

Guide for Shoring/Reshoring of Concrete Multistory Buildings

Reported by ACI Committee 347

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Richard C. Moore
William R. Phillips
Douglas J. Schoonover
W. Thomas Scott
Aviad Shapira
Rolf A. Spahr

*Principal author.

This guide presents information and design criteria for shoring/reshoring operations during the construction of reinforced and post-tensioned multi-story buildings. It provides methods for developing safe construction schedules and provides design examples. It is written for the use of formwork engineer/contractors and engineer/architects.

Keywords: construction loads; falsework; form removal, formwork; post-tensioning; reshoring; shoring.

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CHAPTER 1—INTRODUCTION

In multistory cast-in-place concrete building construction, freshly cast floors are placed on formwork that is temporarily supported by a system of shores and reshores until the concrete has the ability to be self-supporting. Construction loads, imposed by the shoring system on the slabs below, may be significantly larger than the design loads of those floors. Furthermore, the concrete of slabs below may not have attained sufficient strength before the construction loads are applied. As a result, it is critical to determine the early-age load strength of the floor slabs, including punching shear strength, to avoid the possibility of partial or total failure of the structural system due to construction overload. To reduce and distribute the large construction load on the floor immediately below, to several lower floors, it is important to add reshores on lower levels. Therefore, an engineering analysis that considers both the construction load distribution and the early-age load-carrying capacity of the concrete slabs should be performed before shoring/reshoring operations begin.

Formwork failures and failures caused by improper reshoring or premature removal of supports and inadequate lateral bracing, have periodically occurred throughout the history of concrete construction. Premature removal of shores and reshores can contribute to construction failures or defects such as permanent excessive deflections (sagging) or cracking in the completed structure. Also, if over-loaded prematurely, time-dependent deflections under load (creep) will be larger, and sagging is more likely to be both noticeable and objectionable.

Decisions regarding the removal of forms and relocation of the shores are too often made without the benefit of a proper analysis of the structural effects, or in many cases, without any analysis at all. Still, there is no commonly accepted method considered as the proper analysis in the construction industry.

To ensure satisfactory performance and structural safety during construction, a thorough understanding of construction loads applied to the slabs at early ages is necessary. Equally important is knowledge of the behavior and the strength of early-age concrete members that support their own weight and construction loads.

The formwork engineer/contractor is usually guided in formwork operations by the following codes, standards, or guides:

- ACI 347, "Guide to Formwork for Concrete"
- ACI 318, "Building Code Requirements for Structural Concrete"
- ACI 301, "Specifications for Structural Concrete"
- ANSI A10.9, "American National Standard for Construction and Demolition Operations—Concrete and Masonry Work—Safety Requirements"
- OSHA 29 CFR, "Construction Safety and Health Regulations for Construction"
- SEI/ASCE 37, "Design Loads on Structures During Construction"

Other documents that can provide formwork design requirements or guidelines include state and local building codes, and guidelines prepared by contractors, formwork manufacturers, and certain construction agencies.

The above referenced documents provide basic guidelines for general formwork operations. At the present time, however, there are no codes or standards that provide detailed design and construction requirements specifically for shoring/reshoring operations for multistory reinforced and post-tensioned concrete construction. Investigation for usable procedures to establish safe and cost-effective shoring/reshoring operations has been ongoing for several decades. The effort has focused on two major areas: determining the distribution of loads carried by the concrete structure during construction, and estimating the strength of the concrete members to resist the construction loads.

This report outlines the importance of proper formwork design for multistory structures and provides basic requirements for safe construction. ACI SP-4, *Formwork for Concrete*, serves as an expanded commentary to ACI 347, "Guide to Formwork for Concrete," and provides detailed information relative to formwork practices, including a discussion of and procedures for shoring/reshoring analysis. ACI 318, "Building Code Requirements for Structural Concrete," requires contractors to furnish the building official, upon request, with the structural calculations and concrete strength data used in planning and implementing shoring/reshoring operations. Such data and information should be furnished to the engineer/architect who should evaluate the effects of construction loads to immediate and long-term deflections. This code requirement obliges contractors and formwork designers to acquire an understanding of the construction loads and the structural behavior of the buildings during construction. This understanding enables them to develop a rational shoring/reshoring system design that is as economical as possible without compromising safety, quality, and serviceability.

The objective of this document is to present practical guidelines for the design of shoring/reshoring operations. This document provides formwork design tools to evaluate the safety of construction schedules for multistory reinforced concrete and post-tensioned concrete structures.

CHAPTER 2—SHORING/RESHORING CONSTRUCTION NEEDS

2.1—Definitions

The following terms will be used in this guide. All these terms may also be found in ACI 347.

backshores—shores placed snugly under a concrete slab or structural member after the original formwork and shores have been removed from a small area at a time, without allowing the slab or member to deflect; thus, the slab or other member does not yet support its own weight or existing construction loads from above.

centering—specialized temporary support used in the construction of arches, shells, and space structures where the entire temporary support is lowered (struck or decentered) as a unit to avoid introduction of injurious stresses in any part of the structure.

engineer/architect—the engineer, architect, engineering firm, architectural firm, or other agency issuing project plans

and specifications for the permanent structure, administering the work under contract documents.

formwork—total system of support for freshly placed concrete, including the mold or sheathing that contacts the concrete as well as all supporting members, hardware, and necessary bracing.

formwork engineer/contractor—engineer of the formwork system, contractor, or competent person in-charge of designated aspects of formwork design and formwork operations.

preshores—added shores placed snugly under selected panels of a deck forming system before any primary (original) shores are removed. Preshores and the panels they support remain in place until the remainder of the complete bay has been stripped and backshored, a small area at a time.

reshores—shores placed snugly under a stripped concrete slab or other structural member after the original forms and shores have been removed from a large area, requiring the new slab or structural member to deflect and support its own weight and existing construction loads applied before the installation of the reshores. If prefabricated drop-head shores for slab formwork systems are used, the shores can become the reshores if a large area of shoring is unloaded, permitting the structural members to deflect and support their own weight. If they are not, then they become backshores.

shores—vertical or inclined support members designed to carry the weight of the formwork, concrete, and construction loads above.

2.2—Advantages of reshoring

In multistory cast-in-place construction, rapid reuse of form material and shores is desired to allow other trades to follow concreting operations as closely as possible. The shores that support the newly placed concrete transmit that weight to the floor slab below, which can exceed that floor slab's design load capacity. For this reason, shoring or reshoring is provided over a number of floors to distribute the construction load to several floor levels below.

Stripping formwork is usually more economical if all the form material is removed at the same time before placing reshores. In this case, the structure system is required to support its own weight, thus reducing the load in the reshores. A combination of shores and reshores usually requires fewer levels of interconnected slabs, thus freeing more areas for other trades.

Backshoring and preshoring are other methods of supporting new construction that are less widely used and involve leaving the original shores in place or replacing them individually so as not to allow the slab to deflect and carry its own weight. These methods require careful supervision by the formwork engineer/contractor and review by the engineer/architect to ensure excessive slab and shore loads do not develop.

2.3—Types of forming systems

An important consideration in multistory cast-in-place concrete building construction is the type of forming system to be used. The selection of the forming system for constructing a cast-in-place concrete structure is a critical decision that affects both the construction schedule and cost.

Systems vary from traditional wood post-and-beam formwork/shoring to modern prefabricated systems involving sophisticated engineering, materials, and equipment.

There are several prefabricated forming/shoring systems that are used to support concrete slabs during construction, including shoring-based systems, flying truss systems, column-mounted systems, and tunnel-forming systems. The following description of these systems is adapted from Jensen (1986).

Shoring-based systems—Deck (slab) forms are supported on shores placed on the slab below. The shores may be single posts of wood, or metal, or assembled from frames. Job-built deck forms usually consist of wood or aluminum stringers and joists (runners) with the deck surface made of plywood, supported on single-post or frame-type shoring. These forms are sometimes made up in larger panels tied or ganged together as tables with attached frame-type shoring for movement by crane. Deck forms may also be assembled on the job from proprietary panels framed in wood, steel, or aluminum, sometimes with their own proprietary shoring systems. Some of these systems allow removal of the slab forms while the shores remain in place until sufficient concrete strength is developed to allow the shore removal and reshoring process.

Flying truss systems—Flying truss systems are made up of steel or aluminum trusses, topped with aluminum or wood joists and decked with plywood. Adjustable legs or shores support the truss on a previously cast slab. The truss-mounted forms are moved as a unit by crane from one casting position to the next.

Column-mounted systems—Column-mounted systems are long-span form panels supported by brackets or jacks anchored to concrete columns and shear walls. The deck panel is generally moved by crane. Similar systems available for bearing wall buildings support slab forms on brackets anchored to the walls. These systems make it possible to eliminate most vertical shoring and reshoring.

Tunnel-forming systems—Tunnel-forming systems are factory-made, inverted, U-shaped steel form systems that permit casting both slab and supporting walls at the same time. When the concrete has gained sufficient strength, the tunnels are collapsed or telescoped and moved to the next pour. For longer slab spans, the tunnel form may be made in two inverted L-shapes (termed half-tunnels).

CHAPTER 3—CONSTRUCTION LOADS ON FORMWORK

3.1—Construction loads

Construction loads are those loads imposed on a partially completed or temporary structure during the construction process. Construction loads on formwork include vertical dead and live loads of both the formwork and the structure, horizontal loads due to wind, vertical and lateral impact of the equipment, and vertical and horizontal forces induced by inclined support members of the formwork. The formwork system is required to support all construction loads that may be applied until these loads can be carried by the concrete structure itself.

3.1.1 Gravity loads—Gravity loads are categorized as either dead or live loads. The dead load includes the weight of reinforcement, freshly placed concrete, and formwork. The live load includes the weight of workers, equipment, tools, runways, and any impact produced by concrete placement or equipment operations. Though impact loads are dynamic, for simplicity they are treated as statically applied loads.

ACI Committee 347 recommends that both vertical supports and horizontal framing components of formwork be designed for a minimum live load of 50 lb/ft² (2.4 kPa) of horizontal projection to provide for weight of workers, runways, screeds, and other equipment. When motorized carts are used, the minimum live load should be 75 lb/ft² (3.6 kPa). The minimum design value for combined dead and live loads should be 100 lb/ft² (4.8 kPa), or 125 lb/ft² (6.0 kPa) when motorized carts are used.

The construction live load is usually applied to the uppermost slab during concrete placement of that slab, and it is assumed to be removed when the concrete placement is completed. If other loads, such as equipment or stored materials are known to be present on lower floors during construction, they should be considered. When justified by an analysis of the construction operations, the construction live load used for design of reshores only may be reduced as provided by SEI/ASCE 37, Chapter 4, “Construction Loads.”

3.1.2 Lateral loads—Lateral loads on the formwork system arise from wind, seismic events, inclined formwork supports, impact of concrete placement, sequence of concrete placement, thermal effects, and mechanical equipment used. ACI 347 recommends a minimum horizontal load as either 100 lb/linear ft of floor edge (1.46 kN/m) or 2% of the total superimposed dead load, whichever is greater. SEI/ASCE 37 provides methods for determining appropriate design wind speeds and seismic lateral loads for short time intervals of construction exposure. Wind loadings can be estimated based on either closed or latticed configurations of shoring and formwork.

3.1.3 Other loads and conditions—The formwork may be subjected to loads due to unsymmetrical placement of concrete, impact of concrete during placement, starting and stopping of equipment, uplift, concentrated loads of reinforcement, form handling loads, and storage of construction materials and equipment. Where possible, such loads should be avoided. Usually these loads occur over a relatively small area and can cause local failures of the formwork, and perhaps the structure, if not controlled. Some loads, such as piling up of concrete, cannot be anticipated and must be avoided. Additionally, large point loads from shoring bearing on a thin slab may create excessive flexural and shear stress.

3.1.4 Post-Tensioning load distribution—Shores, reshores, and backshores need to be analyzed for the load redistribution that occurs when slabs and beams are post-tensioned. This analysis should also include members of floors below the post-tensioning activity because the relieved shoring loads above the post-tensioned members are transferred to the other supporting members.

While the engineer/architect is ultimately responsible for the structure, close coordination between the engineer/architect and the formwork engineer/contractor is recommended to estimate the magnitude and location of construction loads when members are post-tensioned. An understanding should be reached between the engineers as to who is responsible for the determination of the post-tensioning sequence and the subsequent analysis of the construction load redistribution.

3.2—Load combinations

A combination of construction loads, based on the proposed construction method and sequence, should be considered to establish the critical loading conditions on the formwork and temporary construction loads on the structure. For example, concrete placement and shore/reshore removal are the most critical construction phases for concrete slabs and the formwork. The construction phase after the form and shore installation and before concreting presents the most critical condition for the effects of wind load. During this stage, the formwork must be designed to resist its own weight, any other gravity loads, as well as horizontal and/or uplift wind loads.

3.3—Typical phases of construction

In a typical construction cycle for a multistory cast-in-place concrete building where both shores and reshores are used, there are four construction phases:

- *Phase 1*—Installation of the shores and formwork followed by the casting of the floor slab;
- *Phase 2*—Removal of the shores and formwork allowing the slab to deflect and carry its own weight;
- *Phase 3*—Removal of reshores at the lowest interconnected level; and
- *Phase 4*—Placement of reshores in the story from which the shores and forms were removed. The reshores are placed snugly without initially carrying any load.

If only shores are used, then the third and fourth phases are eliminated. According to ACI Committee 347, the reshores should be installed snugly under the slab, just stripped so that they are relatively load-free upon installation. This stripping procedure allows the slab to deflect under its own weight and the reshores are installed without preload.

The following example of one level of shores and two levels of reshores in a simple three-bay, multistory structure illustrates the above four phases.

Figure 3.1(a) shows Phase 1, when the (n+4) floor is being cast. The weight of the fresh concrete and the formwork along with the 50 lb/ft² (2.4 kPa) or 75 lb/ft² (3.6 kPa) construction live load is distributed among the interconnected slabs (n+1), (n+2), and (n+3) through the shoring/reshoring system.

Figure 3.1(b) shows Phase 2 when the slab has hardened and the construction live load is gone. Shores are removed from the (n+3) floor and any remaining load in these shores is redistributed to the slabs above.

Figure 3.1(c) shows the removal of the reshores from the (n+1) floor, Phase 3. Any load in the reshores is removed

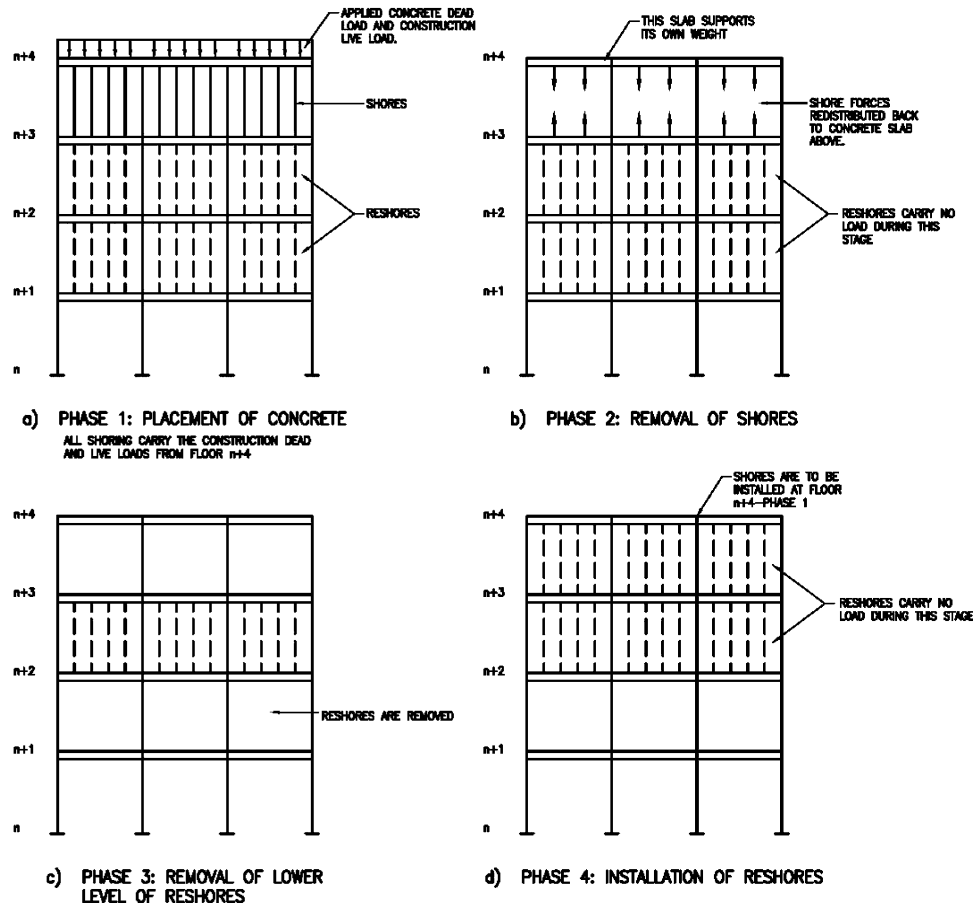


Fig. 3.1—Typical construction phases for multistory reinforced concrete buildings.

from the lowest slab ($n+1$) to which this load was supported and distributed to the slabs above.

Figure 3.1(d) shows the installation of the reshores on the ($n+3$) floor, Phase 4. During Phases 3 and 4, there is no structural disturbance to the floor above because the reshores are assumed to be relatively load-free upon installation.

While this example uses two levels of reshoring, each structure and job-specific circumstances should be individually evaluated. Depending on the specifics of the structure's capacity and the planned construction sequence, more or possibly less levels of reshoring may be required.

3.4—Construction load distribution

The question of how construction loads are distributed between the formwork system and the newly cast supported concrete members has been a subject of debate in the construction industry. Several designers and researchers have published proposed methods to determine the forces in concrete structures during construction.





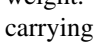
The most significant work was published in 1963 by Grundy and Kabaila. This landmark paper presents a simple method of calculating construction loads carried by slabs and shores during the construction of multistory flat plate and flat slab concrete buildings. The method is known as the simplified method. The model consists of a single bay structure with the following assumptions:











- The deformations of concrete slabs are considered as elastic (shrinkage and creep of concrete are neglected);
- The shores are infinitely stiff relative to the supported slabs;
- The reactions of the shores are assumed as uniformly distributed;
- The lowest level of shores and reshores are supported on a rigid foundation at the beginning of the construction; and
- The loads applied to the slab/form system are distributed between the supporting slabs in proportion to their relative flexural stiffnesses. The original simplified method did not include the reshoring levels (Grundy and Kabaila 1963).

Obviously, the assumptions of the simplified method are not precisely true. Analytical studies by other researchers based on the simplified method verified its validity by comparing the predicted values with field measurements. Field measurements have consisted of measured loads on shores and reshores during the construction process. Most of the available field observations were found to be in fair agreement with the predicted values. The assumptions and limitations of the method have been investigated and the simplified method has been refined in various ways: in construction methods and schedules, introduction of reshores, analysis of short- and long-term deflections, and in structural reliability. Further information on the simplified

Table 3.1—Simplified analysis of loads on shores and slabs using one level of shoring, two levels of reshoring

D = weight of slab
 Assumed construction live load = 0.4 D
 Assumed shore and form weight = 0.1 D
 Reshore weight is neglected

 RIGID SUPPORT AT STARTING LEVEL
 FRESHLY PLACED SLAB
 HARDENED SLAB
 STORY OF RESHORES
 STORY OF SHORES AND FORMWORK

STEP	OPERATION AND REMARKS	STRUCTURE STATUS	Load on slab in multiples of D			Shore/reshore load at end of operation
			At beginning	Change during operation	Total at end of operation	
1	Place Level 1 concrete. Full load is transmitted to ground by shores		0	0	0	1.5 D
2	Construction live load is gone. Remove Level 1 shores, allowing Slab 1 to carry its own weight. Then place reshores beneath it, snug but not loaded.		0	+1 D	1 D	0
3	Form, shore, and place Level 2 concrete. Slab 1 cannot deflect and all added load goes through reshores to ground.		0	0	0	1.5 D
			1 D	0	1 D	1.5 D
4	Slab 2 hardens and construction live load is gone. Remove the Level 2 forms and shores, allowing Slab 2 to carry its own weight. Then place reshores beneath it, snug but not loaded.		0	+1 D	1 D	0
			1 D	0	1 D	0
5	Form, shore, and place Level 3 concrete, including the 0.5 D construction live load and shore load. All added load goes through shores to the ground since slabs can't deflect further.		0	0	0	1.5 D
			1 D	0	1 D	1.5 D
			1 D	0	1 D	1.5 D
6	Construction live load is assumed removed as Slab 3 hardens. Remove shores beneath Level 3, allowing it to carry its own weight. This leaves no net load in reshores beneath Level 1, and they are removed and installed snugly beneath Level 3. They carry no load.		0	+1 D	1 D	0
			1 D	0	1 D	0
			1 D	0	1 D	0
7	Form, shore, and place Level 4 concrete with the assumed 0.5 D construction live load and shore load. The total new applied load, 1.5 D, is distributed equally to the three interconnected slabs.		0	0	0	1.5 D
			1 D	+0.5 D	1.5 D	1 D
			1 D	+0.5 D	1.5 D	0.5 D
			1 D	+0.5 D	1.5 D	0
8	Level 4 concrete hardens and the construction live load of 0.4 D is removed in equal parts from the slabs to which it was distributed.		0	0	0	1.1 D
			1.5 D	-0.13 D	1.37 D	0.73 D
			1.5 D	-0.13 D	1.37 D	0.36 D
			1.5 D	-0.14 D	1.36 D	
9	Remove shores beneath Level 4, causing that slab to carry its own weight. The load in those shores including their own weight is removed from the slabs to which it had been distributed		0	+1 D	1 D	0
			1.37 D	-0.37 D	1 D	0
			1.37 D	-0.37 D	1 D	0
			1.36 D	-0.36 D	1 D	0
10	Move reshores beneath Level 2 up, placing them snugly beneath Level 4, where they carry no load. There is no change in system loads. SYSTEM CONDITIONS ARE NOW THE SAME AS AT THE END OF STEP 6, AND WHEN THE LEVEL 5 SLAB IS PLACED, THE CYCLE REPEATS.		1 D	0	1 D	0
			1 D	0	1 D	0
			1 D	0	1 D	0
			1 D	0	1 D	0

method can be found in Agarwal and Gardner (1974); Gardner and Muskati (1989); Gardner (1985); Liu, Chen, and Bowman (1985); Liu, Lee, and Chen (1988); Gross (1984); Gross and Lew (1986); Stivaros and Halvorsen (1990, 1992); and Arafat 1996.

3.5—Application of the simplified method

Table 3.1 demonstrates the application of the simplified method. The example uses one level of shores and two levels of reshores. The construction live loads and weight of forms and shores are included in the load analysis. The slabs are assumed to have equal thickness and stiffness and, therefore, the construction loads are distributed equally among the slabs. The shores and reshores are assumed to be infinitely stiff relative to the supported slabs.

Following the four phases of construction, each floor level is subjected to construction loads that vary in magnitude as the construction advances.

In Step 1, the first elevated floor slab is placed, and the full load is transferred to the ground by the shores. In Step 2, the shores are removed and the slab is now carrying its own weight. The reshores are placed snugly under the slab, carrying no load. In Step 3, the second elevated floor slab is shored and placed. The first floor slab cannot deflect and all added load goes through the reshores to the ground. In Step 4, the shores are removed, and the second elevated floor slab carries its own weight. The reshores are placed under the second floor, but do not carry load. In Step 5, the third elevated floor slab is shored and placed. All added load goes through the shores and reshores to the ground.

In Step 6, the shores are removed, and the third elevated floor slab carries its own weight. The reshores are removed from beneath Level 1 and are placed under the third floor without carrying any load. During this step, the support conditions have changed because there is no longer a continuous support to the ground. When the fourth floor slab is shored and placed during Step 7, the added load is equally shared between the supporting slabs below.

The removal and relocation of shores and reshores, and the placement of a new slab at the top active floor, continues in a similar manner for the remaining steps. After Step 6, the cycles repeat throughout the full height of the building.

The load in shores at the end of each step is calculated on the basis of a summation of vertical forces. The total weight of slabs and construction loads above the shore level being considered, less the loads carried by slabs above, gives the load transmitted by the shores.

Similar construction load calculations can be developed for shoring systems utilizing more than one level of shores. Examples of calculating the construction loads when more than one level of shores is used are discussed by M. K. Hurd in ACI SP-4.

While the simplified method assumes distribution of the construction loads between the supported floors in proportion to their relative stiffness, some project-specific circumstances may necessitate altering the distribution slightly.

Some prefabricated commercial forming and shoring systems allow removal of the slab forms while the shores remain in place for a longer duration. Depending on the sequence of operations, the sequence of steps in the analysis would need to be appropriately modified.

3.6—Factors affecting the construction load distribution

Some of the major factors affecting the construction load distribution and the performance of concrete buildings during construction are slab continuity, slab type and stiffness, type and stiffness of shoring/reshoring system, and the rate of construction. Several studies (Gross 1984; Stivaros and Halvorsen 1990) investigated the effects of these factors on the construction load distribution.

3.6.1 Shore/reshore stiffness—The shoring/reshoring system stiffness can be a factor affecting the construction load distribution. The simplified method assumes infinite stiffness of the shoring/reshoring system, as compared with the flexural stiffness of the supported slabs (Grundy and

Kabaila 1963). ACI 347 raises caution when a compressible system is used. With a more compressible shoring/reshoring system, the structural system tends to shift as much as 15% of the slab loads to the uppermost interconnected floors as compared with rigid shores/reshores (Gross 1984; Gross and Lew 1986; Stivaros and Halvorsen 1990). The floors immediately below the level to be cast may have limited strength and are more sensitive to possible overload. The estimated construction loads at the upper floor may be increased to compensate for the error in calculating the construction loads when using the simplified method. Otherwise, the relative stiffness between the shoring/reshoring system and the supported slabs should be considered while calculating the construction load distribution among the interconnected slabs.

3.6.2 Floor stiffness and type—The increased slab stiffness resulting from concrete's strength gain during construction does not significantly affect the construction load distribution among the slabs. Any increase in slab stiffness due to the presence of beams, drop panels, or increase of slab thickness results in higher construction loads resisted by these slabs, because the stiffer members in a structural system attract a higher percentage of distributed loads. To the extent that higher strength contributes to slightly higher stiffness, it would result in slightly more load carried by the lower interconnected floors and, thus, partly compensate for the opposite effects due to finite reshore stiffness. Though the difference of concrete strength in the interconnected slabs does not significantly affect the construction load distribution among the slabs, it does, however, make a significant difference in the early age slab's resistance to cracking and deflection.

3.6.3 Shore system configuration—The shore or reshore placement configuration affects the construction load distribution. Where fewer shoring supports are located close to columns or structural walls, the floor slabs will share less construction load with the floors below, because a significant amount of the load will be transferred directly to the columns or walls. Where fewer shoring supports are located throughout the interior of the structural bays, however, such as truss-table systems, the large point loads will cause more severe loading conditions in the structure than the uniformly distributed loads assumed by the engineer/architect. This configuration may necessitate an increase in the number of floors of reshores to safely transfer the construction load into the floors below.

3.6.4 Number of shored levels—An increase in the number of shored levels is usually accompanied by an increase in the maximum applied slab loads. The increase in the number of shored levels, however, delays the occurrence of the maximum slab loads, allowing time for the slabs to develop greater strength. Also, as the number of shored levels increases, so does the accuracy of the simplified method of analysis.

3.6.5 Number of reshored levels—The use of reshored levels tends to decrease the maximum applied load on a floor, because the reshores spread the construction loads to the lower floors. The maximum slab load decreases at a decreasing rate as the number of the reshored levels increases (Stivaros and Halvorsen 1990). Therefore, the

number of reshored levels is effective only up to a certain number beyond which any additional reshore levels will not significantly affect the maximum construction load on the slab. Furthermore, as the number of reshored levels increases, the simplified method may underestimate the maximum construction loads at the upper level slabs significantly depending on the compressibility of the reshores used. The larger the stiffness of the reshoring system, the greater the accuracy of the simplified method. Other factors, such as how snug or plumb the reshores are installed and how much vibration has occurred on the floor to loosen them, can affect the effectiveness of reshores. The number of reshored levels should be optimized to reduce the applied construction loads to values that the early age slabs can withstand.

3.6.6 Rate of construction—The rate of construction does not significantly affect the construction load distribution between the various slab levels. The rate of construction determines number of days between when the concrete slabs are placed and when the slabs are subjected to the maximum construction loads. Because concrete strength gain is time-dependent, the rate of construction has an effect on the building's performance during construction.

3.7—Post-tensioning load redistribution

Load redistribution occurs during the application of post-tensioning to various concrete structural members such as slabs, beams, and girders. Depending on the level of tensioning, the shoring that supports these members can be partially or totally relieved of load. The loads from these members are transferred to supporting members and, therefore, to the shores supporting those members. If not carefully evaluated, the load redistribution due to post-tensioning can overload shores or reshores, as well as concrete members.

Therefore, it is necessary to analyze the construction load distribution on shores and reshores of post-tensioned structures in two stages:

- During concrete placement; and
- During post-tensioning.

The determination of construction loads during concrete placement is similar to the methodology described in the previous sections of this chapter.

The construction load redistribution depends on the sequence and the magnitude of tensioning at each stage of stressing. When a slab is post-tensioned, a portion of the shore load is transferred to the supporting beams. If the beam is shored, the beam shoring needs to be able to carry this redistributed load. When the beams are post-tensioned, a portion of the shore load is transferred to the supporting columns or girders.

The maximum construction loading condition for shoring occurs when slabs are fully stressed first, followed by beams and then by girders. In this case, a careful analysis of the load transfer to the beam and girder shores/reshores will be required. Should the tensioning sequence be reversed, then the construction load redistribution during tensioning will be different and most likely will result in lower shore loads.

The design of shoring/reshoring for post-tensioned construction requires the engineer to understand many vari-

ables such as site conditions, type of shoring system, and numerous combinations of stressing sequences and levels of stressing. Thus, only general guidelines are presented in this document. Information should be exchanged between the engineer/architect and the formwork engineer/contractor regarding design details and construction methods. The information required for the development of safe shoring/reshoring operations include:

- Members to be post-tensioned;
- Design service live loads and dead loads, including any allowable live load reductions used in the structural design; and
- Post-tensioning sequence and the magnitude of stressing at each stage of stressing.

Given the variability of design and construction methods, the construction of each project should be planned carefully in advance by the formwork engineer/contractor in close coordination with the engineer/architect. A clear understanding should be established between the engineer/architect and the formwork engineer/contractor on each party's responsibility in the determination of the post-tensioning procedures and the shoring/reshoring operations.

CHAPTER 4—STRENGTH ADEQUACY OF CONCRETE SLABS AND FORMWORK

The strength of an early age slab is influenced primarily by the rate of concrete strength gain and loads for which the slab has been designed. Instead of more detailed calculations, the flexural, tensile, shear, and bond strengths of the early age slab can be conservatively assumed to be proportional to the concrete compressive strength at that age. A more refined analysis can be used to take advantage of the member strength gain, which may be greater than the rate of concrete strength development. Also, the strength gain for post-tensioned slabs often significantly exceeds the proportion of concrete compressive strength gain. Cracking and deflections are dependent on the early age concrete tensile strength and modulus of elasticity, respectively.

The early-age strength of a slab needs to be checked against anticipated construction loads. When the applied construction load on a slab is more than the slab's early age strength, even though these construction loads may be less than the slab's design, distress may occur and the proposed construction scheme should be modified. In such a case, there are two basic alternatives: either reduce the load on the slab at the critical concrete age or change the concrete mixture for accelerated strength gain. The first alternative can be achieved by modifying the type of shoring system or the number of shored or reshored floor levels in such a way that the applied construction load is reduced to an acceptable level. The second alternative can be achieved by using high early-strength concrete, controlling curing temperatures to achieve the required early concrete strength, increasing the duration of the construction cycle to permit the concrete to gain enough strength before the application of construction loads, or all of the above. In no circumstances, however, should the factored construction load exceed the factored design load.

4.1—Early-age concrete material strength development

Determination of concrete strength is the decisive factor for the earliest possible removal of formwork. In general, the decision regarding safe formwork removal depends on the rate of concrete strength gain, the accuracy of strength determination of in-place concrete, and the level of load and deformation that the structure can withstand.

4.1.1 Compressive strength—The traditional method to determine the early-age concrete compressive strength is testing of field-cured cylinders. A drawback of this method is that the curing history and strength development of the cylinders and the structure will not be the same simply because of the difference in shape and the size of the actual structural members. Depending on the curing conditions of both the actual structure and the concrete cylinders, the compressive strength of the field-cured cylinders may vary significantly from that of the structure. Also, the testing of concrete cylinders becomes cumbersome mainly due to the large number of required cylinders.

The employment of reliable nondestructive test methods, in combination with concrete cylinders, to estimate the concrete compressive strength for formwork removal operations is desirable. Several nondestructive methods are available for estimating the in-place strength of concrete. Such methods include rebound hammer, penetration resistance, pulse velocity measurements, pullout test, and maturity methods. These methods do not measure strength directly, only indirectly, such as by estimating strength by the resistance to penetration probe, or estimating strength by keeping a log of concrete temperatures and other data and comparing them to the strength gain over time of laboratory-cured specimens, or estimating the modulus of elasticity by the amount of rebound of an impact hammer or the time of travel of an ultrasonic pulse from which strength can be inferred. Accuracy of the strength estimate requires carefully developed calibration data based on tests of cylinders made from the same concrete mixture proposed for use.

4.1.2 Tensile strength—Concrete at early age is susceptible to tensile cracking. A concrete failure due to deficiency in tensile strength and, consequently, low shear resistance, is the most serious type of slab failure, because most shear failures are preceded by little, if any, advance warning. Furthermore, the tensile cracks caused by excessive construction loading of early age concrete can contribute to unanticipated non-recoverable deflections.

The importance of concrete tensile strength cannot be overlooked, but there is no agreement as to how early age concrete tensile strength relates to cylinder compressive strength. In addition to the cylinder compression tests, split cylinder tests or tensile beam flexural tests may be considered to determine the actual early age tensile strength. The concrete tensile strength is critical for flat plate and flat slab floors because these slabs are susceptible to cracking and deflections, as well as potentially catastrophic punching shear failure.

4.1.3 Modulus of elasticity—Another important property of concrete is the modulus of elasticity, which is inversely

related to deflection. ACI 318 relates the modulus of elasticity to the concrete unit weight and the square root of the compressive strength. Though this empirical relationship has not been adequately verified with early age concrete, it can be used with caution for calculating the deflection of early age concrete members.

4.2—Construction load factors

ACI 318 specifies load factors for specific combinations of design loads used in design of the permanent structure. It does not, however, specify load factors for construction stage loads. ACI 347 does not specify construction load factors. ANSI 10.9 recommends a combined load factor of 1.3 for both dead and live construction loads. SEI/ASCE 37 specifies a minimum load factor of 1.4 for dead load when combined with only construction and material loads and 1.2 for all other combinations, and a load factor of 1.6 for construction live loads. SEI/ASCE 37 also permits allowable stress design as well as load and resistance factor design (LRFD). Care should be taken to apply load factors consistently while performing strength or LRFD design checks.

It is recommended to use the same design load factors and load combinations required by ACI 318, that is, 1.2 and 1.6 for construction dead and live load, respectively. The specified strength reduction factors ϕ by ACI 318 should also be applied during the strength evaluation of the partially completed structure. The ACI 318 alternative load and strength reduction factors should be used if the structural design of the building is based on the alternative factors.

The load and strength reduction factors of previous ACI 318 editions should be used if the structural design of the building is based on earlier ACI 318 codes. It is recommended to consider the load factors discussed by SEI/ASCE 37 for construction loads not included in ACI 318.

4.3—Early-age capacity of concrete slabs

4.3.1 Flexural strength—The flexural strength gain of young slabs can conservatively be taken as proportional to the concrete compressive strength gain. Although the flexural strength of the lightly reinforced member is not affected very much by the available concrete compressive strength, other properties such as shear and bond strength are directly affected by concrete compressive strength.

It is reasonable to assume that the structure has been designed to satisfy the governing code provisions for flexure. Therefore, the available flexural strength of early age concrete members can be expressed as:

$$\phi R_c = \beta_c \phi R_{28}$$

where

- R_c = early-age nominal flexural strength;
- β_c = ratio of the early age concrete compressive strength to 28-day specified strength;
- R_{28} = nominal strength at 28 days; and
- ϕ = strength reduction factor; ϕ factors are assumed to be the same for both the service conditions and during construction.

Let $U_{28} < \phi R_{28}$ and $U_c < \phi R_c$, then $U_c < U_{28}$, where U_c and U_{28} are the applied early age factored loads and the design load, respectively.

If the design loads consist of dead and live loads, and assuming that the building design is based on ACI 318, the design load can be written as

$$U_{28} = 1.2D + 1.6L$$

also,

$$U_c = 1.2D_c + 1.6L_c$$

where D_c and L_c are the applied construction dead load and live load, respectively.

4.3.2 Shear strength—For flat-slab and flat-plate structures, one of the critical strength parameters during construction is usually punching shear strength at columns. The available punching shear strength depends on the size of the shear perimeter and the concrete tensile strength. If loads applied during construction do not exceed the permanent structure design loads (reduced to take into account the early strength of concrete), then the formwork designer may assume that the punching shear strength at the columns is adequate.

ACI 318 relates the concrete punching shear strength of slabs to the square root of the concrete compressive strength, for example,

$$V_c = K \sqrt{f'_c} b_o d; \text{ and } \phi V_c \geq V_u$$

where

- V_c = nominal shear strength provided by concrete;
- V_u = factored shear force, lb (N);
- b_o = perimeter of critical section for shear in slabs, in. (mm);
- d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm);
- f'_c = specified compressive strength of concrete, psi (MPa);
- ϕ = 0.85, strength reduction factor for shear; and
- K = varies from 2 to 4 (0.17 to 0.33).

Therefore during construction,

$$V_{uc} \leq \phi K \sqrt{\beta_c f'_c} b_o d$$

where V_{uc} is the factored construction shear force.

ACI 318 provides similar shear strength equations for beams and one way slabs and joists. The available shear strength of these members is directly related to $\sqrt{f'_c}$ as indicated above with $K = 2$ ($K = 0.17$). For a reinforcement ratio less than 0.012, the K value is reduced as required by ACI 318.

Split cylinder tests (ASTM C 496/C 496M) or tensile beam flexural tests (ASTM C 78) may be used to determine the concrete tensile strength in relation to the compression strength of the specific concrete mixture used.

Consideration should be given to punching shear forces due to loads from shores/reshores on top of the slabs, espe-

cially when the shores-reshores are not aligned from one level to another, or at the bottom level of reshores. Though in most cases the shore/reshore axial strength governs over the punching shear strength of the slab, punching shear forces imparted by shores/reshores can be critical in cases of very thin slabs. In such cases, an analysis should be made to ensure that maximum punching shear force is within code limits. Also, a beam shear may control in a one-way slab when shore loads are placed near a concrete beam.

4.4—Serviceability requirements

The construction loads that are imposed upon the supporting slabs at early ages are comparable in magnitude with the design loads. Excessive construction loads at an early age can cause higher creep deflection and cause the concrete to crack more extensively than anticipated. These factors, in combination with normal shrinkage and many other factors, can adversely affect the long-term serviceability of the concrete structures. As mentioned earlier, excessive construction loads are usually the result of an inadequate number of shored/reshored levels, early stripping, or both.

The early-age concrete slab non-recoverable deflections and cracking are primarily due to the initial low concrete strength. Early loading of concrete members having a low modulus of elasticity and stiffness will cause larger non-recoverable long-term deflections, compared to concrete members loaded after attaining the specified 28-day strength and stiffness (Sbarounis 1984; Fu and Gardner 1986; Asamoah and Gardner 1997). Low modulus of elasticity of concrete produces relatively large immediate non-recoverable deflections. Low modulus of rupture of concrete promotes concrete cracking, which in turn reduces the slab stiffness and increases the slab deflection. The extent of initial concrete cracking depends on the magnitude of the amount of early age shrinkage, the magnitude of construction loads, and the age of the concrete when the loads are applied, which in turn affect the shoring/reshoring schedule. Furthermore, long-term creep deflections are increased because creep effects depend on the magnitude of the stress resulting from the applied loads relative to the concrete strength. Most of the early-age creep deflections are not recoverable. Deflection due to a combination of higher creep and premature cracking caused by excessive construction loads can be several times the normal elastic, creep, and shrinkage deflection.

The ACI 318 requirements for minimum slab thickness do not consider the effects of early age construction loads on the long-term deflections, and slab thickness cannot be used as a safeguard against excessive deflections and cracking when construction loads are improperly applied to an early age concrete slab. After the concrete members are cracked during construction, they will remain cracked throughout the life of the structure, unless repairs are made. Therefore, coordination between the design engineer/architect and the formwork engineer/contractor is recommended for checking slab deflections during construction. The immediate and long-term deflections should be checked using the smaller of the effective moment of inertia, calculated either at the time of construction or calculated at the time of service loads. ACI

435R provides extensive details on deflection calculations and control.

4.5—Formwork adequacy

Forms, shores, and reshores comprising the formwork system should be adequate to carry the applied construction loads. The construction loads are determined by the construction load analysis discussed earlier. The shoring system load capacity can be checked following either LRFD or allowable stress design methods. ACI SP-4 presents a detailed procedure for formwork design including lateral bracing.

Inspection is recommended and is required in some jurisdictions before concrete placement, and shoring/reshoring drawings should be available at the site at all time. No worker should be directly under the forms during concrete placement, unless required to adjust the shores/reshores and forms.

CHAPTER 5—CONSTRUCTION EXAMPLES

5.1—Two-way slab construction

The following construction example assumes various scenarios with respect to the construction rate, the concrete strength development, the slab design loads, and the shoring system.

5.1.1 Construction example data—A multistory cast-in-place reinforced concrete building is to be constructed utilizing a system of shores and reshores. The building is designed based on ACI 318. A typical floor plan and elevation are shown in Fig. 5.1.

a. Member sizes

- Slab thickness: 9.0 in. (229 mm).
- Interior column size: 20 in. (508 mm) square.
- Exterior column size: 12 x 20 in. (305 x 508 mm).
- Spandrel beam size: 12 x 20 in. (305 x 508 mm).

b. Design loads

- Slab self weight: 112.5 lb/ft² (5.39 kPa).
- Superimposed dead load: 20 lb/ft² (0.96 kPa).

Live load cases:

- 1) LL = 50 lb/ft² (2.4 kPa) (No live load reduction taken).
- 2) LL = 100 lb/ft² (4.8 kPa) (No live load reduction taken).

c. Concrete mixtures

- Slabs and beams: design concrete strength $f'_c = 4000$ psi (27.6 MPa).
Cylinder strengths: f_c (7 days) = 3300 psi (22.7 MPa). f_c (28 days) = 4650 psi (32.1 MPa).
- Columns: design concrete strength $f'_c = 5000$ psi (34.5 MPa).

The measured cylinder strengths are assumed strengths of laboratory-cured cylinders. The measured strengths are to be used to develop the concrete maturity relationships to determine the early age concrete strength development. The early age concrete strength can also be established by testing field cured cylinders.

d. Shoring system

- One level of shores with:

- 1) Three levels of reshores.
 - 2) Two levels of reshores.
- Shore/reshore material: Douglas fir larch, construction grade.
 - Shore/reshore size: 4 x 4 in., S4S, (100 x 100 mm) posts.
 - Modulus of elasticity of wood (base value):
 $E_w = 1500 \text{ ksi } (10.34 \times 10^3 \text{ MPa})$.
 - Compressive strength of wood parallel to grain (base value):
 $F_c = 1650 \text{ psi } (11.37 \text{ MPa})$.

e. Construction loads

- Slab self weight: $112.5 \text{ lb/ft}^2 \text{ (5.39 kPa)}$.
- Live load during placement: $50 \text{ lb/ft}^2 \text{ (2.4 kPa)}$.
- Form and shore load: $6.5 \text{ lb/ft}^2 \text{ (0.31 kPa)}$.

f. Construction weather conditions

- Hot weather: assume average daily concrete curing temperature of 80°F (26.7°C).
- Mild weather: assume average daily concrete curing temperature of 60°F (15.5°C).
- Cold weather: assume average daily concrete curing temperature of 40°F (4.4°C).

g. Construction rate scenarios

- One floor per week.
- One floor every 10 days.
- One floor per two weeks.
- Reshores are relocated one day before placing a new floor slab.

Though the one floor per week rate does not provide enough time to recover the forming material from the floor below to install it above the floor, it can be assumed that a second set of forms is available at the site to achieve this rate of construction. An alternate will be to adjust the concrete mixture proportion, concrete curing temperature, or both, to achieve faster concrete strength development, and therefore, quicker stripping time.

5.1.2 Construction load distribution—The construction load distribution between the concrete slabs and the shoring/reshoring system is evaluated by using the simplified method. Though this example utilizes a wood shoring/reshoring system, it is assumed that the compressibility of the shoring/reshoring system does not significantly impact construction load redistribution. The results of the shoring system using one shore level in combination with three reshore levels are shown in **Table 5.1**. A similar construction load distribution table can be developed for two reshore levels. Note that **Table 3.1** can also serve as a basis for the construction load distribution for this example, because the sum of the assumed live load and form weight is the same.

Table 5.1 shows that the maximum slab load first occurs on the fourth floor slab during the placement of the fifth floor slab (see **Step No. 9**). The fifth floor is the first floor level to be placed after the reshores have been removed from the first floor, thus removing the direct path of the construction load to the ground. The maximum slab load is repeated for all the

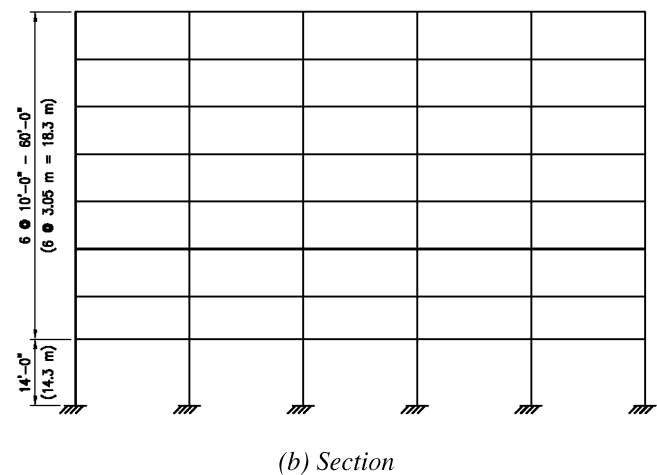
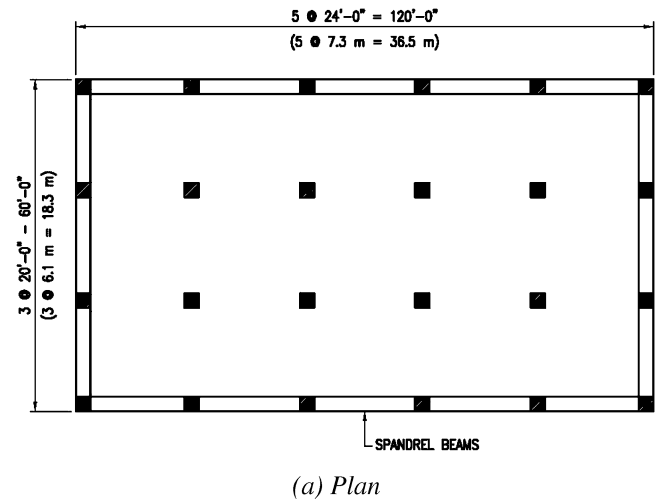


Fig. 5.1—Two-way construction example building.





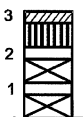
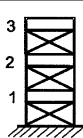
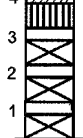
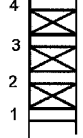
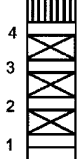
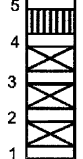
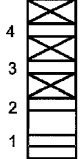
floors above the fifth level every time the shoring system is installed at the active level and the new slab is placed. The maximum slab construction load is $1.38D$, or 155 lb/ft^2 (7.42 kPa), for the three reshore system, and $1.5D$, or 169 lb/ft^2 (8.09 kPa), for the two reshore system.

The maximum shoring and reshoring construction load occurs during the placement of the top floor level. This load includes the slab selfweight of 112.5 lb/ft^2 (5.39 kPa), the form weight of 6.5 lb/ft^2 (0.31 kPa), and the construction live load of 50 lb/ft^2 (2.4 kPa) during the concrete placement. The maximum shore/reshore construction load is $1.5D$, or 169 lb/ft^2 (8.09 kPa), for both the three- and two-reshore system.

Both the upper shoring level and all the reshore levels carry the same maximum construction load as long as the shoring/reshoring system is supported on the ground. After the removal of the lowest level of reshores from the ground, the maximum applied construction load on the reshores becomes less at the lower reshored levels and increases at the upper reshored and shored levels. Therefore, the lower reshored levels will require fewer reshore posts than the upper floors.

According to the simplified method, the construction loads are distributed between the supporting slabs in propor-

Table 5.1—Construction example: simplified analysis of load on shores and slabs using one level of shoring, three levels of reshoring

STEP	OPERATION AND REMARKS	STRUCTURE STATUS	Load on slab in multiples of D			Shore/reshore load at end of operation
			At beginning	Change during operation	Total at end of operation	
1	Place Level 1 concrete. Full load transmitted to ground by shores.		0	0	0	1.5 D
2	Construction load is gone. Remove Level 1 shores and place reshores snug but not loaded. Level 1 slab carries its own weight.		0	+1 D	1 D	0
3	Form, shore, and place Level 2 concrete. Slab 1 cannot deflect, so all load goes through reshores to ground.		0	0	0	1.5 D 1.5 D
4	Slab 2 hardens and construction live load is gone. Remove Level 2 forms and shores, allowing Slab 2 to carry its own weight. Then reshore Slab 2 snugly, but without picking up load in reshores.		0 1 D	1 D 0	1 D 1 D	0 0
5	Form, shore, and place Level 3 concrete. Slabs 1 and 2 cannot deflect and therefore don't pick up any added load. All added load of Level 3 is carried to ground by shores and reshores.		0 1 D 1 D	0 0 0	0 1 D 1 D	1.5 D 1.5 D 1.5 D
6	Slab 3 hardens and construction live load is gone. Remove shores beneath Level 3, allowing slab to deflect and carry its own weight. Then place reshores beneath Level 3 slab, snug but not loaded.		0 1 D 1 D	+1 D 0 0	1 D 1 D 1 D	0 0 0
7	Form, shore, and place Level 4 concrete. All added load including construction live load is carried to the ground through the reshores. Slabs cannot deflect and there is no change in slab loading.		0 1 D 1 D 1 D	0 0 0 0	0 1 D 1 D 1 D	1.5 D 1.5 D 1.5 D 1.5 D
8	Slab 4 hardens and construction live load is gone. Remove the Level 4 forms and shores, allowing Slab 4 to carry its own weight. This leaves no net load in the reshores beneath Slab 1, and they are removed and installed snugly beneath Level 4. They carry no load at this stage.		0 1 D 1 D 1 D	+1 D 0 0 0	1 D 1 D 1 D 1 D	0 0 0 0
9	Form, shore, and place Level 5 concrete. The total new applied load, including construction load, is distributed equally to the four interconnected slabs.		0 1 D 1 D 1 D 1 D	0 +0.38 D +0.38 D +0.37 D +0.37 D	0 1.38 D 1.38 D 1.37 D 1.37 D	1.5 D 1.12 D 0.74 D 0.37 D 0
10	Level 5 concrete hardens and the construction live load of 0.44 D is removed in equal parts from the slabs to which it was distributed.		0 1.38 D 1.38 D 1.37 D 1.37 D	0 -0.11 D -0.11 D -0.11 D -0.11 D	0 1.27 D 1.27 D 1.26 D 1.26 D	1.06 D 0.79 D 0.52 D 0.26 D
11	Remove forms and shores beneath Level 5, allowing it to carry its own weight. The load in those shores, including their own weight, is removed from the slabs to which it had been distributed, and the reshores under Level 2 are brought up and placed snugly under Level 5, without carrying any load. THE SYSTEM IS NOW IN THE SAME CONDITION AS IN STEP 8 AND THE CYCLE WILL REPEAT WHEN LEVEL 6 CONCRETE IS PLACED.		0 1.27 D 1.27 D 1.26 D 1.26 D	+1 -0.27 D -0.27 D -0.26 D -0.26 D	1 D 1 D 1 D 1 D 1 D	0 0 0 0 0

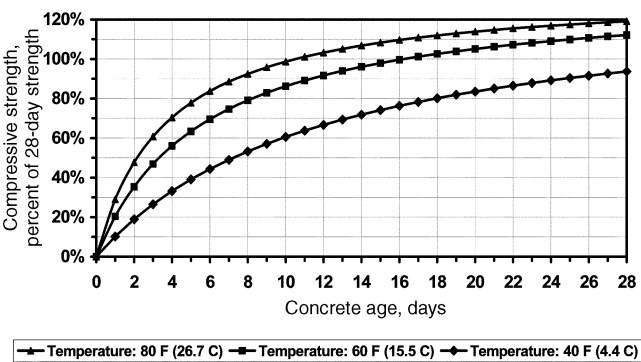


Fig. 5.2—Concrete compressive strength development.

tion to their relative stiffnesses. The floor slabs of this example have equal thickness and approximately equal flexural stiffness. Thus, the construction load is distributed equally between the interconnected floor slabs. In cases where the floor slab thicknesses and slab weight varies, the slab stiffness should be considered when calculating the slab and shore/reshore construction loads.

5.1.3 Concrete strength development—The engineer/architect should specify the minimum strength of concrete to be attained before removal of forms or shores. The strength may be determined by tests on field-cured specimens or on the in-place concrete. Other tests or evaluation procedures may be used, but should be verified by field-cured specimens and approved by the engineer/architect.

For this example, the concrete maturity method is employed to determine the concrete strength development. The strength-maturity relationship of concrete mixtures is based on the principle that the strength of concrete depends on the time-temperature history of concrete during the curing period. A detailed description of the maturity method and application is given in ACI 228.1R and Carino (2004).

Figure 5.2 shows the concrete compressive strength development based on the application of the maturity method for the concrete mixture assumed for this example. Figure 5.2 indicates a significant difference for the 40, 60, and 80 °F (4.4, 15.5, and 26.7 °C) curing environments. The concrete strengths given in Fig. 5.2 are valid only for the assumed specific concrete mixture used in this example and the assumed curing conditions. These concrete strengths should not be used beyond this example. The maturity method can be applied to predict the concrete strength development for other concrete mixtures and curing conditions.

While it is useful to demonstrate the differences in strength gain for a given mixture proportion at 40, 60, and 80 °F (4.4, 15.5, and 26.7 °C) curing environments, in practice, different mixture proportions would likely be used to account for the ambient temperature differences. The strength gain curve for each specific concrete mixture proportions should be obtained from the concrete supplier for the project.

5.1.4 Adequacy of concrete slabs

5.1.4.1 Available early-age slab load capacity—The concrete slabs for this example have been designed for the slab dead load of 112.5 lb/ft² (5.39 kPa), superimposed dead

Table 5.2—Construction load distribution summary

Construction cycle, days	Design	Available ultimate slab load capacity at selected temperatures, lb/ft ² (kPa)			Maximum slab factored construction load, lb/ft ² (kPa)	
	Live load, lb/ft ² (kPa)	40 °F (4.4 °C)	60 °F (15.5 °C)	80 °F (27.6 °C)	Two reshore levels, lb/ft ² (kPa)	Three reshore levels, lb/ft ² (kPa)
7-day cycle	50 (2.4)	117 (5.60)	179 (8.57)	213 (10.20)	210 (10.5)	191 (9.15)
	100 (4.8)	156 (7.47)	239 (11.44)	284 (13.60)	210 (10.5)	191 (9.15)
10-day cycle	50 (2.4)	146 (6.99)	206 (9.86)	237 (11.35)	210 (10.5)	191 (9.15)
	100 (4.8)	195 (9.34)	274 (13.12)	316 (15.13)	210 (10.5)	191 (9.15)
15-day cycle	50 (2.4)	177 (8.47)	234 (11.20)	239 (11.44)	210 (10.5)	191 (9.15)
	100 (4.8)	236 (11.30)	312 (14.94)	319 (15.27)	210 (10.5)	191 (9.15)

load, 20 lb/ft² (0.96 kPa), and a live load of 50 lb/ft² (2.4 kPa), and 100 lb/ft² (4.8 kPa). This example assumes that the designer of the structure did not consider any live load reductions for the floor slabs. If live load reduction was taken by the engineer/architect, the design strength of the structure will be reduced and should be accounted for in the reshore design. The concrete specified strength is 4000 psi (27.6 MPa). Considering that the building design is based on ACI 318, the design load for the slabs is:

1) $U_{28} = 1.2 (112.5 + 20 \text{ lb/ft}^2) + 1.6 (50 \text{ lb/ft}^2) = 239 \text{ lb/ft}^2$ (11.44 kPa); and

2) $U_{28} = 1.2 (112.5 + 20 \text{ lb/ft}^2) + 1.6 (100 \text{ lb/ft}^2) = 319 \text{ lb/ft}^2$ (15.27 kPa).

Based on the discussion presented in [Chapter 4](#), both the flexural and shear strengths of the young concrete slabs can be taken conservatively as proportional to the compressive strength development. [Figure 5.2](#) shows the ratio of early age concrete compressive strength to the 28-day design compressive strength. For both the two-and-three reshore system cases and for the one floor per week construction rate, the maximum construction load occurs on a seven-day-old slab. The ratio of concrete strength at seven days to 28 days is 0.49, 0.75, and 0.89 for the 40, 60, and 80 °F (4.4, 15.5, and 26.7 °C) curing environments, respectively. The maximum early age slab load is obtained by multiplying these ratios with the above calculated design loads. Similar strength ratios and maximum slab loads can be determined for a 10- and a 15-day construction rate.

5.1.4.2 Applied construction load—For the system with two levels of reshores, the maximum slab load during construction occurs on Level 3 during the placement of the fourth level slab. The total load is 169 lb/ft² (8.09 kPa), with dead load $D_c = 152 \text{ lb/ft}^2$ (7.27 kPa) and live load $L_c = 17 \text{ lb/ft}^2$ (0.82 kPa), (1/3 pro-rata share at each level) and the factored construction load is:

$$U_c = 1.2 D_c + 1.6 L_c = 1.2 \times 152 \text{ lb/ft}^2 + 1.6 \times 17 \text{ lb/ft}^2$$

$$= 210 \text{ lb/ft}^2 (10.05 \text{ kPa})$$

Similarly, for the system with three level of reshores, the maximum slab load during construction occurs on Level 4 during the placement of the fifth level slab. The total load on Level 4 is $1.38D$ or 155 lb/ft² (7.44 kPa), with dead load $D_c = 142.5 \text{ lb/ft}^2$ (6.82 kPa) and live load $L_c = 12.5 \text{ lb/ft}^2$

(0.60 kPa), (1/4 pro-rata share at each level) and the factored construction load is:

$$U_c = 1.2 D_c + 1.6 L_c = 1.2 \times 142.5 \text{ lb/ft}^2 + 1.6 \times 12.5 \text{ lb/ft}^2$$

$$= 191 \text{ lb/ft}^2 (9.15 \text{ kPa})$$

The construction loads and maximum allowable slab loads are summarized in Table 5.2.

5.1.4.3 Strength adequacy—Table 5.2 shows that for a 7-day cycle and with 50 lb/ft² (2.4 kPa) live load, two levels of reshoring will be adequate only for the 80 °F (26.7 °C) curing environment. The table also shows that, except for the 100 lb/ft² (4.8 kPa) live load on the 15-day cycle, all 40 °F (4.4 °C) cured slabs will be overloaded when only two floors of reshores are used. This overload condition can be avoided by changing the mixture proportion, increasing the ambient curing temperatures, or by increasing the number of reshore levels.

5.1.4.4 Slab deflections—Though the slabs may have enough flexural strength to carry the high construction loads, they may lack the concrete tensile strength and stiffness required to prevent extensive cracking and excessive deflections.

Deflection calculations for service load conditions should be based on the least-effective moment of inertia determined from either the construction loads with partial concrete strength or the service loads with full concrete strength. A detailed deflection calculation method taking into consideration the construction loads is provided in ACI 435R.

According to ACI 318, the contractor is required to produce structural calculation and concrete strength data used in planning shoring/reshoring operations. Such data and information should be furnished to the engineer/architect who should evaluate the effects of construction loads to immediate and long-term deflections. A team effort between the contractor and the engineer/architect is required to avoid deflection problems associated with construction procedures.

5.1.5 Adequacy of shoring/reshoring system—The wood shores/reshores used in this example are construction Grade S4S, Douglas fir larch sawn lumber with base value of compressive stress parallel to grain $F_c = 1650 \text{ psi}$ (11.37 MPa) and $E_w = 1500 \text{ ksi}$ ($10.34 \times 10^3 \text{ MPa}$). The unbraced shore/reshore length for a typical floor is taken as 9 ft 3 in. (2.82 m). The shores are assumed to be pin-ended. The allowable wood stress is calculated to be 417 psi (2.87 MPa). The allowable

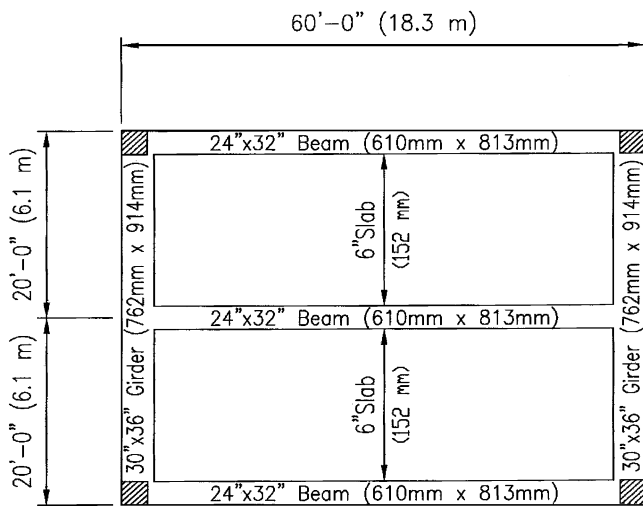


Fig. 5.3—Floor plan at typical beam and slab structural bay used in the post-tensioned construction example.

stress is calculated according to the requirements of the National Design Specifications for Wood Construction for visually-graded sawn lumber. Based on the allowable wood stress, the maximum allowable axial compressive load on a single post is 5100 lb (22.68 kN).

As calculated previously, the maximum allowable construction load on the shores or reshores is 169 lb/ft² (8.09 kPa). Based on the maximum allowable axial load of each shore or reshore, the maximum tributary area of each post is calculated to be approximately 30 ft² (2.80 m²). A practical shore or reshore spacing can be chosen, provided the maximum tributary area of each post is kept within the calculated limit.

Special consideration should be given to the first floor shores and reshores because the first floor is taller than a typical floor, and therefore, the allowable axial load of the shores and reshores is lower. The unbraced shore/reshore length of the first floor is 13 ft 3 in. (4.04 m). The allowable wood stress and axial load are 212 psi (1.46 MPa) and 2600 lb (11.56 kN), respectively. The maximum tributary area of the shores and reshores at the first floor is approximately 15 ft² (1.40 m²), which requires a dense spacing of wood posts. Lacing, bracing, or both, is required to increase the shore/reshore load capacity, and therefore, the post spacing.

Similar calculations should be performed for the lower floor reshores which, according to Table 5.1, receive reduced construction loads as the construction advances and the reshores are removed from the ground floor.

ACI SP-4 provides extensive details for formwork design. Where manufactured shores/reshores are used, the manufacturer's data should be consulted for safe working loads and other safety requirements of the shores/reshores and hardware.

5.2—Post-tensioned construction example

This construction example illustrates the effects of post-tensioning on the shoring/reshoring loads. After stressing of tendons, construction loads are partially or totally relieved from the shores that support the tensioned concrete members. The relieved shore loads are transferred to shores that support other members. Thus, the selection and design

of the shoring-reshoring system should be based not only on the placement load but also the post-tensioning stressing sequence and resulting transfer loads.

This example does not account for any load redistribution that will occur due to structural deflections, shoring/reshoring system axial shortening, or both. Further, the example assumes that the structural members do not have the capacity to carry added post-tensioning transfer loads before stressing of such members is complete. Often in the case of large transfer girders, post-tensioning is provided to support above levels of the structure that are not present at the time the girder floor is post-tensioned. Finally, the example assumes 100% of the structure's dead load is balanced by the post-tensioning. A safe method is to utilize the full dead load; however, the shoring designer may elect to determine the actual load transfer, or use information furnished by the engineer/architect.

ACI SP-4 provides general guidelines on formwork for post-tensioned structures. Bordner (1987) presented a detailed method on how construction loads are distributed during the post-tensioning process. The following example is based on the concepts and examples given in the above two references.

5.2.1 Post-tensioned example data—A post-tensioned multistory reinforced concrete building is to be constructed using a system of shores and reshores. A partial floor plan of a typical story level is given in Fig. 5.3. The post-tensioned members include the slabs, beams, and girders.

5.2.1.1 Member sizes

- Slab thickness 6 in. (152 mm).
- Beams 24 x 32 in. (610 x 813 mm).
- Girders 30 x 36 in. (762 x 914 mm).
- Columns 24 x 24 in. (610 x 610 mm).
- Story heights 10 ft (3.0 m).

5.2.1.2 Design loads

- Slab self weight 75 lb/ft² (3.59 kPa).
- Beam stem 650 lb/ft (9.48 kN/m).
- Girder stem 937.5 lb/ft (13.68 kN/m).
- Superimposed dead load 20 lb/ft² (0.96 kPa).
- Live load 50 lb/ft² (2.4 kPa).

Live load reductions have been considered in the design of beams and girders.

5.2.1.3 Concrete mixtures—Same as the two-way slab construction example presented in the previous section.

5.2.1.4 Shoring system

- One level of shores with two levels of reshores.
- Shore/reshore material and sizes: same as the two-way slab construction example.

5.2.1.5 Construction loads

- Slab, beam, and girder selfweight.
- Live load during concrete placement: 50 lb/ft² (2.4 kPa).
- Live load during post-tensioning: 20 lb/ft² (0.98 kPa).
- Form and shore selfweight:

For slabs: 5 lb/ft² (0.24 kPa)

For beams and girders (estimated): 20 lb/ft (0.29 kN/m).

5.2.1.6 Construction weather conditions

- 60 °F (15.5 °C) average daily concrete curing temperatures.

5.2.1.7 Construction rate

- One floor level every 10 days.

5.2.1.8 Post-tensioning sequence—The slabs, beams, and girders are to be post-tensioned at the end of each 10-day cycle in the following sequence:

1. Temperature tendons (no load transfer).
2. Slab tendons, 100%.
3. Beam tendons, 100%.
4. Girder tendons, 100%.

This sequence represents the worst condition for calculating shoring loads, which should be assumed, unless the tensioning sequence is known.

5.2.2 Construction load distribution—The construction load distribution is calculated corresponding to two construction stages. The first stage is during the concrete placement of the top active level, and the second stage is during post-tensioning. The method of calculation of construction loads during the concrete placement is the same as the previous example.

5.2.2.1 Concrete placement stage—The construction load distribution between the concrete slabs and the shoring/reshoring system is evaluated by using the simplified method. A construction load table, similar to [Table 3.1](#), for one level of shoring with two levels of reshoring is developed (not included here). The maximum slab load occurs on the third floor slab during the placement of the fourth floor slab. The maximum slab load is repeated for all floors above the fourth level every time the shoring system is installed at the active level and the new slab is placed.

During concrete placement, it is assumed that the three slab levels interconnected by reshoring equally share the weight of the newly placed slab. Thus, the maximum slab construction load includes the slab selfweight and one-third of the dead and live loads from the new slab.

Slab dead load

$$= \text{self-weight} + 0.333(\text{new slab weight} + \text{formwork load})$$

$$= 75 \text{ lb/ft}^2 + 0.333(75 + 5 \text{ lb/ft}^2)$$

$$= 75 + 0.333(80) = 101.7 \text{ lb/ft}^2 (4.87 \text{ kPa}).$$

Slab live load = $0.333(50 \text{ lb/ft}^2) = 16.7 \text{ lb/ft}^2 (0.80 \text{ kPa})$.

Total maximum slab load = $118.4 \text{ lb/ft}^2 (5.67 \text{ kPa})$.

The maximum shoring load occurs during the placement of the top floor level. The shoring construction load includes the dead load of concrete and form weight, and the live load of $50 \text{ lb/ft}^2 (2.40 \text{ kPa})$. The shoring construction load is as follows:

Slab shores—dead load:

$$\text{Concrete} = 6/12 \times 1 \text{ ft} \times 150 \text{ lb/ft}^3 = 75 \text{ lb/ft}^2 (3.59 \text{ kPa}).$$

$$\text{Forms (estimated)} = 5 \text{ lb/ft}^2 (0.24 \text{ kPa}).$$

$$\text{Sub total} = 80 \text{ lb/ft}^2 (3.83 \text{ kPa})$$

$$\text{Live load} = 50 \text{ lb/ft}^2 (2.40 \text{ kPa})$$

$$\text{Total} = 130 \text{ lb/ft}^2 (6.23 \text{ kPa})$$

Beam shores—dead load:

$$\text{Concrete} = 2 \text{ ft} \times 32/12 \times$$

$$1 \text{ ft} \times 150 \text{ lb/ft}^3 = 800 \text{ lb/ft} (11.67 \text{ kN/m})$$

$$\text{Forms (estimated)} = 20 \text{ lb/ft} (0.29 \text{ kN/m})$$

$$\text{Sub total} = 820 \text{ lb/ft} (11.96 \text{ kN/m})$$

$$\text{Live load} = 2 \text{ ft} \times 50 \text{ lb/ft}^2 = 100 \text{ lb/ft} (1.46 \text{ kN/m})$$

$$\text{Total} = 920 \text{ lb/ft} (13.42 \text{ kN/m})$$

Girder shores—dead load:

$$\text{Concrete} = 2.5 \text{ ft} \times 3 \text{ ft} \times 150 \text{ lb/ft}^3 = 1125 \text{ lb/ft} (16.4 \text{ kN/m})$$

$$\text{Forms (estimated)} = 20 \text{ lb/ft} (0.29 \text{ kN/m})$$

$$\text{Sub total} = 1145 \text{ lb/ft} (16.70 \text{ kN/m})$$

$$\text{Live load} = 2.5 \text{ ft} \times 50 \text{ lb/ft}^2 = 125 \text{ lb/ft} (1.82 \text{ kN/m})$$

$$\text{Total} = 1270 \text{ lb/ft} (18.52 \text{ kN/m})$$

5.2.2.2 Post-tensioning stage—The post-tensioning of slabs, beams, and girders causes some upward movement of these members so that they carry their own weight and any other construction live load. Thus, the shores supporting these members, once stressed, are relieved from some or all loads. The relieved shore loads are transferred by the post-tensioned members directly to other supporting members, which in turn transfer these loads to the shores supporting them. For example, the post-tensioning of the slab relieves the construction load from the slab shores and transfers it to the beams. The shoring of the beams is called to carry the additional load from the slabs. When the beams are post-tensioned, the beam shores are relieved from the load and the load is transferred to the girders and columns. [Figure 5.4](#) illustrates the construction load transfer due to post-tensioning.

Following the prescribed post-tensioning sequence, the shore loads are estimated as follows:

5.2.2.3 Post-tensioning of slabs

Slab shores—Carry only $5 \text{ lb/ft}^2 (0.24 \text{ kPa})$ form load. All other shore load is transferred to the beams.

Beam shores (center beam)

$$\text{Dead load: } 820 \text{ lb/ft} + 75 \text{ lb/ft}^2 \times 18 \text{ ft} = 2170 \text{ lb/ft} (31.66 \text{ kN/m})$$

$$\text{Live load: } 20 \text{ lb/ft}^2 \times 20 \text{ ft} = 400 \text{ lb/ft} (5.84 \text{ kN/m})$$

$$\text{Total: } 2570 \text{ lb/ft} (37.50 \text{ kN/m})$$

Girder shores

$$\text{Dead load: } 1125 + 20 \text{ lb/ft} = 1145 \text{ lb/ft} (16.70 \text{ kN/m})$$

$$\text{Live Load: } 2.5 \text{ ft} \times 20 \text{ lb/ft}^2 = 50 \text{ lb/ft} (0.73 \text{ kN/m})$$

$$\text{Total Uniform: } 1195 \text{ lb/ft} (17.43 \text{ kN/m})$$

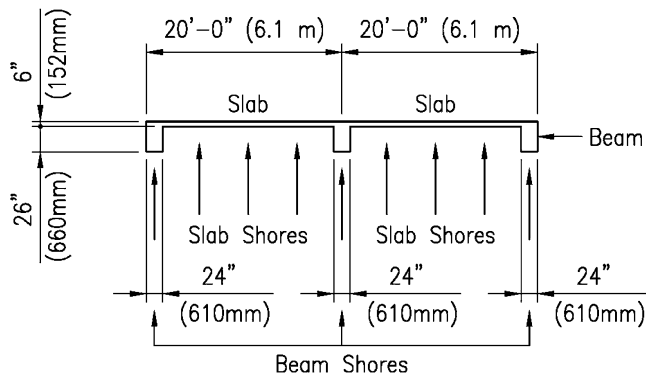
5.2.2.4 Post-tensioning of beams

Slab shores—No load change from the previous step.

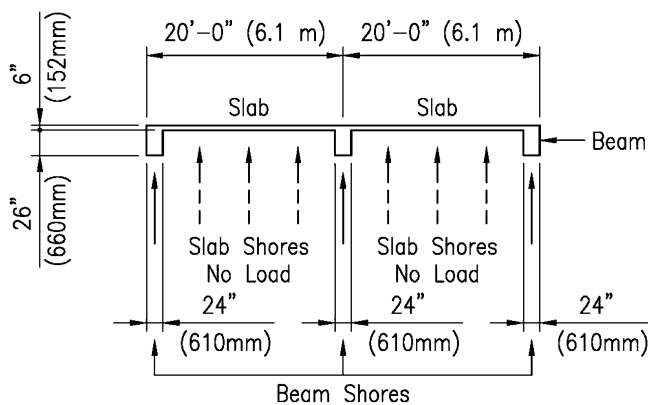
Beam shores—Carry only $20 \text{ lb/ft} (0.29 \text{ kN/m})$ form load. All other shore load is transferred to the girders and columns.

Girder shores

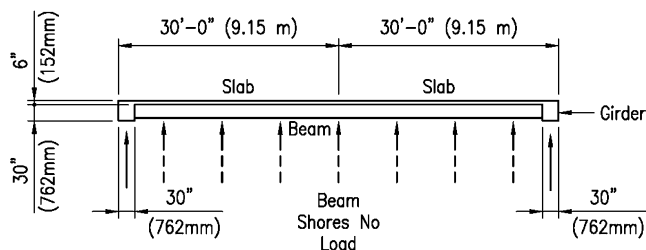
$$\text{Uniform load: } 1125 \text{ lb/ft} + 20 \text{ lb/ft} = 1145 \text{ lb/ft} (16.70 \text{ kN/m})$$



- a. Concrete placement stage:
Slab shores carry the slab load.
Beam shores carry the beam load.



- b. Slab is Post-tensioned:
Slab shores carry no load (except forms).
Beam shores carry the slab and beam loads.



- c. Beams are Post-tensioned:
Beam shores carry no load (except forms).
Girder shores carry beam reaction load and girder load.

Fig. 5.4—Post-tensioning sequence and construction load redistribution.

Live Load:
 $2.5 \text{ ft} \times 20 \text{ lb/ft}^2 =$ 50 lb/ft (0.73 kN/m)
Total uniform: 1195 lb/ft (17.43 kN/m)

Concentrated load at center span (reaction from beams):
Dead load:
 $(2170 \text{ lb/ft} - 20 \text{ lb/ft}) \times 27.5 \text{ ft} =$ $59,125 \text{ lb}$ (263.00 kN)

Live Load:
 $400 \text{ lb/ft} \times 27.5 \text{ ft} =$ $11,000 \text{ lb}$ (48.93 kN)
Total concentrated: $70,125 \text{ lb}$ (311.93 kN)

5.2.2.5 Post-tensioning of girders—The post-tensioning of the girders will relieve the load from the girder shores and all construction loads are transferred to the columns.

Based on the foregoing shore load analysis of both the concrete placement stage and the post-tensioning stage, the maximum shore loads are summarized as follows:

Slab shores— 130 lb/ft^2 (6.23 kPa), during concrete placement.

Beam shores— 2570 lb/ft (37.50 kN/m), during slab tensioning.

Girder shores— 1195 lb/ft (17.43 kN/m) uniform; $70,125 \text{ lb}$ (311.93 kN) concentrated, during beam tensioning.

This example shows that the maximum shore loads can occur during the tensioning process. These loads are much larger than the shore loads during the concrete placement. The shore load redistribution is very much affected by the sequence and the level of post-tensioning. For example, should the sequence of post-tensioning be reversed, such as, girders, beams, and slabs, then the shore loads during tensioning could have been lower than those calculated above. Such sequence, however, is limited to the amount of stage load balancing. Usually, the amount of load balancing is less than the dead load of the structural members. Excessive post-tensioning may cause excessive upward deflections as well as development of damaging reverse stresses because the expected service loads are not necessarily present during post-tensioning.

5.2.3 Adequacy of concrete members—The maximum allowable slab load at the age of 10 days with curing temperature of 60°F (15.5°C) is estimated as follows:

$$U_{28} = 1.2 \times (75 \text{ lb/ft}^2 + 20 \text{ lb/ft}^2) + 1.6 \times 50 \text{ lb/ft}^2$$

$$= 194 \text{ lb/ft}^2 \text{ (} 9.29 \text{ kPa)}$$

The factored construction load on the slab is:

$$U_C = 1.2 D_C + 1.6 L_C$$

$$= 1.2 \times 101.7 \text{ lb/ft}^2 + 1.6 \times 16.7 \text{ lb/ft}^2 = 149 \text{ lb/ft}^2 \text{ (} 7.12 \text{ kPa)}$$

The ratio of early-age concrete compressive strength to the 28-day specified compressive strength is obtained from Fig. 5.2 as 0.86. Therefore, the maximum allowable slab load is 167 lb/ft^2 (8.00 kPa), which is larger than the construction factored load of 149 lb/ft^2 (7.12 kPa).

Similar design checks should be performed for the beams and girders. The beams and the girders of the floor below should be checked for the construction load that is transferred onto them during the post-tensioning of the floor above. In addition to the strength adequacy, the concrete slabs, beams, and girders should be checked for deflections as well.

5.2.4 Adequacy of shoring/reshoring system—The shores/reshores used in this example are the same as those for the previous example. The allowable compressive stress on a 4 x 4 in., S4S, (100 x 100 mm), 9.5 ft (2.90 m) long wood shore is estimated to be 400 psi (2.75 MPa). Therefore, the allowable axial load on a wood shore is 4900 lb (21.80 kN).

The shores and reshores should be sized and spaced in such a manner that the construction loads do not exceed the maximum allowable load for each individual shore/reshore member.

The following shore design considers only the shores below the top active level. Similar analysis and design should be performed for the reshoring that supports the floors below.

5.2.4.1 Slab shores—The maximum slab shore load and maximum allowable axial shore load were previously estimated to be 130 lb/ft² (6.23 kPa) and 4900 lb (21.80 kN), respectively. The maximum tributary area of each shore is calculated to be approximately 36 ft² (3.34 m²). Based on the maximum shore tributary area, a practical shore spacing can be chosen.

5.2.4.2 Beam shores—The maximum beam shore load is estimated to be 2570 lb/ft (37.50 kN/m). Allowable axial shore load for beams may be higher because the unbraced length is smaller. Based on the maximum allowable axial shore load, a practical shore spacing is determined to be 22 in. (559 mm) on center. If only the concrete placement loads are considered and the post-tensioning transfer loads are ignored, the shore spacing would be as much as 5 ft (1.52 m). With such shore spacing, the shores would have been highly overstressed, leading to possible failure of both the shoring system and the supported concrete beams and slabs.

5.2.4.3 Girder shores—The maximum girder shore load is estimated to be 1195 lb/ft (17.43 kN/m) and 70,125 lb (311.93 kN) concentrated load at midspan. Based on the maximum allowable axial shore load, the practical shore spacing is determined to be 48 in. (1219 mm) on center along the girder length. Additional shores are required at the girder midspan to carry the expected concentrated load. Considering the magnitude of the concentrated load, it is not practical to use the 4 x 4 in., S4S, (100 x 100 mm) wood shores. Larger size timber or steel shores should be considered.

CHAPTER 6—REFERENCES

6.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)

228.1R	In-Place Methods to Estimate Concrete Strength
301	Specifications for Structural Concrete
318	Building Code Requirements for Structural Concrete and Commentary
347	Guide to Formwork for Concrete

435R	Control of Deflection in Concrete Structures
SP-4	Formwork for Concrete

American National Standards Institute (ANSI)

ANSI A 10.9	Safety Requirements for Concrete and Masonry Work—American National Standard for Construction and Demolition Operations
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American Society of Civil Engineers (ASCE)

SEI/ASCE 37	Design Loads on Structures During Construction
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ASTM International

ASTM C 78	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
ASTM C 496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

Occupational Safety and Health Administration (OSHA)

OSHA 29 CFR	Safety and Health Regulations for Construction
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These publications may be obtained from the following organizations:

American Concrete Institute

PO Box 9094
Farmington Hills, MI 48333-9094
www.concrete.org

American National Standards Institute

1819 L Street, NW
Washington, DC 20036
www.ansi.org

American Society of Civil Engineers

1801 Alexander Bell Drive
Reston, VA 20191
www.asce.org

Occupational Safety and Health Administration

U.S. Department of Labor
200 Constitution Ave.
Washington D.C. 20210
www.osha.gov

ASTM International

100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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AF & PA, 2001, "National Design Specifications (NDS) for Wood Construction (ANSI/AF & AP-2001)," American Forest and Paper Association, Washington, D.C.

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