e** and this wet screed is used in conjunction with the west edge angle to screed the concrete in quadrant 2.
- The concrete placement operation continues and follows a similar process in quadrants 3 and 4. However, the concrete surface of quadrant 1 is used as the screed edge line for quadrant 3 and the floated concrete surface of quadrant 2 is used as the screed edge line for quadrant 4 in lieu of the slab edge angle.
- The placement operation proceeds from quadrant to quadrant in the sequence indicated by the quadrant numbers shown on Fig. 5. The area of concrete placement to be accomplished in a single operation is determined prior to starting. The boundary of the placement area is usually defined by the floor edge angle on two or three sides. The remaining boundary edges are established by affixing a screed board of a thickness equivalent to the slab thickness to the floor deck.

Reflections on Construction Process

Concrete is placed to match the top of the edge angle at the building perimeter. The elevation of this angle is not constant since the concrete weight deflects the substrate to which the angle is attached. Control points that are monitored from a fixed reference are set at only three positions during concrete placement within a bay. These points are set prior to superimposing the full concrete weight and displace vertically immediately following their establishment. Concrete is worked to screed boards at interior placement boundaries. These bulkheads are used as surface screed lines and, since they are attached to the decking, they dictate that the surface conform to the deflected deck shape.

Since concrete is screeded to the top of the edge angle at the building perimeter, the slab thickness is maintained at a constant thickness at these locations. As concrete placement progresses away from the perimeter, previously placed and floated concrete surfaces are used to screed concrete. These interior screed surfaces exist over a varying slab thickness. Consequently, the concrete volume per unit area increases as the placement operation progresses away from the perimeter. Conversely, as the placement operation approaches an interior bulkhead, the concrete volume per unit area decreases.

Investigations

The [procedures in the full paper] consistently predict volumes greater than those realized in practice. This is due to deviations of the concrete placement operation from a classical ponding phenomenon.

The modeling process is initiated by creating a grid of linear elements representing the girders, beams, and deck forming a typical corner bay. The first quadrant of this corner bay is loaded with a uniform concrete weight equivalent to the load imposed by a uniform slab thickness. Figure 6 depicts schematically this first placement quadrant. Within the quadrant, assurance that the concrete is placed to the required elevation is controlled at only two locations, mid-bay (Location **e**) and at the corner column (Location **a**). At the remaining two corners (Locations **b** and **d**), concrete is placed to an edge angle and deflections are not compensated for. The surface which is used to monitor the concrete placement may be designated the control surface and is depressed from the horizontal plane. The additional concrete placed is that volume necessary to compensate for the difference between the deflection and the depression of the control surface. The computer model calculates that additional concrete weight and adds the result to the initial load. A second displacement analysis is made using the new loads. Deflections determined at Locations **b** and **d**, in conjunction with correct surface elevations at mid-bay and the column (Locations **a** and **e**), define a new control surface. Subsequently, additional concrete weights for the next cycle are calculated. Load iterations are continued until the variation in elevation between successive cycles of the monitored control point is negligible.

The process is repeated over the remaining quadrants of the bay. The control surface is defined by the surface deflection of previously placed concrete as placement proceeds beyond the first quadrant. Ultimately, the placement sequence can be modeled over an entire floor area and concrete volume variations between corner, perimeter, and interior bays can be determined.

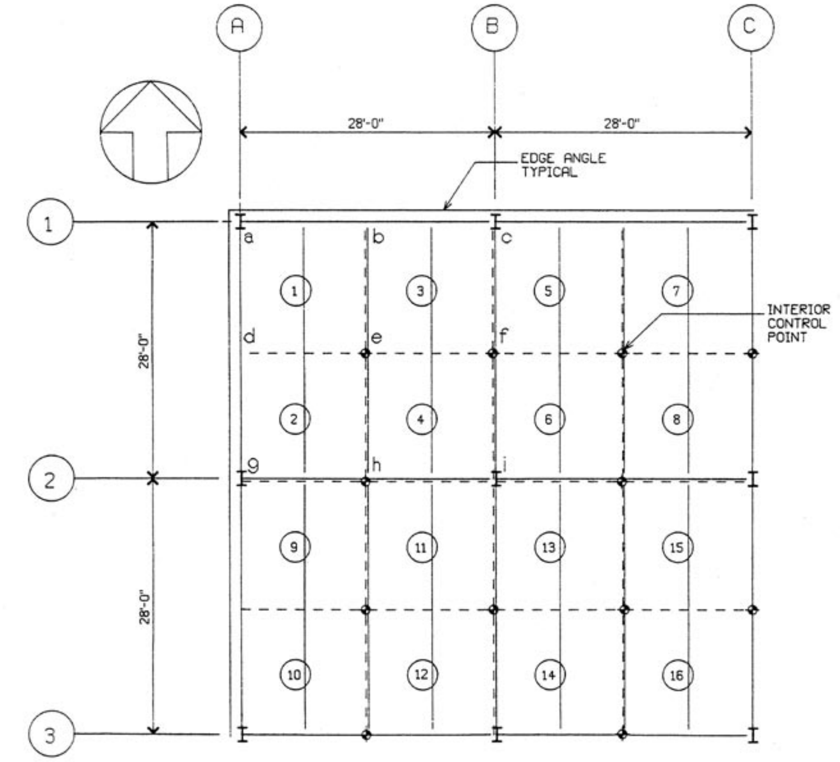

Figure 5. (Figures 3 and 4 appear in the full article available online.)

Observations

Figure 7 presents graphically the results of applying the cyclic loading model to [the example given in the full paper]. The figure represents final surface and soffit profiles using an exaggerated vertical scale prior to concrete placement in the adjacent bays. The model of the bay was formed using a grid of points 19″ o.c. in each direction (289 nodes). It was found that three cycles of load within a quadrant were sufficient to limit variations between successive elevations to less than 1/32″. Consequently, the placement operation for the full bay is completely modeled after twelve computer runs.

A concrete volume increase of 21.8 ft ^{3} was realized. This is an increase of 9.5% over the volume calculated by multiplying the uniform slab thickness times the bay area. [The calculation process] predicts a 34.4% increase for an interior bay. The maximum soffit deflection is 1.22″ (5.72″ – 4.5″). However, the maximum surface depression is 0.89″. The results substantiate the assumption that the deck contribution to the volume increase is negligible. A maximum slab thickness increase of 0.54″ was calculated and the fact that a level surface cannot be created by the placement process was confirmed.

The surface and soffit shapes are those which are anticipated intuitively. Yet, confirmation of the validity of the model through field measurements is difficult due to normal construction tolerances.

Tolerances

Specifications to control slab surface profiles generally fall far short of meeting that objective. A typical criterion is "depressions in floors between high spots shall not be greater than 5/16″ below a 10′-long straightedge." This is the definition of a Class BX Surface Finish Tolerance as defined by ACI and is indicated as appropriate for offices, churches, schools, hospitals, etc. This and similar straightedge criteria do not limit the inclination of the surface nor are the number of 5/16″ waves which can occur over the straightedge specified. The specifications commonly employed do not control levelness or flatness.

Recognizing those faults, the proposed 1986 version of ACI 302-86 *Guide for Concrete Floor and Slab Construction* presents a significant improvement over present specifications by specifying both flatness and levelness based on Face Floor Profile Numbers. The proposed specification recognizes the difference between flatness (waviness) and levelness (inclination) and uses elevation measurements with statistical methods to calculate flatness numbers (F_F) and levelness numbers (F_L). These values, based on field measurements, can be compared to specified values to check conformance of a slab to required tolerances.

The approach is rational and does satisfy the intent of a tolerance specification. It is based on measurements over millions of square feet of on-grade concrete floors and is appropriate for rigid-base slab systems. Limited surface profile data is available for elevated slabs and the method is disqualified for flexible base applications. However, a review of findings from slab-on-grade observations is helpful. Slab-on-grade flatness is influenced by the method used in finishing the surface. Flatness is the property measured by the F_F number. Slab-on-grade levelness is influenced by the method of concrete placement (deposition and screeding). Levelness is the property measured by the F_L number and is the property normally of concern for elevated slabs.

As the magnitude of either F number increases an improvement in levelness or flatness is realized. A floor survey resulting in a F_L number of 60 would be indicative of a surface over which 99% of the surface measurements would show deviations from a 10′ straightedge of less than 0.21″, a much better than average condition. Slabs-on-grade placed using a wet screed technique generally result in surface levelness represented by a F_L number of 15. A F_L of 15 would represent a surface over which 99% of the surface measurements would show deviations from a 10′ straightedge of less than 0.83″.

If the surface deflections predicted by the cyclic loading of the computer model

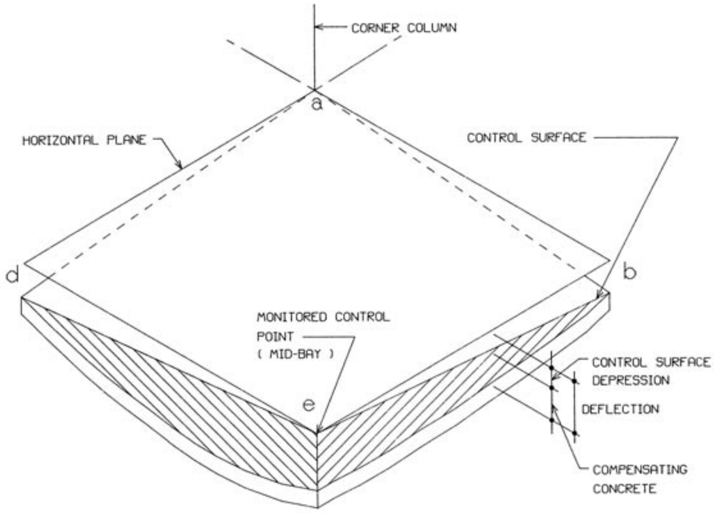

Figure 6.

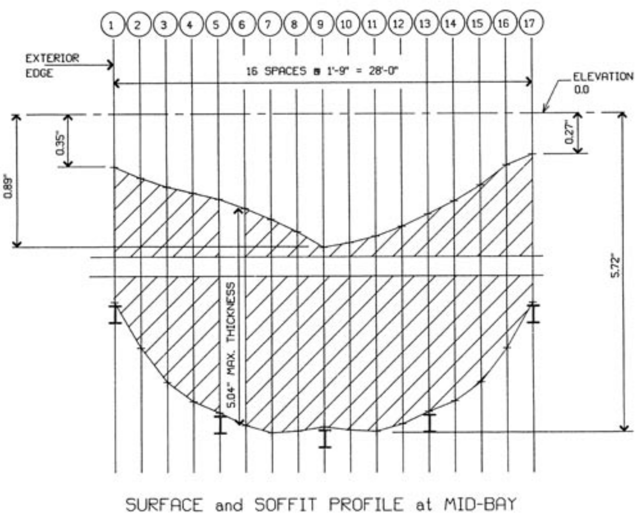

Figure 7.

are used to calculate the levelness floor profile number, a value for F_L of 14 is determined. This result is not an accurate indication of what should be expected over a floor. The sample of values is too finite to be conclusive. Also, the surface elevation will be influenced by concrete placement in adjacent bays and the deflection data used does not represent the final deflected shape. The objective of this calculation of the Face Floor Profile Number for levelness is to emphasize the difficulty of correlating model data with field measurements.

The mathematical model has been developed under the assumption that concrete placement is ideal. Concrete is assumed to be struck in perfectly straight lines. Yet, the deflection of the substrate results in a poor conformance to levelness. Measurements of surface levelness for concrete placed over a rigid base, using a wet screed placement procedure, also result in poorly leveled slabs. Consequently, in reviewing field verified surface elevations of slabs placed over a flexible base, there is no way of determining what percentage of the variation is a consequence of a deflecting base and what percentage is a consequence of the placement method.

The definition of an acceptable level and flat elevated slab seems to be one which nobody complains about. The construction components which follow the slab placement can be adjusted to conform to the deviation from levelness of the floor slab in most instances. And, unless the furniture is leaning noticeably away from or toward walls, the occupants are not immediately aware of the slope. However, at some threshold, adjustments in drywall partitions, shortening of doors, and adjustments in baseboards become excessive. That threshold has not been defined, in part due to the inadequacies of present tolerance specifications.

Summation

The justification for stating the purpose of this paper as an interim report should be apparent. Additional analytic effort and field data collection is necessary to refine and verify this approach to predicting concrete slab volumes. The problem is complex and the parameters influencing a volume calculation numerous. The complexity of the problem is directly proportional to the importance of a solution. Increases in concrete volume cause increases in load, variations in slab thickness result in section property variations of composite steel/concrete systems, and added material is reflected in added cost.

Common construction practice is to anticipate a 10% concrete volume increase will be required to accomplish slab placement. That increase represents a load increase of approximately 3,500 lb per floor per column for the example used. This condition should be considered in the design process. However, the accuracy of a 10% value requires confirmation.

The relationship between an increase in load and the increase in flexural capacity due to a slab thickness increase has been investigated in a limited number of cases. These investigations generally have confirmed moment capacity increases, which exceed the increased dead load induced moment, for floor beams. However, the reverse is true for floor girders and actual flexural moments for girders have been found to exceed the moment capacity by ± 10%. A basic assumption in flexural capacity investigations is that the steel section and concrete slab act compositely. Moment increases due to increased concrete weight can be in the range of 15%. If the system investigated is not designed compositely, the capacity reduction can be substantial.

Perhaps, if the time expended and expense incurred in disputing liability for additional concrete cost, expense of adjusting finish components, etc., were redirected toward establishing a method for predicting concrete volumes, the problem would disappear. The establishment of a reasonable and enforceable tolerance specification is needed for elevated floor slabs. The review of placement and finishing procedures undertaken to establish the tolerance criteria for slabs on grade suggested alternatives to the commonly employed placement and finishing practices. The application of those alternative methods has resulted in significant improvements in levelness and flatness with reductions in construction labor costs. Concentrated effort toward resolution of the elevated slab placement problems may have similar results. ★

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