

Slipformed Core Construction

By Thomas Taylor, PE



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Preface

This manual was written as a guide for Datum's engineers to use on future projects. It is an effort to assure that the benefits of our past experience with slipform is incorporated into our future projects. Each engineer starting a new slipform project is requested to read this manual and discuss his findings with the team members that were associated with the previous slipform core projects designed by Datum's Engineers.

I also want to thank Doug Pruitt of Sundt Corporation for the illustrations he provided, for the previous articles he wrote on slipforming, and for the superior work Sundt Corporation did on Williams Square, Harwood Center in Dallas, Texas, and the Atlantic Center project in Atlanta, Georgia.

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Introduction

Although slipform concrete construction was used somewhere around the first of the century (1904 - 1905) in Kansas City for a rectangular grain tank that was approximately 25 to 30 feet high, slipform core construction for building construction did not start until the mid 1950's. To the best of our knowledge, the first indication of a slipform core for building construction was the Buffalo Bank Building constructed in the mid 1950's. The slipping operation was done by Heede International, utilizing hydraulic jacks.

The original slipform construction was primarily used for the construction of grain silos and then evolved into the construction of missile silos. The slipping operation on the silos typically continued around the clock until the slipping operation was complete.

The erection of these silos was considerably simpler to construct than a concrete core for a building due to the absence of blockouts for doors, mechanical units, embeds for steel floor beams, conduit, etc.

The slipping process has evolved from small hand screwed jacks with threaded rods (in which everyone turned one-quarter of a turn at the sound of the foreman's whistle) to pneumatic jacks developed sometime in the 1930's and then hydraulic jacks developed in the early 1940's.

Datum's first project, using slipform core construction, was in 1969. Although we were not pioneers in either the process of slipforming or the utilization of slipforming for concrete building cores, we have participated in refining the process from the typical mid-rise concrete cores to the construction of the Atlantic Center core, which was 725'-6" tall and was the tallest slipform concrete core in the United States at the time of its construction.

We have had many experiences (some good and some bad) with slipform core construction. The purpose of this manual is an attempt to document our experiences for our staff's future reference when constructing slipform concrete cores. We hope that it will not only be useful for this purpose but will also serve as a valuable reference tool for our colleagues.



A Brief Outline of Datum's Slipform Construction Experience

Datum has been the structural designer on numerous mid-rise and high-rise slipform concrete core projects, starting in 1969 with the Parkway Central office building in Arlington, Texas. The Atlantic Center/IBM Tower in Atlanta, Georgia, was completed in 1990, and at the time, was the tallest slipform core project in the United States. Over the past years we have had the opportunity to accumulate a vast amount of experience and information regarding slipform concrete core design on a number of highly successful projects. We would like to share our experiences with you.

The following is a list of some of our more notable slipform concrete core projects:

Atlantic Center / IBM Tower | *Atlanta, Georgia*

50 story, 1,100,000 sq. ft. office building with slipform core and steel frame. The building is 800 feet tall and the core is 725'-6" tall. This project was designed by the Datum-Moore Partnership under the guidance of Thomas Taylor. (See Figures 1, 2, and 3).

The Towers at Williams Square | *Irving, Texas*

27 story building with 1,000,000 sq. ft. steel frame braced by the concrete core. This project was designed by the Datum-Moore Partnership.

Harwood Center | *Dallas, Texas*

38 story office building, 1,000,000 sq. ft. slipform core with structural steel floor (See Figures 4, 5, and 6).

Citizens Bank | *Dallas, Texas*

13 story, 120,000 sq. ft. slipform core with structural steel floor and precast concrete perimeter. (See Figures 7 and 8).

Park Central Tower | *Dallas, Texas*

22 story, 700,000 sq. ft. slipform core with structural steel floor. Datum was the conceptual design engineer on this project.

Parkway Central Tower | *Arlington, Texas*

14 story, 300,000 sq. ft. office building with a slipform concrete core and structural steel floor.

Southland Corporation Corporate Headquarters | *Dallas, Texas*

11 story, slipform core with structural steel floor and precast concrete exterior.

Central Research Library | *Dallas, Texas*

12 story, structural steel frame with slipformed stair shafts and central core.

Slipform construction was selected on these buildings for reasons that were specific to each project. However, all shared in the common economic advantages that will be outlined in the next chapter.



Figure 1
Atlantic Center/IBM Tower
Atlanta, Georgia



Figure 2
Atlantic Center/IBM Tower
Atlanta, Georgia



Figure 3
Atlantic Center/IBM Tower
Atlanta, Georgia



Figure 4
Harwood Center
Dallas, Texas

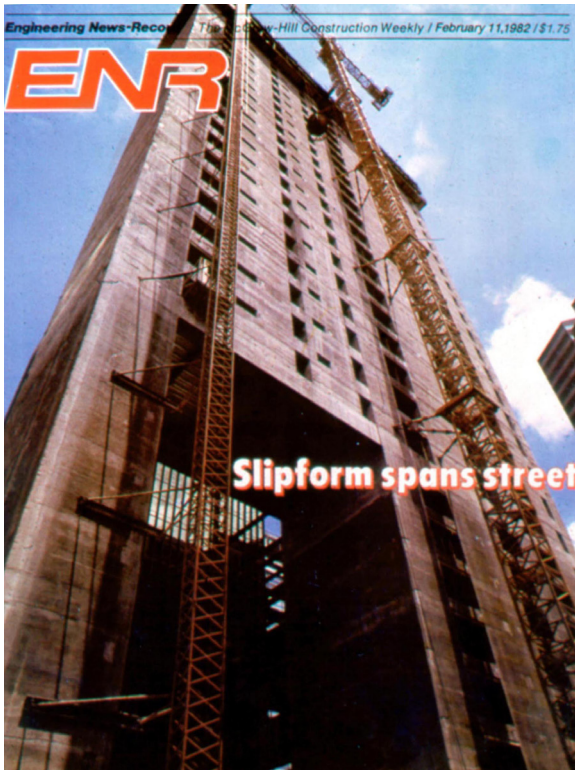


Figure 5
Harwood Center
Dallas, Texas



Figure 6
Harwood Center
Dallas, Texas



Figure 7
Citizens Bank Center
Richardson, Texas



Figure 8
Citizens Bank Center
Richardson, Texas



Economics of Slipform Construction

The primary economic advantage of a slipformed concrete core in a building is arrived at by organizing the concrete walls in the core to correlate with fixed walls that are otherwise required by function. This arrangement allows the walls to perform “double-duty.” The walls become the structural wind bracing element of the building, also providing gravity load-carrying capacity, while at the same time providing the fire separation around stair and elevator shafts required by the Building Code.

These slipform concrete walls are located where fixed walls (those which will not be relocated over the life of the building) occur, such as walls around lavatories, mechanical rooms, electrical rooms, telephone closets, and vertical chases for mechanical and electrical systems. Therefore, when cost estimating various structural framing options, one must include the added value of these walls as architectural separation walls when compared to framing systems that do not create fixed walls or provide fireproofing.

A major savings when using slipform construction comes from the low cost of forms per square foot of contact area. Typically, slipforms are only four feet high and are commonly used up to heights of 400 feet (on the Atlantic Center project the same form was utilized up to 725 feet). This gives a form reuse factor of 100, with no stripping or resetting required. Furthermore, working decks and finishing scaffolds are part of the form assembly eliminating the scaffolding that would otherwise be required.

The reduced construction time produces an additional savings of in-place construction cost. On the 50 story Atlantic Center project over ten weeks of total construction time was eliminated by the use of slipformed concrete core construction, resulting in faster occupancy and reduced interim interest cost.

Another economy, which turns out to be fairly significant, is in the simplicity of fabrication and erection of structural steel floors and columns when associated with the stabilizing slipform concrete core. This became immediately apparent to us on our original 1969 Parkway Central project, when a smaller more competitive structural steel fabricator, who would have been unable to fabricate the more complex structural steel normally associated with high-rise office buildings, turned in the lowest bid. Since the core resists all of the wind forces (which transfer from the exterior wall through the floor diaphragm to the core), the structural steel can be designed as simple beams and braced columns with simple bolted connections, thus eliminating moment connections between beams and columns, which reduces the cost of steel fabrication below the standard anticipated cost. Similar economies occur for the erector as well, since the steel frame can be quickly stabilized by simply welding it to the steel anchor plates cast in the core.

We have continued to experience highly competitive pricing for structural steel on all of our slipform projects. Due to the wind bracing and gravity load capacity furnished by the core, the amount of structural steel per square foot is reduced to below that required to support gravity loads only. In summary, low tonnage, simplicity of fabrication and erection contribute to substantial savings in structural steel framing costs.

Other economies associated with slipform core construction include the rapid installation of elevators and stairs and their early use for construction purposes. The mechanical contractor can install all of the vertical plumbing risers from the finishing scaffold and the slipform contractor can install all of the structural steel inside the core, including elevator divider beams, during the slipping operation.

Almost every slipformed concrete structure can realize a majority of these economies. Whether or not the benefits of slipform construction are applicable on a given project, slipform construction should be taken into consideration during the initial value engineering process.



Three Methods of Slipform Construction

There are three basic methods of constructing a building with a slipformed concrete core:

One, which is the method we recommend, is to construct the core completely independent of the floor construction, with the core topping out either before the structural steel erection begins or shortly thereafter.

Another method is to erect the core on a floor-a-day basis for five to ten days, then pause and build the floor up to the same level as the core, continuing this process incrementally throughout the project.

A third method is to carry on slipforming and floor construction operations simultaneously, on a daily one-floor-at-a-time basis. This method should only be used if the core is not entirely stable within itself and needs the additional horizontal support of the floor system.

On all of our projects we have used the first method of slipforming. The core is always designed to be capable of extending all the way from the foundation to the top without bracing from the adjacent floor members. The core is designed to have the strength and stability to act as an independent element which can resist all of the wind and construction loadings that are imposed on it during construction. The engineer must pay special attention to the stability of the core cross-section and utilize the appropriate interior cross-walls as bracing walls. Additional bracing walls, that may be required, are generally minor and are offset by the fact that they can be located where architectural functional walls are stipulated. Horizontal diaphragms can also be cast periodically inside the core to strengthen the core during construction. If effective diaphragms in the core are not attainable, due to elevator openings, vertical shafts, etc., then diagonal guy wires can be employed within the core to provide diaphragm strength.

Our experience has shown the first method to have more benefits than the second or third. The slipforming subcontractor's specialized crews are able to work continuously without delays. Whereas the other methods require waiting for floor construction to catch up, which generally takes three to five times longer than the slipforming operation itself.



Slipform Core Resists All Wind Forces

On six of our slipform core projects we designed the core to resist all of the wind forces on the building. The additional cost of the extra concrete and reinforcing steel required for complete bracing has proved to be far less expensive than adding rigid moment-resistant frames in the structural steel. Since a large part of the cost of building a slipform core is already incorporated into the system (regardless of the thickness of the walls), a slightly thicker wall only adds the cost of the concrete. Also, it is desirable to have thick walls with less reinforcing steel in slipformed construction due to the difficulty of placing congested reinforcing steel and embeds during a slipforming operation. Therefore, the minimum wall thicknesses that are desirable for reduced steel congestion generally give the required stiffness to resist the wind forces without increases in wall thicknesses.

On two of our projects, the slipform core was not capable of or was not designed to resist all of the wind loads. Those projects were Harwood Center and Citizens Bank. On Harwood Center (**See Figures 4, 5, and 6**) the site was extremely narrow which limited the core size, causing the core to be unable to meet the lateral sway criteria that we were designing to. In this case we used moment-resistant exterior frames in the transverse direction to help stiffen the building. On Citizens Bank we used a precast concrete perimeter spandrel beam and column system for architectural considerations which entailed rigid connections between the beams and columns of the precast. The precast perimeter frame, due to its inherent stiffness, resisted 40 percent of the wind force while the concrete core resisted the remaining 60 percent of the wind force (**See Figures 7 and 8**).

In summary, we have experienced the best results when the slipformed core is constructed to be a totally independent element, able to be extended to the top without constructing the surrounding floors and designed to resist all of the wind forces on the building without help from the perimeter framing.



Discontinuous Slipform Construction

On all of our projects the form has been slipped during the daytime. All concrete is placed during the day in addition to installation of horizontal reinforcing steel, embeds, and blockouts. The night crew prepares the site for the next day's placement by installing the complicated reinforcing steel for the large link beams, the vertical reinforcing steel and embeds, and performing cleanup and maintenance work.

For example, on the Atlantic Center Project there was an 85 person day crew that slipformed approximately 13'-0" (or one story) each day, and a 60 person night crew, both working in eight hour shifts. This staffing arrangement allowed the 50 story core to be completed in 57 working days, one story per day, plus 7 days of down time for blocking out wall thickness changes at two locations.

The traditional concept of slipforming was to continuously slip the form until completion of the element being cast. This continuous approach would considerably increase the premium time pay associated with a tall concrete building core. Also, on major building cores, as opposed to simple grain silos, the reinforcing steel placement can become extremely complicated and time-consuming due to the large number of blockouts for doors, mechanical openings, weld plates, etc. This requires time and attention that is not available on continuous pour operations.



The Key to Success with Slipform Construction

PREPLANNING

Preplanning and coordination are key to the successful completion of any slipform project and the design and construction team have to adjust accordingly. The architectural, structural, electrical, and mechanical decisions have to be completed and coordinated in advance of the slipping operation in order to allow the contractor enough time to fabricate the required blockouts and embeds. Electrical and mechanical decisions, that normally lag behind structural decisions on a fast-track schedule, cannot do so in a slipform core project. On taller slipformed projects, planning and installation work required by different trades, may be moved up as much as nine months to a year from that typically required on conventionally built structures.

Time is a critical issue on a slipping operation. All items needing to be installed in the concrete core must be identified, located, and ready to install before slipping operations begin. There is no time available for planning or revising during construction when the form is moving up one floor per day. For these reasons alone we cannot overemphasize the need for preplanning and coordination.

CONTRACTOR

Probably the most important key to success is an experienced and qualified slipform contractor and staff. Slipforming a concrete core is clearly a speciality operation that can only be successfully accomplished by an experienced construction team. There is no turning back once a slip has begun, and it is too late to discover that the contractor has built a form that can not resist the stresses or has a disorganized staff that can not maneuver the form back into alignment, or sticks the form on hardened concrete and can not continue.

We have heard a lot of horror stories about slipform construction problems. Many can be attributed to the inexperience of the design team but the majority are attributable to inexperience on the part of the contractor. Do not proceed with a slipform project without an experienced contractor.



Figure 9
Jacking Grid

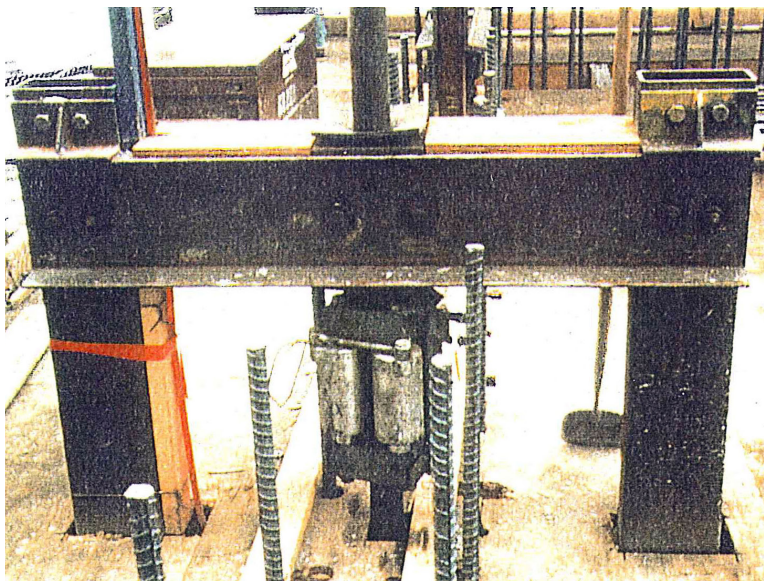


Figure 10
Slipform Yoke

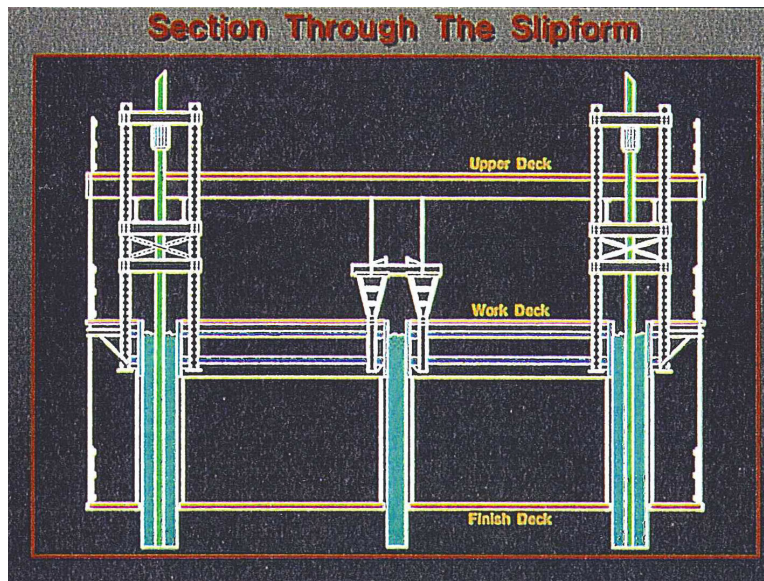


Figure 11
Section Through Upper Deck
Work Deck and Trailing Deck

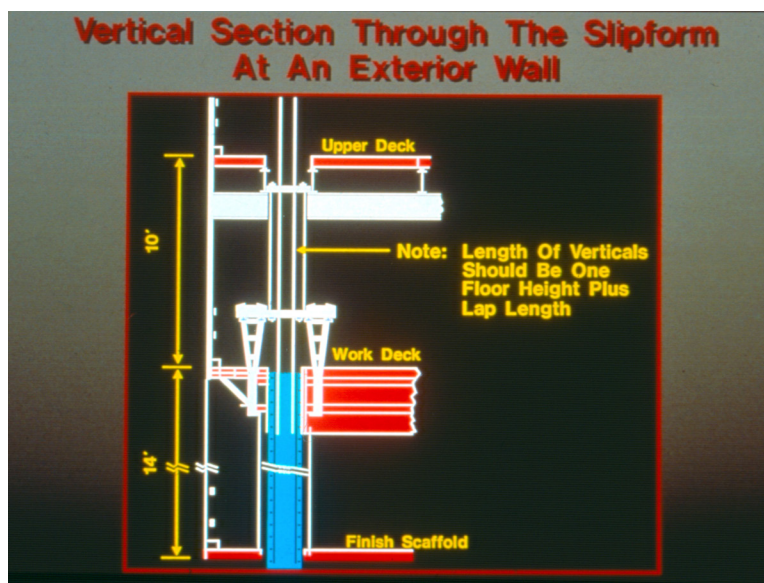


Figure 12
Typical Relationship of
Jacks and Decks



The Slipform Process

Slipforming was originally developed for simple storage silo projects and has since evolved into the sophisticated, refined procedure used in cores on today's high-rise buildings. It would be hard to find many similarities between the original silo concept and the slipforming for concrete core building structures. There are many differences between the two. Some of the more predominant characteristics of today's slipform are:

1. Very rigid form panels with a fiberglass reinforced plastic surface on a structural plywood substrata.
2. A structural steel jacking grid or diaphragm, approximately 10'-0" above the slipform.
3. Instead of 3 ton jacks in each slipform yoke, we use 22 metric ton hydraulic jacks. The 22 ton jacks are mounted on the jacking grid (**See Figure 9**) and the slipform is suspended by rods from the jacking grid, connecting to each slipform yoke (**See Figure 10**).
4. Rigid slipform yokes with the spread necessary to place, tie, and inspect the horizontal reinforcing steel before it is covered with concrete.

Slipforms consist of three decks; an upper deck, work deck, and trailing deck (or finishing scaffold). The following is a brief description of each (**See Figures 11 and 12**):

1. The upper deck, supported on the jacking grid, is used for landing, sorting, and storage of reinforcing steel, placement and lateral support of the vertical reinforcing steel, distribution of concrete, and control of the slipform jacking system (**See Figures 13 and 14**).
2. The work deck, located at the same elevation as the top of the slipform, provides a platform for the distribution and consolidation of the concrete, placement of horizontal reinforcing steel, inspection of reinforcing steel, concrete placement, and installation of weld plates and opening forms (**See Figures 15 and 16**).
3. The finishing scaffold, suspended 10'-0" or so below the work deck, accommodates the finishing operations on the concrete to be exposed in the finished building, application of curing compound, installation of T-clips on weld plates for structural beam anchorage, stripping of blockout forms, installation of steel beams inside the core, and installation of vertical plumbing risers (**See Figures 17 and 18**).

Once the foundation is ready for the slipforming operation to begin (**See Figure 19**), it ordinarily takes four to six weeks to erect the slipform for the usual range of core sizes, assuming the form components and jacking grid have been prefabricated. On the Atlantic Center project, Sundt Construction Company allowed for five weeks in their contract to assemble the slipform. It is desirable to organize the construction activity to start with the foundation construction under the core in order to allow construction of the slipform to proceed simultaneous with the remainder of the foundation construction.

As previously mentioned, a two-shift workcrew operation is usually used during construction of the core. This personnel scheduling, along with a 22 ton jack system, was developed by the slipform division of Heede International, Inc.



On all of our slipform projects, a 4'-0" deep form, configured to produce the shape of the building core plan, was selected by the Contractor. The vertical movement of the form is accomplished by jacks. These jacks rise on smooth steel rods (or pipes) cast into the hardened concrete at the foundation. The jacks are usually hydraulic, with a lifting capacity of up to 25 tons and operate at speeds of about 18 to 20 inches per hour. The top deck, working deck, and finishing scaffolds are all supported by the form framework and ascend along with it.

Any form material may be used for sheathing as long as it has a smooth, strong, nonabsorptive surface and has structural stability throughout the range of moisture and temperature conditions expected. Steel form linears and Finnish plywood sheathing are commonly used.

The design of the yokes must provide for adequate clearance to install horizontal reinforcing bars and admittance into their correct locations prior to their submergence in the rising concrete. Generally, a typical yoke extends 24" above the top of the form (**See Figure 20**).

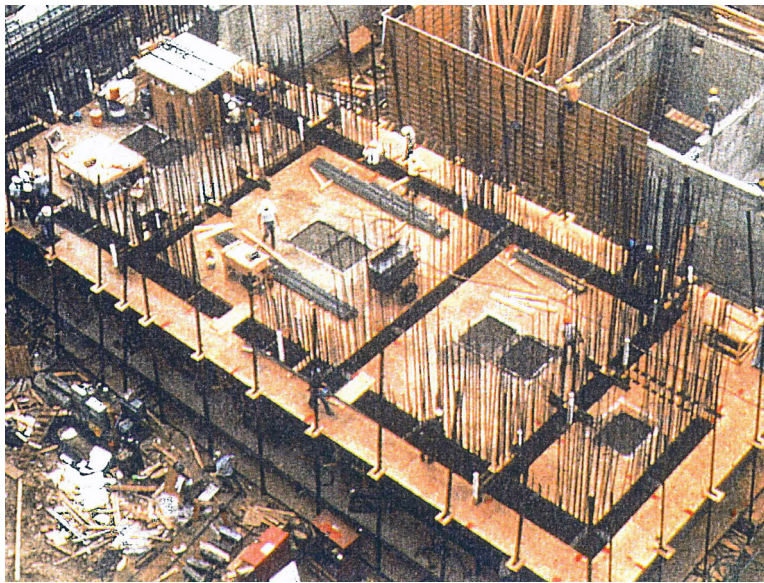


Figure 13
View of Upper Deck



Figure 14
View of Upper Deck



Figure 15
View of the Work Deck

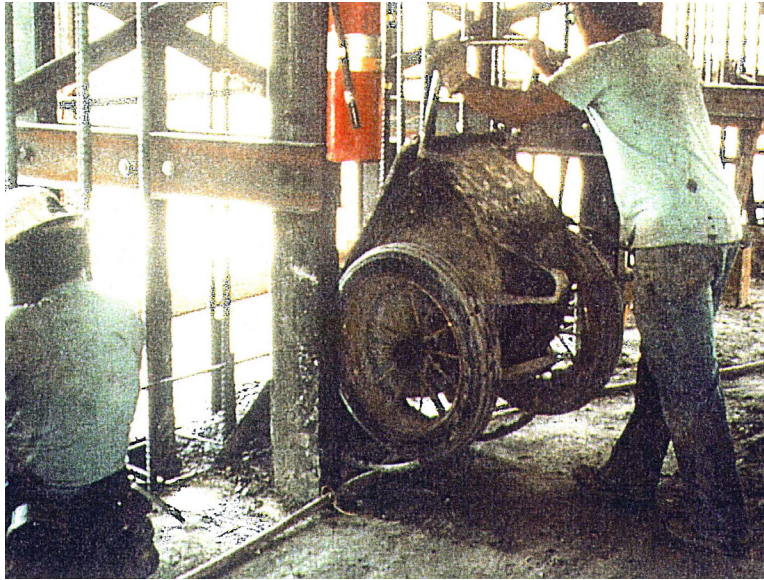


Figure 16
View of the Work Deck



Figure 17
Installation of Vertical Plumbing Riser

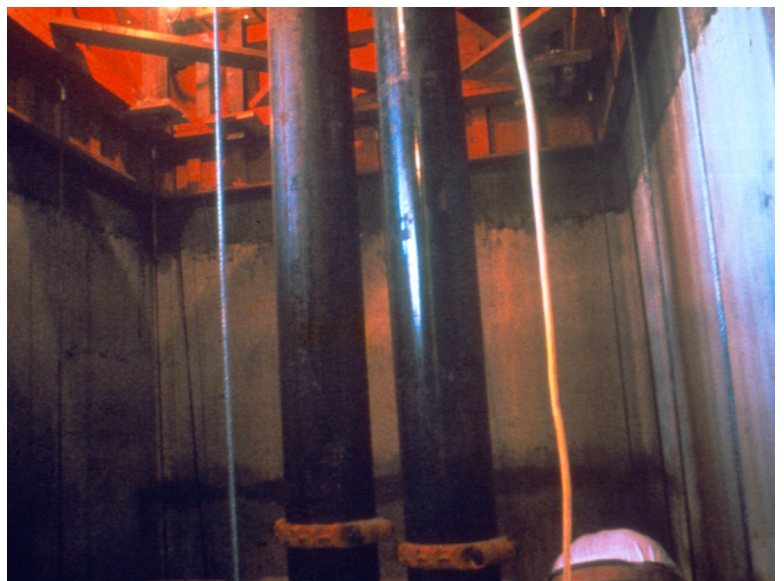


Figure 18
Installation of Vertical Plumbing Riser

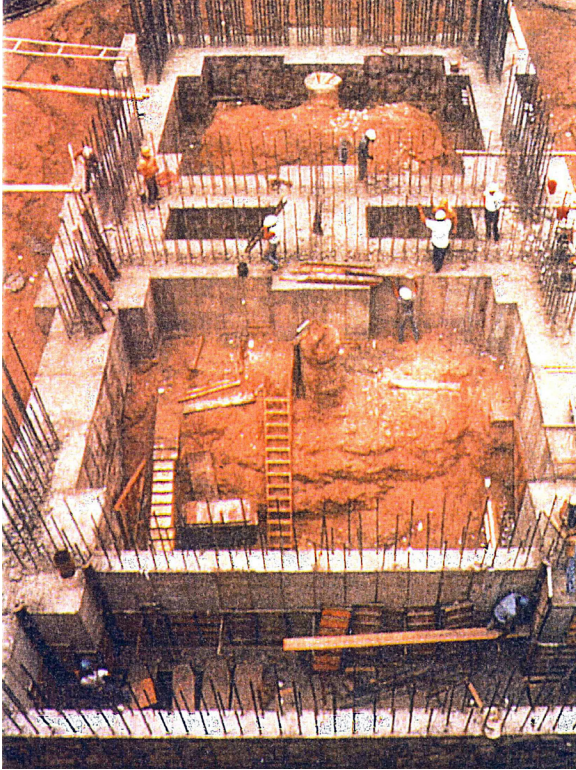


Figure 19
Foundation Ready to
Receive Slipform



Figure 20
Typical Yoke



Figure 21
Laser at Ground Level to Guide Slipforming

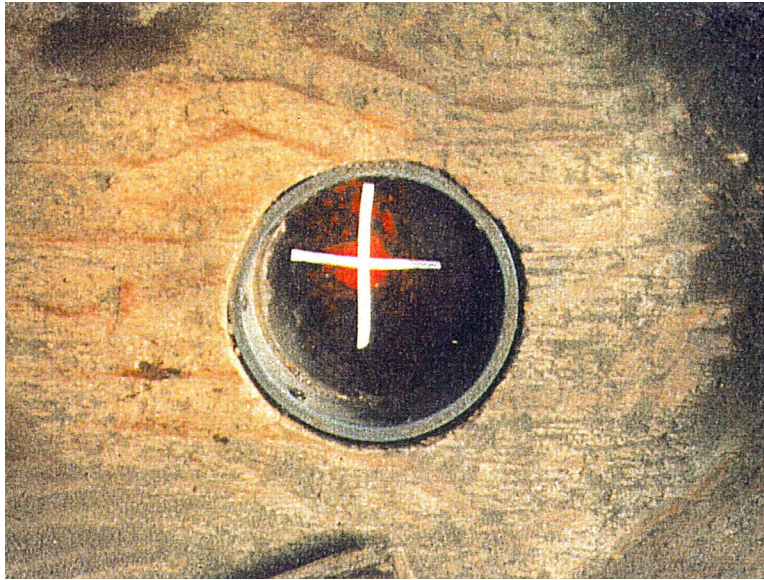


Figure 22
Target for Laser



Figure 23
Laser at Corners of Form



Figure 24
Structural Steel Erected From Slipform



Design Loads on A Slipform System

The entire weight of the decks and supporting scaffolds is transmitted onto the wales through the yokes and into the jacks and jackrods. The only functions of the concrete during construction are to support its own weight and to prevent the jack rods from buckling. In addition to the dead loads, live loads of 40 to 50 pounds per square foot of deck and 50 pounds per linear foot of scaffold must be supported. Storage loads for reinforcing steel, blockouts, inserts and other construction necessities must also be provided for in the design.

An influential part of the load on a slipform is the friction (or drag force) of the concrete against the form as the form is jacked up. This loading is highly variable depending on the temperature, moisture content, workability, and rate of set of concrete, as well as the ambient temperature and smoothness (cleanness) of the form surface. This force is kept within limits by building in a slight batter of approximately 1/16 inch per foot on the exterior form. A drag load of 100 pounds per linear foot of forms is commonly used in form design. To further reduce this friction load, the form is made impermeable by oiling or plastic treatment to prevent water absorption. Non-absorption of water is important because a film of excess surface moisture has a beneficial lubricating affect.

Since the slipform is subjected to the hydrostatic pressure of the plastic concrete, the sheathing must support this lateral pressure through beam action between the wales and as a cantilever at the bottom. The wales in turn must carry the hydrostatic pressure as beams spanning horizontally between yokes (**See Figure 12**).

The yokes are shaped like inverted U's, consisting of two legs and a crossbeam. The legs are attached to the wales and carry the vertical and lateral loads as cantilever beams (**See Figure 20**). The cross arm of the yoke must be designed as a beam supported at the center by the jack and subjected to the moments of both the vertical and lateral leg loads.

Usually, the rate of speed of the slipping operation is controlled by the time required for the concrete to set and not by the capabilities of the jacking system. The reason for this is that if the jacks are advanced too fast, the plastic concrete may not have had time to set before the form passes, thus allowing concrete to extrude from the bottom of the form. However, if the advancement rate is too slow the risk of concrete bonding to the forms becomes a concern. Bonding can cause tearing of the concrete or binding of the form in place. We have found that it is preferable to proceed at faster rates in hot, dry weather and slower rates in cold, wet weather.

The engineer should attempt to maintain wall thicknesses of the various walls in the core in a range that would allow the concrete to set in all walls within a reasonably close time frame or the contractor will not be able to obtain a rate of speed that is favorable for all walls in the core.

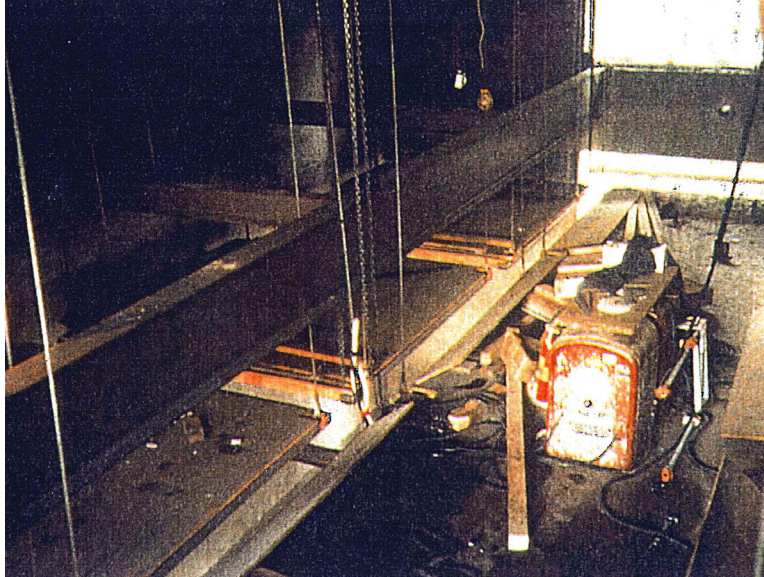


Figure 25
Trolley on Slipform Used to Erect Steel

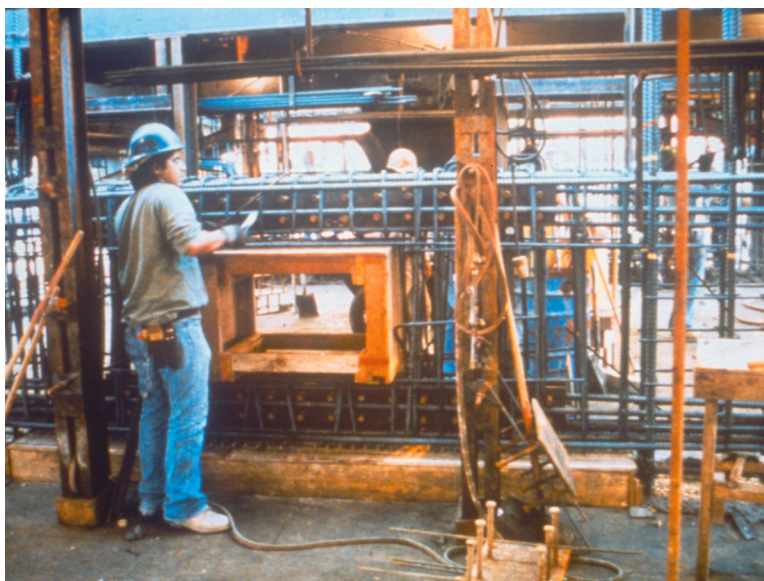


Figure 26
Large Lifting Yokes at Special Conditions

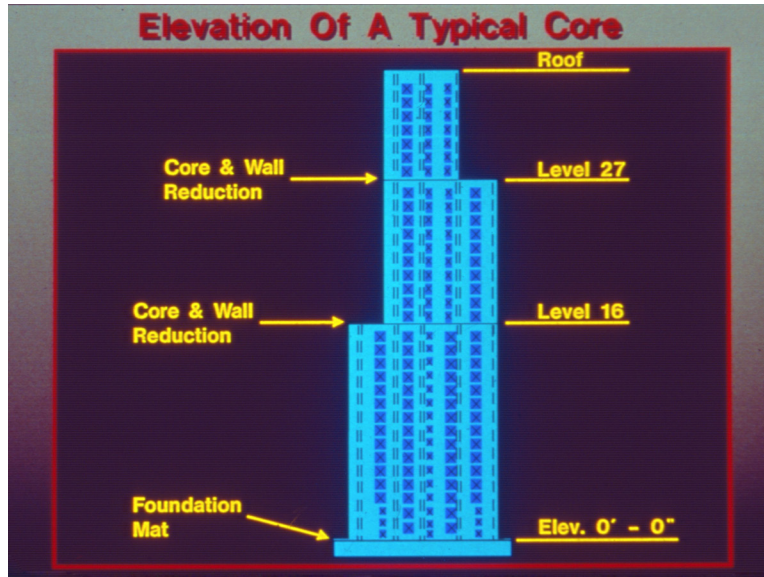


Figure 27
Diagram of Typical Elevator Core Offsets

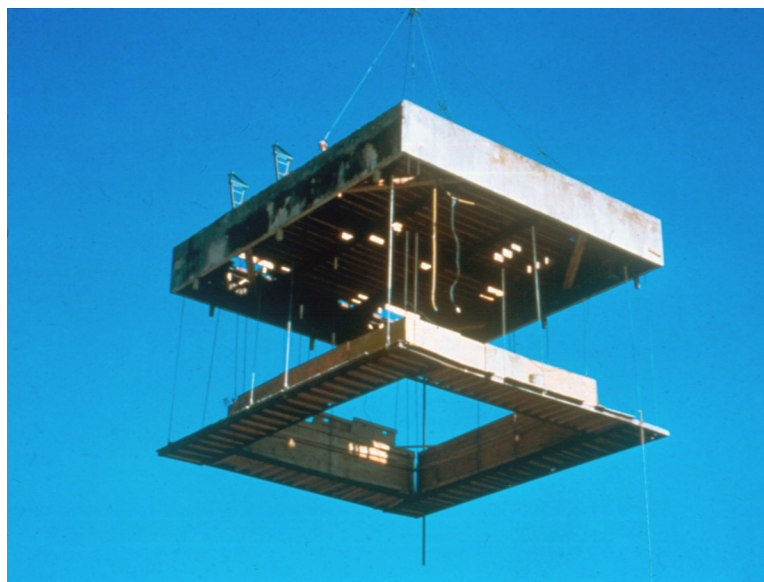


Figure 28
Lowering Unnecessary Forms to Ground



Figure 29
Reduced Form Above
Offset in Core

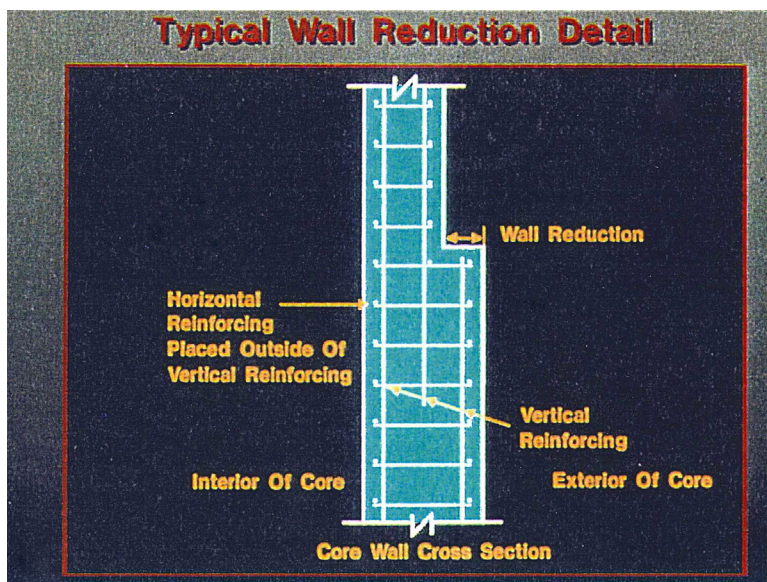


Figure 30
Diagram of Offset in Wall Thickness

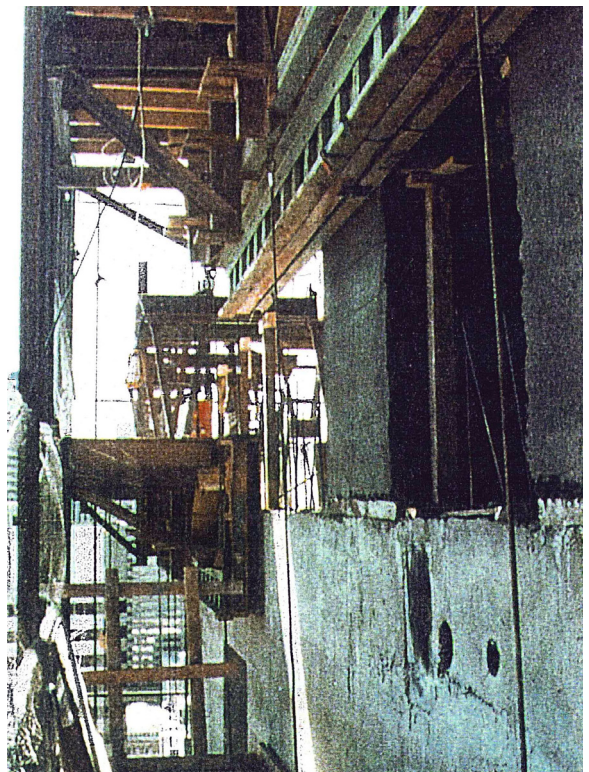


Figure 31
Actual Formed Offset



The Slipping Operation

The American Concrete Institute (ACI 347) recommends that personnel experienced in slipform construction be present on the deck at all times during the slipping operation. This person should have the expertise to determine the rate of speed at which the slipping operation should proceed, factoring in changes in weather, concrete slump and workability, and many emergency which arise during the operation that cannot be predicted beforehand.

Since the concrete provides the necessary lateral support, which prevents buckling of the jacking rods during the slipping operations, a problem arises wherever there are openings or where walls are discontinuous. When this occurs, supplemental jack rod bracing must be built in. It may also be possible to set the jacks to miss such openings.

Two critical areas of concern during slipforming are 1) keeping the slipform level (which sets core plumbness) and 2) preventing rotation of the form. One way to protect against these misalignments is by using lasers to guide the slipforming. On the Atlantic Center project, Sundt Construction Company used the laser method successfully (**See Figures 21, 22, and 23**). The lasers were set up at ground level, at opposite corners of the core (**See Figure 21**), and aimed up at clear plastic targets that were set in holes cut in the metal work deck (**See Figure 22**). At approximately two hour intervals, paper was placed over the plastic targets and the spot where the laser hit the paper target was monitored and recorded. By determining where the laser hit the target, the jacking operator could tell if the slipforming had rotated or was out of plumb, thus allowing immediate corrective adjustments when required.

Another indirect use of lasers is to determine the vertical location of embeds, blockouts, and sleeves. By using lasers one person can take the measurements at these locations, where, in the past, it normally took three workers with a transit and measuring tapes. This is accomplished through the following procedure:

1. A horizontal laser is mounted on one of the jack rods above the upper deck (**See Figure 23**). The rotating laser creates a level plane of light that strikes all the vertical rebars at the same elevation.
2. An electronic distance meter (EDM) is mounted on another jack rod. Then, when pointed at the ground, the EDM measures its own elevation.
3. Then, at critical locations around the upper deck, the elevation of the finish floor slab is marked on the vertical rebar for reference.

Due to the \$2.00 per linear foot cost of jacking rods on the Atlantic Center project, Sundt Corporation chose to remove and reuse the jacking rods. In staggered order, after every 100 to 150 feet of slipforming, work crews pulled each jacking rod out of its sleeve in sections and then laid a steel plate over the empty sleeve, mounted another section of sleeve on top of the steel plate, and continued this process with the same section of jacking rods they had just removed.

Also, on the Atlantic Center project, to erect the structural steel for the elevator and the elevator lobby (**See Figure 24**), workers erected a special winch and trolley system in each quadrant of the core below the work deck (**See Figure 25**) capable of reaching any point in the quadrant. This system minimized the tower crane's role in erecting steel inside the core, freeing it up for other tasks.

A minimum of 12 inches and a maximum of 30 inches of hardened concrete is recommended in the forms during the slipping operation. If there is less than 12 inches of hard concrete in the forms, the slipping operations time must be reduced to allow for the concrete to set further. If the amount of hard concrete exceeds 30 inches, the rate of the slipping operation must be increased to prevent binding of the forms.

On the Atlantic Center project, the Sundt Corporation started slipforming at the top of the doorway at one floor and stopped at the top of the doorway on the succeeding floor. This allowed the nightcrew to install the complicated steel for the link beams over the tops of the doors without time pressures due to movement of the forms. To provide more available space for placing of the large amounts of steel required for the link beams, extra large lifting yokes which could be spaced farther apart were used in these areas (**See Figure 26**). This also allowed for required items that could not normally be placed during slipping operations, such as closed stirrups and other types of details, to be placed.



On most high-rise buildings, the slipform core needs to have drop-off sections of the form, where low-rise and mid-rise elevators terminate, etc. (**See Figure 27**). This is accomplished by detaching the unnecessary section of the formwork and lowering it to the ground (**See Figure 28**) and continuing up with the remaining portion of the form (**See Figure 29**).

On these taller slipform cores, for economic reasons, it is also desirable to reduce the wall thickness two to three times as the core progresses upward. Such changes create an added expense due to work slowdown while the slipforming contractor stops forming operations to insert filler panels in the forms to reduce the thickness of the concrete pour (**See Figures 30 and 31**). To offset this expense, we typically locate a step in the wall thickness at the same level where there is a change in core geometry, such as where the low-rise or mid-rise elevators terminate. The slipform contractor has to stop the forming operation at this point anyway, to remove the section of form that is not to continue upward and, therefore, he can install the filler panels at the same time without additional delay. An example of this procedure is shown in Figure 31, where the filler panel has been installed and (in the background) part of the form is continuing upward. You can also see where the form has been discontinued at the top of the mid-rise elevator banks.

Finishing is easy when using slipforming construction, requiring only a float and brush finish, because of the excellent condition in which the concrete emerges from the form. Curing is usually achieved by use of sprayed-on membrane curing compounds. If water curing is used, we recommend the use of fog type nozzles to prevent erosion of the green concrete paste. These procedures are easily performed from the hanging scaffold.



Figure 32
Placing of Vertical Steel
to Bypass Yoke

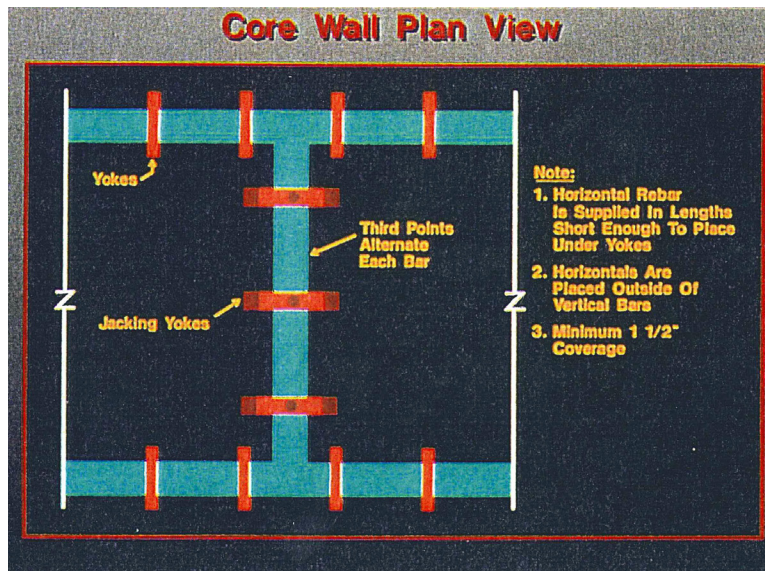
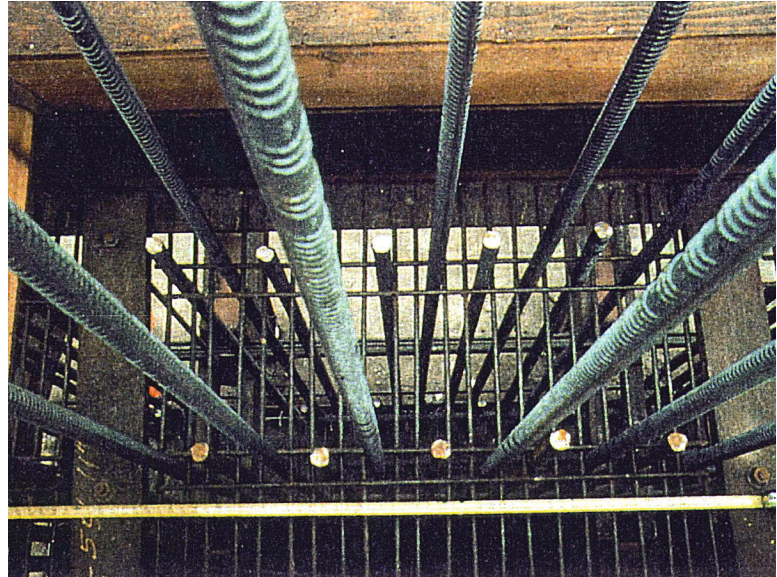


Figure 33
Templates Used to Place Steel

Figure 34
Recommended Tolerances
for Overall Core

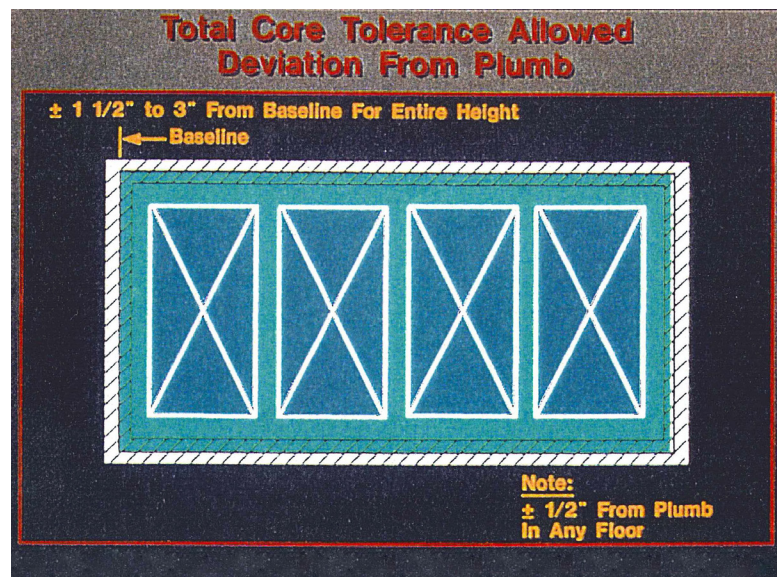




Figure 35

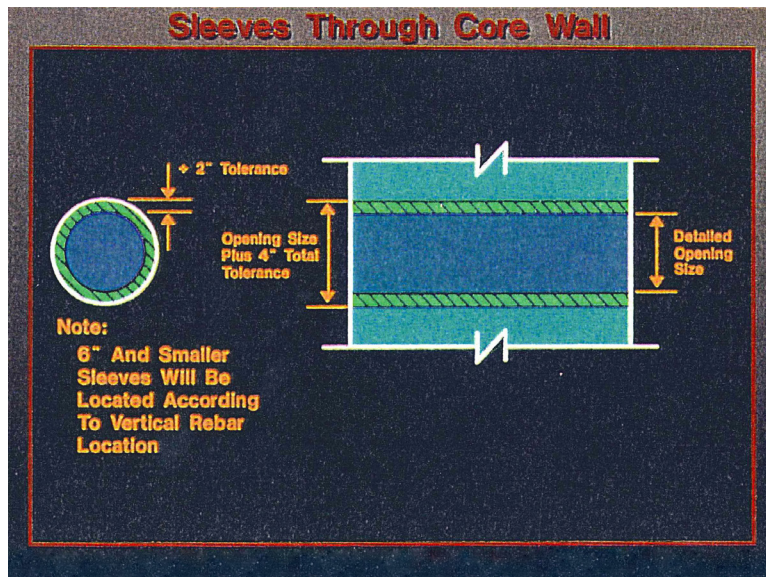
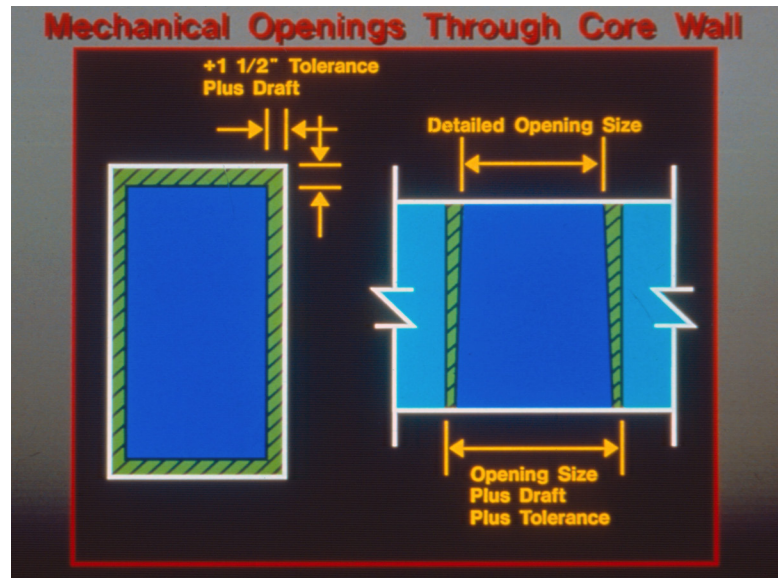
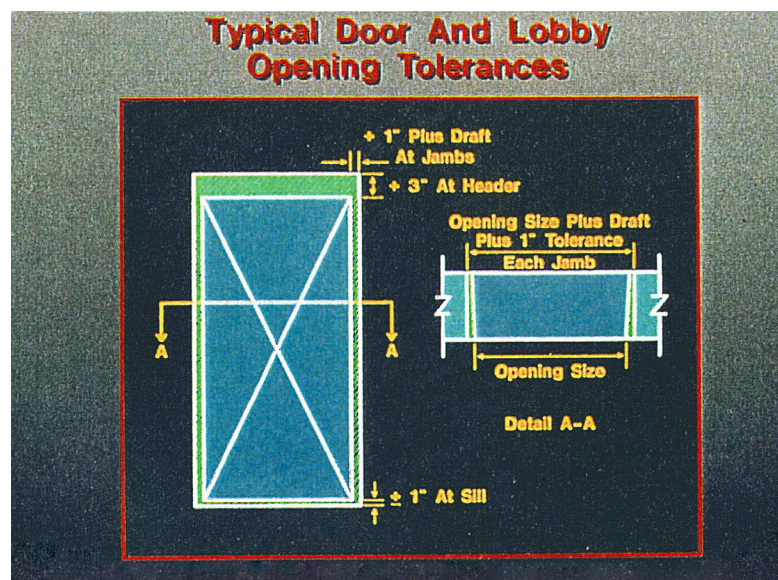


Figure 36

Figure 37





Details of Reinforcing Steel

Reinforcing steel for slipform work is not placed in a conventional manner and, therefore, must be detailed differently from conventional concrete construction. The vertical steel must be positioned to miss the yokes (**See Figure 32**). In order to accomplish this, the vertical steel is designed to be held in place with templates, which are attached to the top deck (**See Figure 33**), and are capable of moving with it. The vertical steel is lapped and tied to the row below. The laps are staggered for structural reasons and also to distribute the workload more evenly between the iron workers. Lengths of these vertical bars are usually limited to approximately 15'-0", depending on the size of the bar, so that they do not extend too far above the templates, helping to reduce the whip effect which may develop on a windy day.

Horizontal steel is passed under the yoke beams as the work progresses, one level at a time, and tied to the vertical steel and jack rods (**See Figure 20**). Horizontal bars are generally placed on the outside of the vertical bars and are limited to about 20'-0" lengths to facilitate placing.

It is desirable to have a continuous spacing of vertical reinforcing throughout the height of the building and to reduce the bar size, instead of the spacing, if possible. This allows the use of a standard template for placing reinforcing steel.

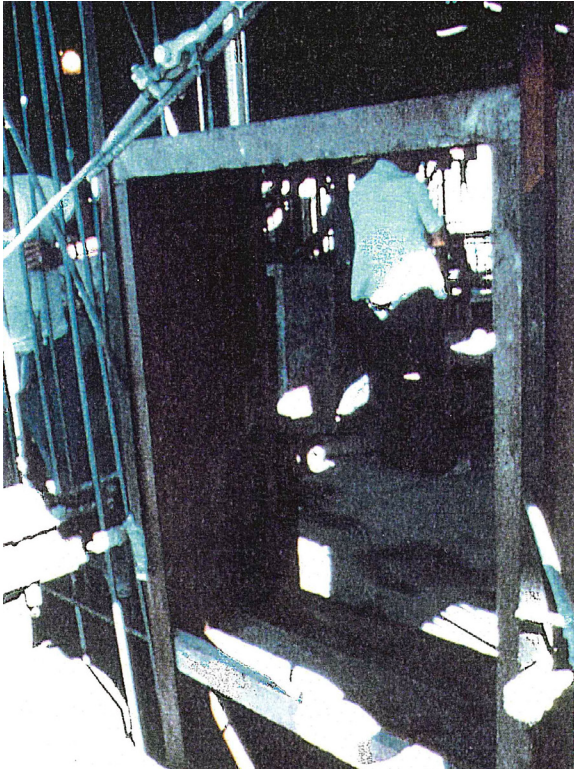


Figure 38
Blockout for Door Opening

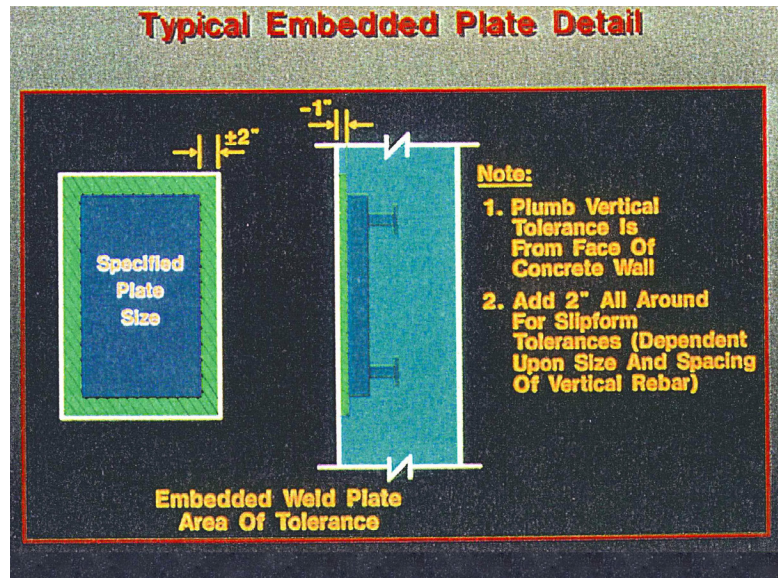


Figure 39
Tolerances for Location of Weld Plate

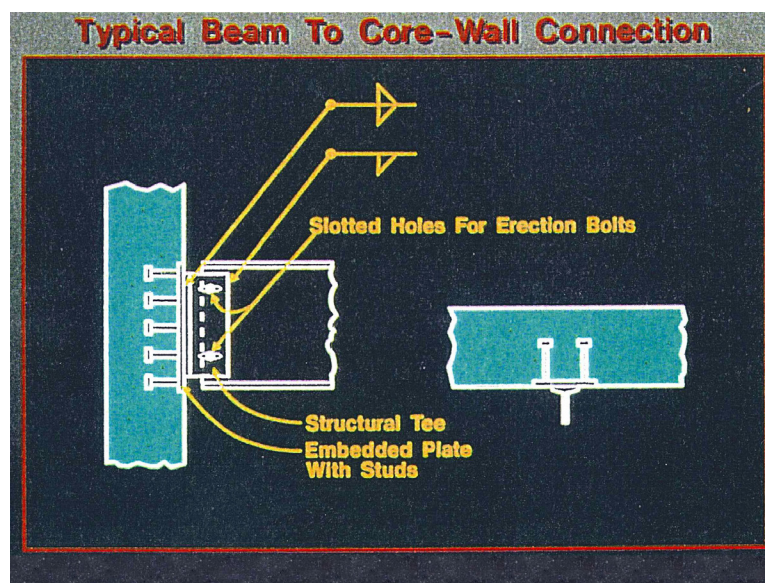


Figure 40
Detail for Connection of
Beam to Weld Plate

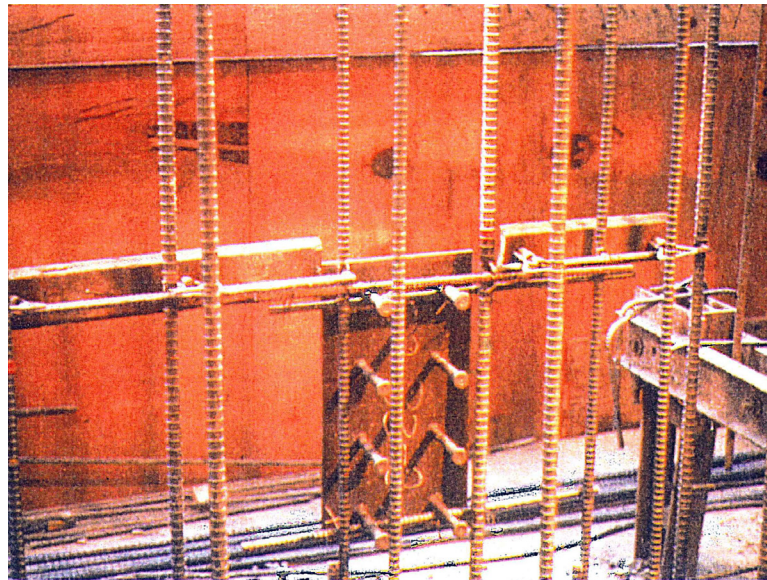


Figure 41
Weld Plate Tied to Reinforcing Steel

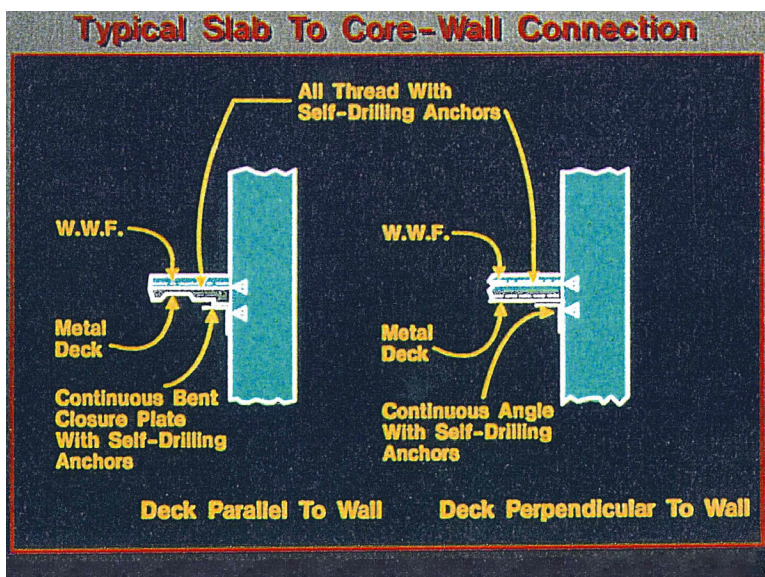


Figure 42
Detail of Angle Attached to Core

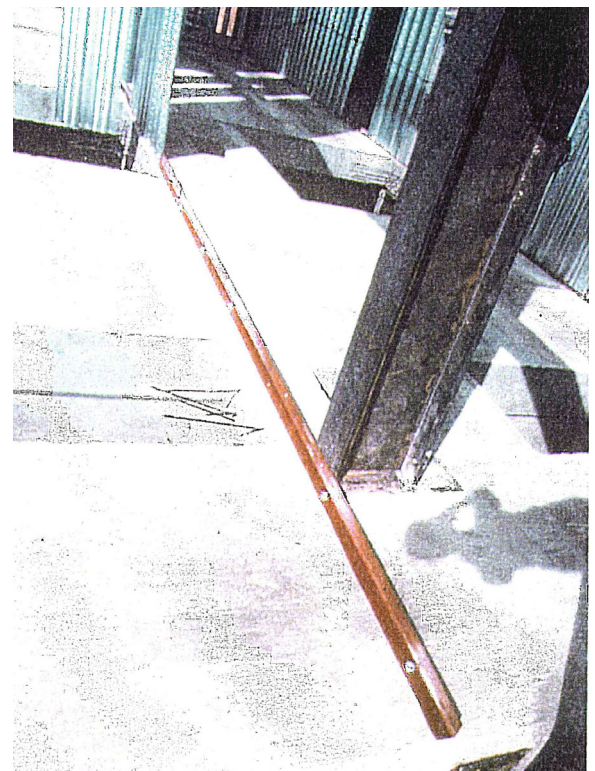


Figure 43
Angle Attached to Core



More Tolerance Required for Slipform Construction

An understanding by the design architect and engineer of the need for greater tolerances than are normally used in concrete construction is critical to the success of a slipform operation. ACI committee 347 recognized this need and addressed it in their recommendations for greater tolerances in their report.

There are recommended tolerances for the overall dimensions of a typical core (**See Figure 34**). In addition to the tolerances shown, the core can rotate from .25 to .50 degrees. This becomes significant to the architect. In order to accommodate an architectural layout requiring a corridor wall which needs to be squared with the rest of the building, the architect must recognize the possibility of both rotation and out-of-plumbness of the overall core when he establishes the tolerances in his details.

There are also recommended tolerances for blockouts, pipes, mechanical openings, doorways, etc. (**See Figures 35, 36, and 37**). These greater tolerances need to be acknowledged and incorporated into the structural design of the reinforcing steel and concrete. The architect also needs to recognize and allow for these increased tolerances when detailing the doorjamb, heads and finishes. The mechanical engineer may be affected as well.

The primary reason for greater tolerances is that the embeds, blockouts, beam pockets, etc., cannot be tied to the form, as is the case in conventional construction. The blockout for the door opening shown in **Figure 38** is a prime example. Even if the contractor could install this door opening in the exact location, tying it to the guide angles at each side and to the reinforcing steel does not provide a perfectly secure and fixed location. The blockout can also become dislocated during the concreting operation. With all of the assemblies mentioned above, tying to the reinforcing steel, which is not rigid and is subject to dislocation when the form slides past it or when the concrete is placed against it, necessitates greater tolerances.

Our experience has indicated that the following tolerances, which in most cases are greater than those recommended by the ACI Committee 347 report, are more desirable and can be obtained without severe penalty to the project. We specify a tolerance of plus or minus 2 inches vertically and horizontally for the installation of weld plates to receive steel framing members (**See Figures 39, 40, and 41**).

However, we generally oversize the plate so that being 3 inches off would still be acceptable. We also design the shear studs on the backs of the plates to resist a 3 inch eccentric load on the group of studs. The amount of extra steel and studs per weld plate is minor in comparison with the disruption caused by having a weld plate rejected due to being out-of-tolerance.

It is also desirable to utilize self-drilling anchors or expansion bolts, in lieu of cast-in-place inserts where possible, to avoid tolerance problems associated with tying inserts to reinforcing steel (**See Figures 42 and 43**). The elimination of costly delays associated with chipping out concrete at misplaced blockouts and with relocating steel beam insert plates makes close attention to these details well worthwhile.

Although we have seen projects where the front wall of the elevator shaft has been slipformed, we have always selected to omit this wall from the operation and construct it on dry wall. The number of door openings and blockouts for call buttons and direction signals make this a difficult wall to slip.



Conclusion

Slipform cores in mid-rise and high-rise structures deserve to be considered by the design and construction team. If slipform construction is selected by the team, a successful project should be realized if a qualified slipform contractor is selected and the previous recommended details and tolerances are followed.

Every project is different and will present a different set of circumstances that have not been addressed herein. There is no substitution for personal experience with slipforming to be able to anticipate these circumstances in advance. These recommendations represent our best experience at this time, but, as we address new project and new circumstances, we are sure to meet new conditions that are not addressed herein.



APPENDIX

“Specifying Concrete for Slipforming”



In My Judgment

by Adam Neville

Specifying Concrete for Slipforming

Slipforming is a well-established method of construction of placing concrete in moving formwork for vertical elements, usually of considerable height, such as towers, chimneys, bridge piers, shear walls, silos, oil platforms, water tanks, shaft linings, and nuclear reactor containment vessels (Fig. 1). Horizontal elements can also be slipformed but that method, akin to extrusion, is not considered in this article.

The main advantages of slipforming are the absence of construction joints (which mar the appearance and contribute to leakage of liquids or gases), a high speed of construction, and a good adaptability for construction in bad weather. Slipforming is a specialized operation that requires skill and experience, and it is usually performed by specialist contractors who have the requisite knowledge. Others can learn about slipforming operations from handbooks of slipform contractors or from publications on formwork in general, such as *ACI Special Publication No. 4*,¹ and the *ACI Guide to Formwork*,² or an equivalent guide published by the British Concrete Society.³ However, readily available sources of information about the concrete technology aspects of slipforming do not seem to exist. And yet, designers need to know about the limitations that slipforming imposes on the concrete mix. Likewise, concrete suppliers should be knowledgeable about the kind of mix that may be required.

A particular problem that sometimes occurs is writing a specification for concrete that will be, or may be, slipformed. The method of construction is prescribed in one part of the specification, but it is in various other parts that the properties of concrete are laid down in terms of ingredients to be used, limits on mix proportions, possibly workability, and durability (as influenced by the water-cement ratio and specific cementitious materials), as well as thermal properties in terms of a maximum temperature or thermal gradient.

If the latter parts of the specification are written without due consideration to compatibility with what is needed to ensure a smooth slipforming operation, then problems may arise. These problems can be avoided if the specification writer understands the relevance of concrete technology to slipforming. It is the purpose of this article to highlight this relevance.

This article was selected for reader interest by the editors. However, the opinions expressed are not necessarily those of the American Concrete Institute. Reader comment is invited.

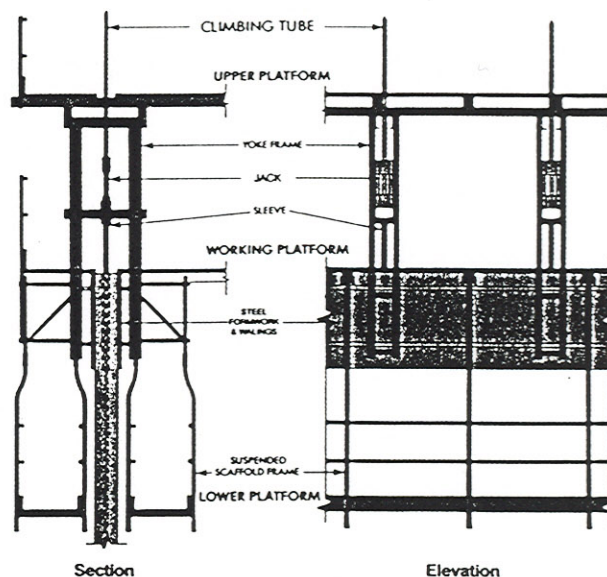


Fig. 1 — An example of slipform.⁵

Stiffening of concrete

Strictly speaking, slipforming is not a continuous operation in that the upward movement of the formwork occurs in steps of 25 or 50 mm (1 or 2 in.). The overall rate of climb of the formwork is variable, generally between 0.15 and 0.4 m (about 6 and 16 in.) per hour. Important factors affecting this rate are the need to place the reinforcement (which may be more or less complex or plentiful) and the need to form box-outs for doors or passages. The required variability in the rate of climb imposes demands on the rate of stiffening of the concrete.

The concrete is placed in the formwork, which is commonly 1.2 m (4 ft) deep, in thin layers, about 200 mm (8 in.) deep. Once a layer has been completed over the entire operational surface, placing concrete in the next layer begins. It is essential that the underlying layer remains in a plastic state long enough for there not to be a "cold joint" or a plane of weakness between the layers. On the other hand, the concrete lower down in the formwork must stiffen sufficiently and achieve an adequate strength when the form is removed by its upward movement so that the concrete does not slough-off or bulge. In simple terms, the concrete must remain plastic "long enough" but must then stiffen and harden "soon enough."

The stiffening of concrete is not measured by any standardized method, such as a Proctor needle, which would be

inappropriate in the congested and busy space available and which requires removal of coarse aggregate. This is why the term "stiffening time" is preferable to "setting time." The stiffening time is determined in a practical manner: a 16 mm (3/4 in.) diameter bar is pushed vertically down into the concrete until its movement becomes halted by the resistance of the concrete. This should occur at a depth of about 0.6 m (2 ft), that is, half-way down the form. Clearly, the "test result" is greatly affected by the operator. Not surprisingly, such a requirement for the stiffening time cannot be readily translated into a specification clause, but then slipforming is an art, and not just a technique.

Given that the stiffening is required at approximately the mid-depth of the form, the time interval between placing of concrete and stiffening in a form 1.2 m (4 ft) deep is as follows: when the rate of climb is 0.15 m/h, the interval is $0.6/0.15 = 4$ h; when the rate of climb is 0.4 m/h, the interval is $0.6/0.4 = 1.5$ h.

Clearly, the faster the rate of climb of the slipform, the shorter the stiffening time required. For practical purposes, the stiffening time has to be reckoned from the time when the concrete is discharged from the mixer. It follows that, to the time interval calculated above, we have to add the time required to transport the concrete from the mixer to the slipform plus the time necessary to place and compact the concrete. Thus, much depends on the actual circumstances, but an additional period of 2 hours is likely. In such a case, the stiffening time required would be between 3.5 and 6 hours. The concrete emerging from the formwork would be between 5 and 10 hours old.

From the above values, it is clear that the concrete needs to retain a high workability for a long time; it follows that a superplasticizer needs to be used, especially at low rates of climb.

Naturally, it is desirable to slipform as fast as possible but an occasional slowing down is inevitable in order to place the reinforcement or box-out apertures, as mentioned earlier. If the density of reinforcement decreases with height, speeding up may be possible. Also, if the cross section being slipformed changes, adjustments to the formwork become necessary, and this takes time. There may also be occasional problems with equipment. With proper planning and good communication between the slipform team and the batcher, the delivery of concrete may be deferred, but the ability to vary the stiffening time is essential. Also, it should also be remembered that the stiffening time of a given mix is affected by changes in temperature. Given that slipforming is a round-the-clock operation, temperature changes are bound to occur, even if the weather does not change.

Because of the multitude of factors involved, ensuring a suitable stiffening time cannot be achieved by a desk study alone. Trials must be carried out at the planning stage to establish reliable values of stiffening times for the likely range of rates of slipforming.

Workability and mix composition

Concrete suitable for slipforming generally requires a slump of about 150 to 200 mm (6 to 8 in.). Much depends on the density of reinforcement, but this is true also in the case of nonslipformed concrete. It may be worth noting, however, that in some slipformed oil platforms the density of reinforcement has exceeded 1000 kg/m^3 (1700 lb/yd^3) of concrete.

To be suitable for slipforming, the fresh concrete has to possess, in addition to workability or "mobility," an adequate cohesion and also a low frictional resistance to the movement of the form; otherwise, despite the outward taper (batter) at the bottom of the form, a streaked or uneven surface may result. Methods of ensuring good cohesion are well established.

The workability and mobility of concrete are affected by the specific cementitious materials in the mix, especially ground granulated blast furnace slag and silica fume. The use of these on the grounds, for example, of improved durability may be considered, and the specification may prescribe them, permit them, or forbid them. In taking an appropriate decision, the needs of the slipforming operation must be borne in mind.

The preceding discussion illustrates an important need for mix selection such that an appropriate retention of workability is ensured, and that the period of retention can be modified by varying the dosage of the superplasticizer, possibly by a re-dosage at a later stage after the initial mixing, or by the use of a retarder. All this should be reflected in the part of the specification dealing with mix ingredients and permitted admixtures.

The need for a high slump means that the mix must have a high water content unless a suitable superplasticizer, and possibly also a compatible water-reducing admixture, is used. A high water content may have implications for the total content of cementitious material when a low water-cement ratio is necessary from strength or durability considerations. Now, a high content of cementitious material may have adverse effects on the maximum temperature in the interior of the concrete element and on temperature gradients in the concrete.

Thus there is a potential incompatibility between the choice of mix proportions to satisfy the thermal requirements and also to satisfy the requirements of fresh concrete suitable for slipforming. Such an incompatibility can be avoided if advance thought is given to the mix desiderata. It is only when some parts of the specification are written without consideration of the consequences of slipforming that difficulties may arise.

Thermal problems in concrete can be alleviated by lowering the temperature of fresh concrete, for which standard techniques are available. In the case of slipforming, such lowering of temperature has the additional advantage of improving the workability and delaying the loss of slump.⁴

Aggregate requirements

For most concrete construction, the specification does not impose particularly onerous conditions with respect to aggregate: after all, it would not be economic to specify aggregate that cannot be obtained locally. For concrete that will be slipformed, it should be borne in mind that good workability is of particular importance. Consequently, the aggregate should have better grading than the minimum laid down in ASTM C 33. Furthermore, the proportion of flaky or elongated particles in the coarse aggregate should be fairly severely limited.

A fairly high proportion of particles passing the 5 mm (No. 4 ASTM) sieve, say 45%, contributes to the cohesion of the mix, reduces friction at the surface of the formwork, and leads to a satisfactory finish.

If possible, the fine aggregate should not consist wholly of

crushed material: rounded fine aggregate helps water retention by the concrete and reduces bleeding. Of the fine aggregate, almost 50% should be smaller than 0.6 mm (No. 30 ASTM) sieve. However, the optimum value would be affected by the content of cementitious material in the mix. Generally, it is desirable to have a lower content of particles smaller than 0.15 mm (No. 100 ASTM) sieve than permitted in national standards. It may be desirable to make up the fine aggregate out of separated fractions. Minor changes in the proportion of smallest particles of aggregate have a large effect on the behavior of the mix.⁴

Curing

Wet curing of slipformed surfaces is not easy, but it is highly desirable in hot weather, especially when accompanied by wind, or when aesthetic considerations preclude the use of membrane curing. One slipforming contractor⁵ recommends a mist spraying circuit suspended from the scaffold frame hanging below the actual formwork, as well as protective plastic sheeting. Such a system requires a continuous water supply and hence pumps, and may appear to complicate the construction process. But then slipforming has many exigencies, including the provision of portable toilets on the platform!

Conclusions

I hope that this article has not given the impression that selecting a mix suitable for slipforming is very difficult. In reality, a mix that can be easily pumped needs only to be

somewhat modified to make it appropriate for slipforming.

The rationale of this article is not to highlight the problems in slipforming in so far as mix selection is concerned. Rather, I have tried to show that, when slipforming is to be used as a method of construction, the specification for concrete must take into account the required properties of the concrete. There is no inherent difficulty in this — all that is needed is knowledge and forethought.

Slipforming is an excellent method of construction. It is also "good" for concrete in that concrete suitable for slipforming is a "good" concrete with respect to mix composition coupled with a low variability in mix properties.

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ACI Honorary Member **Adam Neville** is the author of the book *Properties of Concrete*, whose Fourth Edition appeared in 1996. Arising from his work as a consultant in concrete, he has recently published in *Concrete International* and elsewhere a number of papers developing applied knowledge to produce better concrete in practice.

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