Multilevel Formwork Load Distribution with Posttensioned Slabs

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Abstract: Formwork and the associated shoring represent a significant proportion of the costs associated with the construction of multilevel concrete structures. To minimize these costs, a limited number of formwork and shoring sets are recycled up the structure as construction progresses, eliminating the need for a new set of formwork and shoring with each new slab. When a slab is posttensioned using draped tendons, slab lift occurs as a portion of the slab self-weight is balanced. The formwork and shores supporting that slab are unloaded by an amount equivalent to the load balanced by the posttensioning. This produces a load distribution through the structure that is inherently different from that of a conventionally reinforced slab. This paper presents two design methods suitable for modeling the multilevel formwork process for posttensioned slabs: A modification to the simplified analysis method and a finite element model—both techniques will be of immediate use by industry practitioners and of interest to researchers examining the load distribution phenomenon. The paper also summarizes the findings of one of only a few research projects in which actual shore loads were monitored during the construction of a multilevel posttensioned building, which is used to validate the proposed design models.

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Introduction

In multilevel building design, a fundamental principle of structural engineers designing posttensioned slabs is that as the slabs are posttensioned, a certain amount of slab lift occurs as a portion of the slab self-weight is balanced. Extending this assumption, if the slab lifts, the shores supporting the slab must be unloaded by an amount equivalent to the slab load balanced by the posttensioning. This unloading of the shores produces a situation entirely different from that of a conventionally reinforced slab system in which no load balancing occurs. The load distribution that occurs between interconnected posttensioned slabs should therefore be significantly different from that of a conventionally reinforced slab system.

This phenomenon and the analysis thereof will be of particular interest to researchers and industry practitioners involved in the design of posttensioned slabs and the specification of formwork cycle stripping times as the proposed analysis techniques potentially allow for significantly reduced cycle times, enhanced construction safety, and a reduction in construction cost through the use of a lesser number of formwork and shoring sets.

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Posttensioning and Slab Lift

When the shoring is stripped, all suspended concrete slabs will deflect elastically under the effect of self-weight and any applied loads. If the slab is conventionally reinforced, this deflection is irreversible. If a slab is posttensioned with tendons that are draped parabolically, some portion of the deflection is able to be reversed through a process commonly referred to as load balancing.

When a slab is cast, it is fully supported by the formwork and shoring. The slab is unable to deflect resulting in a level slab that is not subjected to any bending stresses. If posttensioning forces are adopted such that it produces stresses equal but opposite to the self-weight stresses, a level (undeflected) slab results. In this situation, it can be said that 100% of the slab self-weight has been balanced (full load balancing). It should be noted that in practice, structural design engineers do not always design for full load balancing; a lesser or greater load may be balanced depending on the desired effect.

As a concrete slab is poured, the formwork deflects and the shoring supporting that formwork compresses under the load from the concrete self-weight. As the concrete does not have any strength at this stage, the shores are required to carry the full slab self-weight as indicated in Fig. 1(a). If the posttensioning tendons are tensioned before the undisturbed shores are removed (the usual practice), the shoring supporting the slab is unloaded by an amount equal to the portion of the slab self-weight that is balanced. If, for example, full load balancing is adopted, the slab will theoretically lift to a level state forcing the slab to support its own self-weight thus unloading the shores to produce the situation in Fig. 1(b). If less than the full self-weight is balanced, the slab will lift partially forcing the slab to support that portion of the load that was balanced. The unbalanced portion of the load remains in the shores [Fig. 1(c)]. These assumptions have been validated in a research project investigating the effects of posttensioning by Ka-

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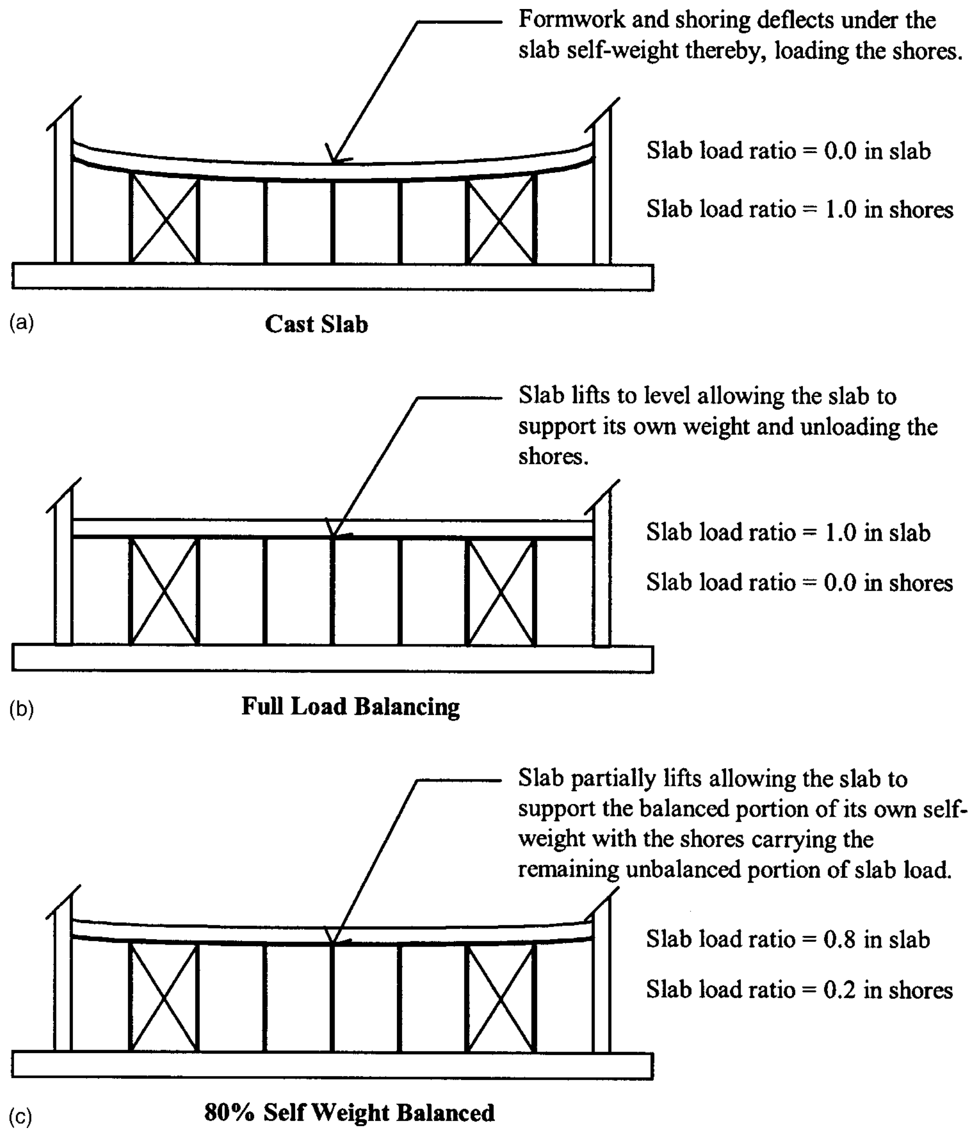

Fig. 1. Effect of posttensioning on shore and slab loads

jewski (1998)—this project is outlined in the later stages of this paper.

Modification to the Simplified Analysis Method

An analysis method, commonly referred to as the "simplified method," first proposed by Grundy and Kabaila (1963) is probably the most widely used analysis method for determining the slab load ratios and hence shoring procedures when multilevel formworking. The method provides a rapid, simple, and relatively accurate procedure for determining slab and shore loads when using multilevel formwork to construct conventionally reinforced concrete slabs. In its present form, it is not suitable as an analysis method when considering multilevel posttensioned slabs as it does not allow for the effect of slab lift during the stressing operation. The method is neither reproduced nor explained in its entirety here—readers unfamiliar with this common technique are directed to Grundy and Kabaila's original publication or the numerous other papers which have followed.

Slab Load Ratios for Posttensioned Slabs with Undisturbed Shores or Backpropping

Undisturbed shoring assumes that the formwork and shores remain undisturbed in their original position for the entire period during which the slab is required to be supported. Backpropping involves the stripping of small areas of slab soffit and reinstalling the shores to support the slab. With both techniques, the slab essentially remains fully supported.

The initial stress that a slab receives at an age of 24 h involves stressing the posttensioning tendons to some percentage of the full stress load. "Initial stress" is a common term used for the initial level of stress that is placed into the posttensioning tendons at an early age (usually 24 h) to limit shrinkage cracking that occurs due to the greatly reduced levels of conventional reinforcement. This initial stress effectively unloads the shores supporting the slab by an amount equivalent to the portion of the slab load balanced by the initial stress. Assuming that the posttensioning has been designed to balance full slab self-weight, if the initial stress was 25% of the full stress, the shores are unloaded by an

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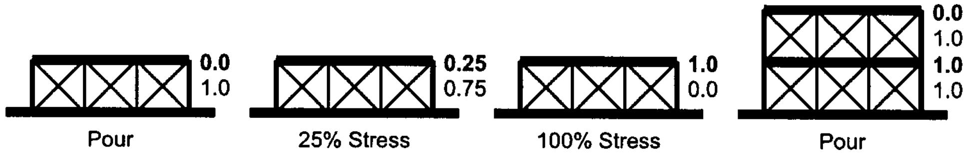

Fig. 2. Effect of posttensioning on slab load ratios

amount equivalent to 25% of the slab self-weight. Similarly, the slab would then support 25% of its self-weight as indicated in Fig. 2. "Full stress" is a common term used for the full level of stress that is placed into the posttensioning tendons at an appropriate age to provide the full design strength and serviceability criteria. The unloading of the shores causes a redistribution of load upward, increasing the load on the upper level slabs and decreasing it on the lower level slabs. The application of full stress has a similar effect but the shores supporting the slab being stressed are completely unloaded (assuming full load balancing).

Fig. 3 indicates the slab load ratios for a multilevel posttensioned slab structure with undisturbed shores. The structure is assumed to consist of three levels of undisturbed supports with a 7 day slab construction cycle (the 7 day construction cycle means that construction of the formwork starts on construction day 1 with the first slab being poured on construction day 7 as indicated in Fig. 7). The formwork is stripped at a slab age of 19 days with the initial 25% stress occurring at a slab age of 1 day (with the slab poured on day 7, the initial stress occurs on construction day 8 as indicated in Fig. 3) and final 100% stress at a slab age of 4 days (construction day 11). Full posttensioning is designed to balance the full self-weight.

When using undisturbed shores on conventionally reinforced multilevel slabs, the shore loads are cumulative at the foundation level shores provided a continuous load path is maintained. Fig. 3 indicates that when multilevel formworking posttensioned slabs, the shore loads are not cumulative to a maximum at the founding level shores. Rather, the founding level shores alternate between a maximum slab load ratio of 1.0 as each new slab is poured and a minimum of 0.0 as that new slab receives full stress. The "slab load ratio" is the ratio of the load carried by the shores to a standard slab self-weight. A slab load ratio of 2, for example, indicates that the shores are carrying the equivalent of two slab loads.

Posttensioned slabs after the founding level shores have been removed, as indicated in Fig. 3, are all subject to a maximum slab

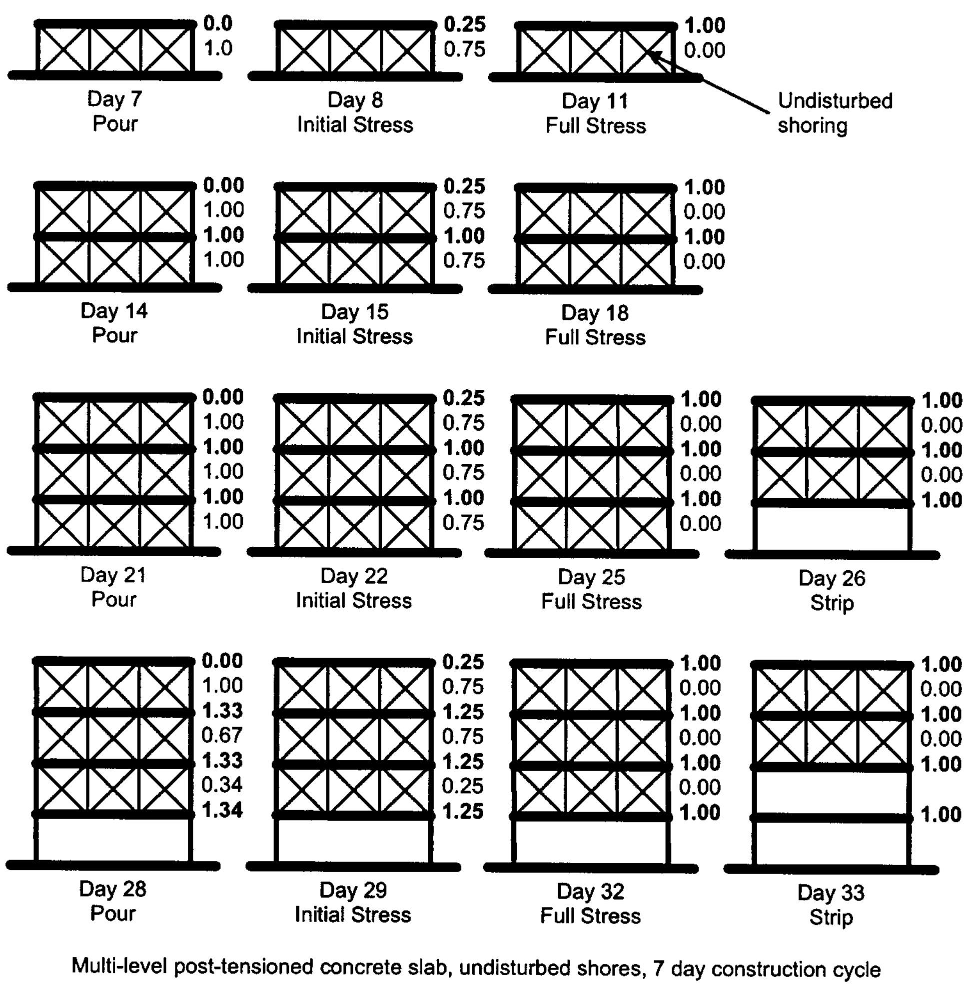

Fig. 3. Slab load ratios for posttensioned slabs with undisturbed shores

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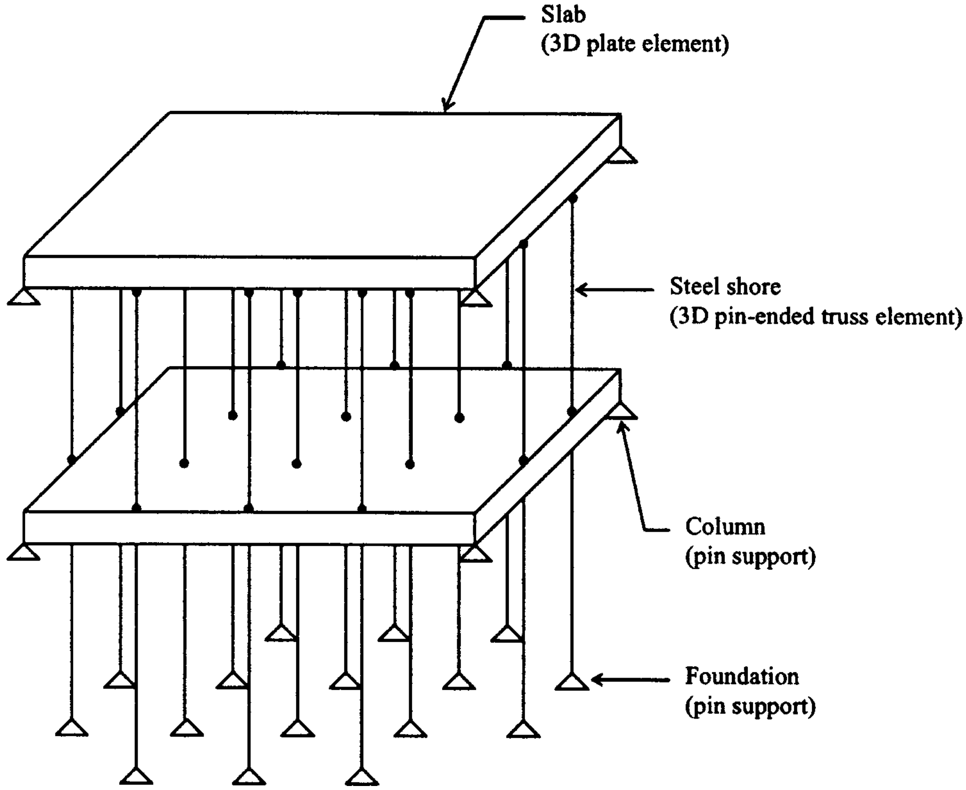

Fig. 4. Schematic structural component model

load ratio of 1.34 as each new slab is poured. This maximum slab load ratio does not converge to a lower value but alternates between 1.34 as each new slab is poured and 1.00 as that new slab receives full posttensioning (thus causing a redistribution of load upward through the structure). Fig. 3 also indicates that each slab is subjected to a slab load ratio of 1.25 at the stage of initial stress. The actual slab load ratio is dependent on the portion of load balanced by the initial stress. Assuming equal slab stiffness, the slab load ratios indicated at day 28 of Fig. 3 repeat up the structure without alteration.

As indicated in Fig. 3, slab loadings vary from 100% of a typical slab load to 134% of a typical slab load. While this might initially appear to result in an "overload" situation, it needs to be remembered that slabs are design for combinations of self-weight, dead load, and live load. Kajewski (1998) presents an analysis of slab factors of safety for the various stages of slab construction and indicates that for the slab construction cycle outlines in Fig. 3, the factor of safety available for the slabs varies from 1.25 to 3.22.

Slab Load Ratios for Posttensioned Slabs with Reshores

The preceding examination was based on an assumption that a backpropping operation was adopted. Reshoring, however, is a technique that involves stripping formwork from large areas of slab soffit before the shores are replaced. With this technique, the slab is allowed to deflect, thus causing a redistribution of shore and slab loads.

Adopting a reshoring procedure produces a situation identical to the slab load ratios for a posttensioned slab with undisturbed supports. This is to be expected as the application of posttensioning produces a situation in which the undisturbed shores are completely unloaded prior to their removal (assuming full load balancing). There is no shore load to be redistributed during the stripping operation and, therefore, the slab load ratios remain unaltered.

Finite-Element Analysis Method

In attempts to model the actual physical properties of the slabs and shoring more accurately, a number of researchers have modeled the structure and shoring procedure using two- and three-dimensional computer models. Liu et al. (1985) for example, used a three-dimensional finite-element model to examine the effects of foundation rigidity, column axial stiffness, slab aspect ratio, and shore stiffness distribution. Numerous other researchers (Aguinaga-Zapata and Bazant 1986; Liu and Chen 1987; McAdam and Behan 1988; McAdam 1989; El-Shahhat and Chen 1992; Mosallam and Chen 1992; Stivaros and Halvorsen 1992; El-Shahhat et al. 1993) have used various computer models to examine a range of criteria influencing multilevel formwork load distribution. It was commonly found that the simplified analysis method was able to predict the location and construction stage at which the maximum slab and shore loads occurred but it did not accurately determine the magnitude of these loads.

An overall schematic representation of the structural component model adopted for this analysis is indicated in Fig. 4. The rationale behind the adoption of the particular elements is described in the following sections.

It is assumed that all slab levels in the regions being monitored are essentially symmetrical about both primary axes. Allowing for this symmetry, only one-quarter of the slab is modeled to save computation time. The edge fixity for the slab edges along the

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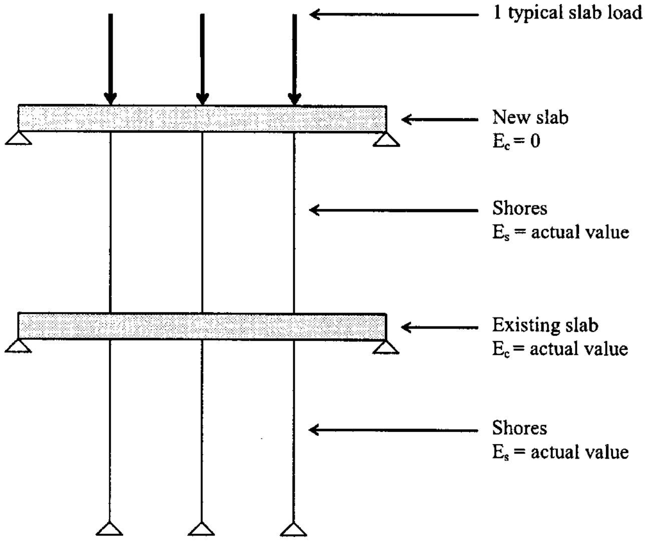

Fig. 5. Construction stage model—Pouring a new slab

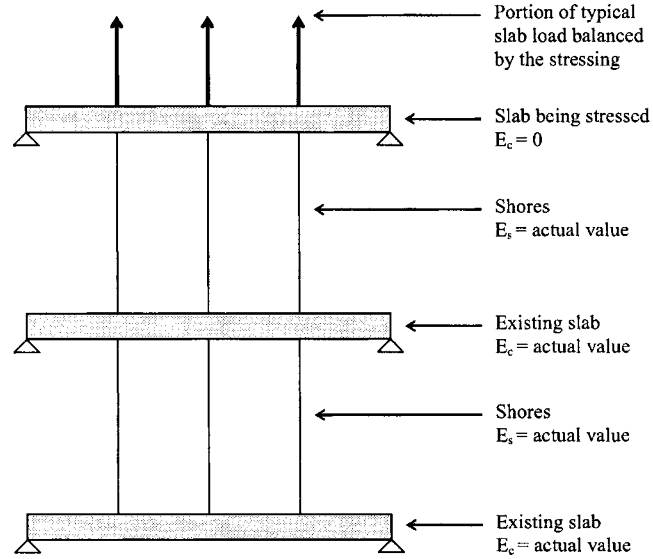

Fig. 6. Construction stage model—Stressing a slab

lines of symmetry are set to allow only vertical translation with all other degrees of freedom (translation and rotation) restrained. The continuous slab edges are restrained such that translation is allowed in the vertical direction and fully fixed in all other degrees of freedom. Translation in the vertical direction at the column support is restrained as described in following sections. Allowance is made in the model for the relative age and hence stiffness of the concrete.

Columns. Under the weight of a slab, the concrete columns compress a negligible amount, particularly when compared with the compression of the shores. The shortening of the columns is, therefore, ignored in the analysis. To confirm this assumption, a number of trial finite-element analyses were performed in which the columns were modeled with their full sectional properties and alternately as fully restrained supports. The results from these trial analyses indicated no discernible difference between the shore loads for the two models. Column shortening is ignored in the finite element analysis and the columns are modeled as pinned supports rather than vertical concrete members with finite sectional properties.

Steel Shores. The steel shores are modeled in the finite-element model as three-dimensional pin-ended truss elements with the material and sectional properties determined from manufacturers' data.

Foundations. Infinite stiffness is assumed.

Construction Stage Modeling.

It is necessary for the finite element model to determine the multilevel formwork load distribution at the stages of pouring a new slab, stressing a slab, stripping shores or reshores, and reshoring. Each of these construction stages was modeled individually with the slab load ratios at any stage of construction being determined through a process of superposition.

Pouring a New Slab. Fig. 5 indicates the construction stage model for the pouring of a new slab. As indicated, when a slab is first poured and in a plastic state, it has no strength or stiffness and the shores are required to support the new slab load fully. To model this stage of construction, the actual shore properties are adopted; the new slab stiffness (E_c) is set to zero; and all other slab stiffnesses are set at their actual time-dependent values.

Stressing a Slab. Fig. 6 indicates the construction stage model for the stressing of a slab. To model the stressing operation, an upward load equivalent to the portion of slab load balanced by the stressing is applied to the slab being stressed. If this load is applied to the slab being stressed, it would place the shores supporting that slab into tension. This in turn would tend to lift the other slabs and shores in the interconnected system. In practice, the shores are unable to develop tension as they are not rigidly fixed to the slab over and slab under. To model this inability for the shore to develop tension, it would be necessary for the shores to be set as zero-tension gap elements. Setting the shores as zero-tension gap elements in the analysis, however, does not result in the required redistribution of loads in response to the stressing. As a process of superposition has been adopted, it is necessary for this stage of construction to "lift" the slab load from the supporting slabs such that reverse loads are induced in the structure. These reverse loads, when superimposed on the existing loads, produce the required load distribution for this particular stage of construction. Zero-tension gap elements, being unable to develop tension, are not able to lift the supporting structure to generate these reverse loads. To overcome this problem, the shores are left as pin-ended truss members, but the stiffness of the slab being stressed is set to zero-regardless of its actual stiffness. This produces the same effect as if the shores were unable to develop tension but provides the required load redistribution. The stiffness for other slabs and shores are set at their actual values.

Stripping Shores and Reshores. Fig. 7 indicates the construction stage model for stripping shores or reshores. As indicated, the load that was in the shores to be stripped immediately prior to their removal is applied to the slab being stripped. To model this stage of construction, the actual properties for the shores and slabs at the particular age are used.

Reshoring. As reshores are installed without any load in them, they do not alter the multilevel formwork load distribution. It is, therefore, unnecessary to model this stage of construction.

Superposition of Construction Stage Models

The analysis of the individual construction stage models provides slab and shore loads for a particular stage of construction as if it was the only stage. A multilevel formwork procedure is a con-

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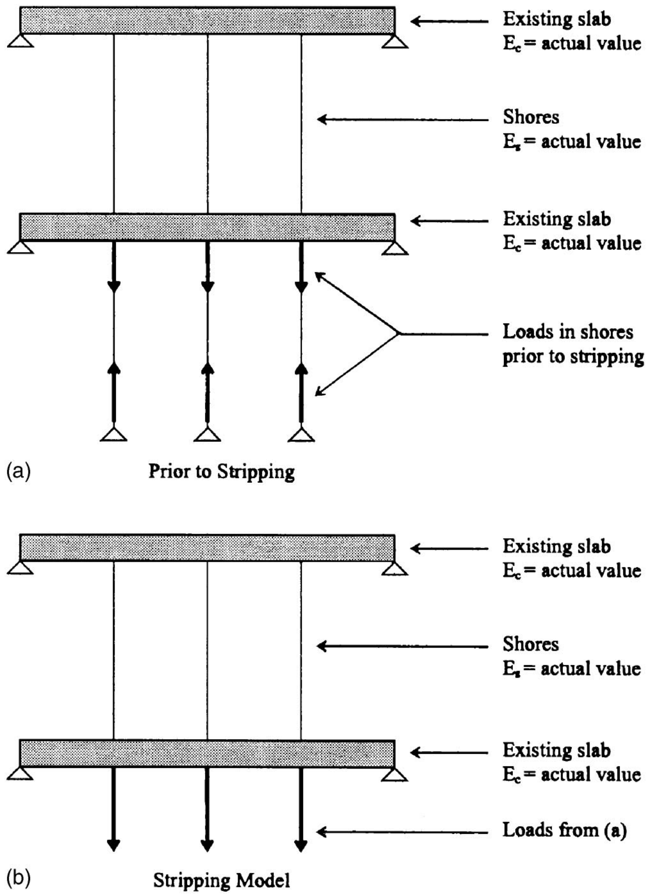

Fig. 7. Construction stage model—Stripping shores or reshores

tinuous activity with the slab and shore loads adjusting at each stage of construction as a new load-sharing equilibrium is reached. As each new slab is added, for example, the load distribution resulting from that new load must combine with loads that already exist in the slabs and shores from earlier construction activities. It is only by examining the cumulative effects that the actual slab and shore loads can be ascertained.

The finite-element model developed for this project is based on a process of superposition in which the load distribution resulting from a particular construction stage is added to the loads already existing in the system. A similar form of superposition was adopted by El-Shahhat and Chen (1992, pp. 529–530) who used the principle of superposition to "*calculate accumulated displacements due to successive loading steps and removing shores and reshores*."

Case Study Project

To validate the proposed analysis methods, the shoring loads from a posttensioned concrete building were monitored during the construction of a multilevel concrete building as a part of research undertaken by Kajewski (1998). The building project consisted of 14 storys of primarily one-way posttensioned concrete slabs and beams. To obtain a greater volume of data and to provide a greater level of redundancy, the shore loads were monitored for each level of the structure in two separate slab regions. The particular slab regions adopted were selected because the reinforcement and posttensioning in the regions were without irregularity; contained reinforcement and posttensioning within the normal percentage ranges; the slab aspect ratios were within the range of 0.6 to 1.0 [identified by Liu et al. (1985) as having little effect on shore loads]; and there were no plans to place abnormally heavy construction loads within these regions. The slabs were typically 160 mm thick with the one-way band beams being 1,500 mm wide by 270 mm deep with splayed sides. Shore loads were measured at approximately the same time every day using a 250 mm Huggenberger Extensiometer. The extensiometer measures extensions and compressions of the shores between two points fixed to the shores after construction of the formwork but prior to pouring of the concrete. The testing procedure and validation of the results, including a pilot study, are outlined in greater detail in Kajewski (1998).

The posttensioning for the full-scale project was designed such that full stress balanced the full slab self-weight. This full stress was to be applied to the slab at an age of 5 days (typically) and a concrete compressive strength of 22 MPa or better. The initial stress was to be 25% of full stress applied at a slab age of approximately 24 h. At the stage of initial stress, data from the project indicated that slabs were forced to carry between 23 and 25% of their self-weight. The unbalanced portion of the slab self-weight (75 to 77%) remained in the supporting shores. At the stage of final or full stress, the slabs lifted to carry between 92 and 100% of their self-weight.

This phenomenon was similar for all of the slabs when receiving initial or final stress, as indicated Table 1. Table 1 indicates that for the initial stress stage, the error in slab load balanced varies from 0.00 to 0.07 of a typical slab load. The error in slab load ratio for the full stress stage varies from 0.00 to 0.09 of a typical slab load. This represents a maximum error of 9%.

From the low error levels and the trends indicated in Table 1, it can be concluded that the effect of posttensioning is to force a slab to carry a portion of its self-weight in direct proportion to the slab load balanced. There is a corresponding reduction in the supporting shore and slab loads. For example, if 25% of the slab self-weight is balanced by the posttensioning, it can be assumed that the slab is forced to carry 25% of its self-weight. The remaining 75% of the slab self-weight being carried by the supporting slabs and shores. If the full slab self-weight is balanced by the posttensioning, the supporting shores and slabs are completely unloaded of this slab's self-weight.

Confirmation of the Validity of the Proposed Analysis Techniques

The slab load ratios obtained from measurements on the full-scale project are used to confirm the validity of the modified simplified analysis method and the finite-element model. The maximum variation in slab load ratios for the slabs on the full-scale project when compared with the values predicted by the simplified analysis method and the finite-element model are summarized in Table 2. The table provides the maximum variation in slab load ratios at the center of the slab and the average across the slab for each of the two slab regions monitored. A variation of 0.10, for example, indicates that the actual slab load ratio and the predicted slab load ratio vary by 0.10 or 10% of a typical slab load. [Word limit restrictions prevent the full presentation of the analysis results—these results are provided in full in Kajewski (1998)].

Table 2 demonstrates that there is little difference in the slab load ratios predicted by the simplified analysis method and the finite-element model. Table 2 indicates that the maximum difference in predicted values using either analysis method is only 0.03

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Table 1. Shore Loads and Errors in Load Balancing

Slab level	Slab location	Initial stress (25% full) Actual slab load ratio	Initial stress (25% full) Error	Full stress (100%) Actual slab load ratio	Full stress (100%) Error
Mezzanine	Grid 7-8	0.23	0.02	0.92	0.08
	Grid 9-10	0.23	0.02	0.94	0.06
Boulevard	Grid 7-8	0.21	0.04	0.97	0.03
	Grid 9-10	0.20	0.05	0.95	0.05
1	Grid 7-8	0.22	0.05	0.98	0.02
	Grid 9-10	0.23	0.02	0.95	0.05
2	Grid 7-8	0.22	0.03	0.95	0.05
	Grid 9-10	0.22	0.03	0.96	0.04
3	Grid 7-8	0.18	0.07	—	—
	Grid 9-10	0.25	0.00	0.95	0.05
4	Grid 7-8	—	—	0.91	0.09
	Grid 9-10	—	—	0.95	0.05
5	Grid 7-8	0.22	0.03	0.91	0.09
	Grid 9-10	0.19	0.06	0.93	0.07
6	Grid 7-8	—	—	0.95	0.05
	Grid 9-10	—	—	0.92	0.08
7	Grid 7-8	—	—	0.93	0.07
	Grid 9-10	—	—	0.95	0.05
8	Grid 7-8	0.26	0.01	0.93	0.07
	Grid 9-10	0.22	0.03	0.91	0.09
9	Grid 7-8	0.27	0.02	1.00	0.00
	Grid 9-10	0.23	0.02	0.94	0.06
10	Grid 7-8	0.25	0.00	1.00	0.00
	Grid 9-10	0.23	0.02	0.92	0.08
11	Grid 7-8	0.23	0.02	0.94	0.06
	Grid 9-10	0.26	0.01	0.96	0.04

or 3% of a typical slab load. Of special note is that the finite element model does not appear to provide any greater degree of accuracy when predicting the slab load ratios.

Table 2 indicates that the finite-element model is only slightly more accurate when examining the center shore or slab value and slightly less accurate when predicting the average values. From this particular project, it is not possible to ascertain if this minor variation between the predicted values would become more pronounced and the finite-element model provide greater accuracy in all circumstances. For example, the structural sections on the typical slabs in this project varied gradually from 160 mm thick slabs to $1{,}500 \times 270$ mm band beams with 900 mm splays. It seems reasonable that the effect of more pronounced section changes may make the simplified analysis method less accurate and the finite-element model more accurate.

Table 2. Slab Load Ratio Variation for the Proposed Analysis Techniques

Location	Maximum variation between actual and predicted slab load ratios: Simplified analysis	Maximum variation between actual and predicted slab load ratios: Finite-element method
Center: Grid 7 to 8	0.10	0.10
Average: Grid 7 to 8	0.12	0.15
Center: Grid 9 to 10	0.09	0.07
Average: Grid 9 to 10	0.10	0.11

The maximum variation in slab load ratios is 12 and 15% of a typical slab load for the simplified analysis method and finite-element method, respectively. Many of the variations in slab load ratios were less than 5% of a typical slab load. The magnitude of the variations indicates that both methods predict the slab load ratios with a reasonable degree of accuracy, therefore, either method could be used with confidence. The small variations arise from a number of possible sources including, but not necessarily limited to, the effects of creep and shrinkage of the slabs; the effects of creep and shrinkage of the columns; the presence of unaccounted construction loads; unaccounted losses in the stressing operation; under- or overstressing; and variations in the concrete density (slab dead load). The variability of these occurrences arising from slightly different structural systems and structural influences might also account for the differences in variations between grids 7 and 8 and grids 9 and 10 (indicated in Table 2). Slab grids 7 and 8, for example, are influenced by the close proximity of a reinforced concrete lift core while slab grids 9 and 10 are not.

In situations, such as where the structural slab section varies significantly, it may be necessary to adopt a finite-element method to improve the accuracy of the solution. In other systems—such as flat slabs, flat plates, or slabs with shallow band beams—the simplified analysis method provides the simplest method for determining the load distribution that occurs when multilevel formworking. The extra analysis time and complexity arising when using the finite-element method appear unjustified on the basis of an insignificant improvement in the accuracy when predicting slab load ratios. Certainly if creep and shrinkage were to be analyzed, the finite-element method would be necessary. Many researchers, however, conclude that ignoring the effects of creep provides a conservative result. Creep really only needs to be considered when examining the long-term deflections arising from the early loading of the slabs.

Conclusions and Recommendations for Further Research

The results obtained from the project allow the following conclusions to be drawn with regard to the effect of posttensioning on multilevel formwork load distribution.

1. The assumption of slab lift, leading to a corresponding reduction in shore loads is valid. The proportion of the slab lifted from the shores is directly related to the portion of the slab load balanced by the stressing. That is, if full dead load is balanced, the shores supporting the slab are completely unloaded of that slab self-weight. If only 25% of the load is balanced, such as at the stage of initial stress, 25% of the slab self-weight will be carried by the slab. The balance of the slab self-weight (75%) remains in the supporting shores.
2. The shores produce a nonuniform load due to the effects of infinite column stiffness, slab edge fixity (or continuity), and changes in slab section profiles.
3. The process of load distribution that occurs in a posttensioned structure prior to stressing is similar to the load distribution for a conventionally reinforced structure. That is, the loads due to the pouring of a new slab are distributed downward through the interconnected slabs in direct proportion to their relative stiffness. As shores are removed, the

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loads are distributed upward through the interconnected slabs in direct proportion to their relative stiffness. The effect of stressing is to cause an unloading of the shores and a redistribution of the loads among the slabs. This redistribution is also in direct proportion to the slab's relative stiffness, with the exception of the slab being stressed, which supports only that portion of the load balanced.

4. Both the proposed simplified analysis method and the finite-element model can be used to predict the slab load ratios.
5. Both analysis methods provide approximately the same degree of accuracy when analyzing flat slabs, flat plates, and slabs with minimal changes in the section properties. The finite-element method provides greater accuracy when the slab sections change significantly.
6. The simplified analysis method is recommended for use when analyzing flat plate, flat slabs, and slabs with minimal changes in the section properties, due to its ease of use.

Much of the research associated with multilevel formwork load distribution for conventionally reinforced slabs has been in the area of time-dependent effects from concrete creep and shrinkage. Although this research confirms that the immediate effects of such influences are minimal for conventionally reinforced slabs, research into these effects on posttensioned slabs is recommended.

It is also recommended that further research be undertaken into the effects of nontypical situations including shock or impact loading from construction activities; sudden destressing of slab sections from anchor or tendon failure; nonuniform load balancing arising from significantly different stress levels being put into adjacent tendons; and nontypical slab sections.

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