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FINAL PROJECT REPORT
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Concrete slipforming is an innovative method. It is becoming increasingly popular in the construction of high-rise building concrete cores. It provides accuracy, a monolithic structure, no joints unless a halt occurs, any structural design shape in plan, strength, high quality surface finish, rapidity, labor saving in long term, savings in formwork materials, and it is economical for structures above a certain size. However, it requires a good coordination and site organization (day and night shifts), large quantities of equipment, continues operation during unsuitable weather, high initial expenses, a 24-hours service facilities. Innovations and problems associated with construction engineering and management of the IBM Tower slipforming in Atlanta, Georgia are described. Recommendations for resolving the problems are presented. A few Japanese construction companies have developed a fully automated slipforming operation. Although, development of a similar automated system is possible in the US, however, no aggressive research is in progress to reach this goal.

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FINAL NSF REPORT

Construction Innovation in Slipforming Concrete Buildings

Presented to the

National Science Foundation
NSF Grant No. MSM-8814244
Georgia Tech Project No. E-20-687

by

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ABSTRACT

Concrete slipforming is an innovative method. It is becoming increasingly popular in the construction of high-rise building concrete cores. It provides accuracy, a monolithic structure, no joints unless a halt occurs, any structural design shape in plan, strength, high quality surface finish, rapidity, labor saving in long term, savings in formwork materials, and it is economical for structures above a certain size. However, it requires a good coordination and site organization (day and night shifts), large quantities of equipment, continues operation during unsuitable weather, high initial expenses, a 24-hours service facilities. Innovations and problems associated with construction engineering and management of the IBM Tower slipforming in Atlanta, Georgia are described. Recommendations for resolving the problems are presented. A few Japanese construction companies have developed a fully automated slipforming operation. Although, development of a similar automated system is possible in the US, however, no aggressive research is in progress to reach this goal.

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CHAPTER 1

INTRODUCTION TO SLIPFORMING

1.1. GENERAL

Slipforming is an innovative and accelerated technique. Slipforming is defined [1] as: "Concrete construction in which forms rise along the surface as layers of concrete are successively poured and hardened within them". Slipforming is unique from various other techniques of concrete construction in that structural support is not provided during the laying of the concrete. Rather, the strength of the slipformed structure is derived from the progressive hardening of the concrete through the successive phases of construction. For this reason, the technique of slipforming requires that special attention be paid to such factors as mix design, and the utilization of special jacking systems.

Therefore, slipforming is a method of moving or raising forms that shape the concrete as they slide over the fresh concrete. It is rapidly forming and continuously placing concrete in coated forms using hydraulic jacks to raise the forms.

The advantages of slipforming are: accuracy, continual casting which provides a monolithic structure; no joints unless a halt occurs; lends itself to almost any shape in plan, strength, high quality surface finish, rapidity, labor saving in long term; saves formwork materials; and it is economical for structures above a certain size. The disadvantages are: good coordination and site organization required; large quantities of equipment required; day and night shifts must be organized; labor forces may require familiarizing with equipment and methods; operations must be continued during unsuitable weather; high initial expenses; need for 24-hours service facilities; communication must be coordinated between ground level and crane driver and slipform and hoist operators; social problems created by long working hours; fixing door and window frames; labor requirements before and during and after the slide; and less site control due to subcontract labor.

The slipforming process was originally designed for use on grain silos. In the late 60's and early 70's contractors looked for faster methods of building, and the adaptation of slipforming was one answer. Its use on the vertical shear walls of high rise buildings reduces the construction time.

The main advantage of the slipforming system is speed, even though it is not the cheapest form of construction and, although somewhat limited in its adaptation to some building

forms, the slipformed core is a great solution for one of the worst enemies of the contractor: time. On the other hand, time may be a great advantage for the developer if the building, somehow, is finished ahead of schedule.

In high rise buildings, slipform can be the key to opening new areas of work to the craftsmen. Areas like structural steel, stairs, other central core items, and a very important item: the elevators, which are normally eliminated from the critical path when the slipform is used.

All these features make the slipforming a system which has been accepted as a construction technique within a relatively short period of time; and every day more contractors and developers are considering it as an alternative method of construction.

There are two basic methods of slipforming. First method is vertical slipforming in which the movement of concrete is vertical. This method is utilized in the construction of tall buildings. Originally, the vertical slipforming was employed primarily for the construction of concrete silos, grain storage bins, and chimney stacks. In recent decades, however, the method has been employed with greatest success in the construction of many high-rise buildings for the central service core of buildings. These service cores usually house elevator shafts, ducts, pipe and conduit spaces, and stair wells. The second method is horizontal slipforming. This method is used for canals, tunnels, and highways. This research is focused on the first method, vertical slipforming.

Slipforming was traditionally confined to single-cell silos construction, but in the 1960's and 70's, financial constraints forced contractors to seek faster methods of construction. Slipforming, therefore, became an adaptive innovative technique for concrete structures such as multicell silos, tall bridge piers, building service cores, towers, water reservoirs, vertical shafts for tunnels and mines, vertical shafts for missile launching bases, and chimney stacks.

Of these structures, service cores of high rise buildings are the most popular in the recent years because of the considerable reduction in construction time, coupled with increasing commonalty of high-rise building constructions. The time factor has made the slipforming system as an alternative method of construction being constantly considered by contractors, developers and owners of projects, even though it is not the cheapest form of construction.

The techniques involved in vertical slipforming were first introduced in the year 1985 by a Texas architect named Carrico. Since that time, numerous innovations have been introduced to standard practices of vertical slipforming, providing additional advantages in terms of cost and labor efficiency. For example, utilization of hydraulic jacks has been incorporated into the process of vertical slipforming. By the mid-1950's, such innovations had become common-place in the construction of concrete silos and similar structures. In the early 1960's, the techniques employed in the vertical slipform construction of silos was first adapted to the construction of buildings.

1.2 RESEARCH OBJECTIVES AND SCOPES

The objective of this research was to explore and investigate construction engineering and management of concrete building core slipforming. The scope was limited to high-rise building concrete cores in the United States. The slipforming is discussed in detail including its principal components, its erection and the sequential construction methods.

Heavy emphases are given to innovative construction problems that arose in particular projects, how they were solved and their limitations. A case study of the IBM slipforming construction is provided. Problems, and recommendations to resolve these difficulties are presented. Design considerations are discussed.

1.3 METHODOLOGY

The report consists of five chapters.

Next chapter provides innovations in construction of the IBM Tower slipforming in Atlanta, Georgia. Chapter three identifies the construction engineering and management problems associated with slipforming of concrete cores, and provides solutions for them.

Chapter four provides a brief historical development of the slipforming system, its principal components and functions. Chapter five describes the main factors to be considered in slipforming of building cores. Chapter six explains the construction techniques applied in slipforming concrete cores. Chapter seven presents design considerations. Chapter eight describes unique construction factors to be considered. Chapter nine describes a microcomputer simulation model for analysis of the production.

Chapter ten summarizes the results, presents conclusions, and provides recommendations for future research. Appendix I contains a description of Westbury Condominium in Honolulu, Hawaii, where the whole forty story reinforced concrete was slipformed under all imaginable challenging circumstances. A list of references are presented in Appendix II.

CHAPTER 2

SLIPFORMING THE IBM TOWER: A CASE STUDY

2.1 INTRODUCTION

The IBM Tower at Atlantic Center, located in Atlanta, Georgia is a massive construction project and one of the ten tallest structures currently being built in the world. The Atlantic Center is a phased construction project which will take from 5 to 8 years to complete. The full project includes the 50 story IBM Tower and parking garage, three future 20 story towers and two future parking garages, as shown in Fig. 2.1. The tower and parking garage architecture is "post modern", using a great deal of granite exterior and high marble arches at the ground entrance [32]. The tower's roof is a 130 foot (39.62 m) copper pyramid roof topped by a cupola as shown in Fig. 2.2. The final height of the structure will be 820 feet (250 m) from ground elevation. The tower which is 50 floors at 13 feet (3.96 m) from floor to floor provides a total of 1.1 million square feet (102,193 square meter) of office space. The ground floor which is two stories of 30 feet (9.14 m) height will be leased to service tenants who will provide a multitude of services to the building's office space tenants. Floors 3-29 will be occupied by IBM, and the remainder of the building will be rented to other tenants.

The parking garage which includes a post tension parking deck, provides space for 2,375 cars. Its structure is comprised of 11 levels, 30 feet (9.14 m) vertical height below grade and 70 feet (21.34 m) above grade. Fig. 2.3 shows an overview of the tower and parking garage in front. All phases of the project, when completed, will provide 2.5 million square feet (232,258 square meter) of office space [5].

Entrances to the tower on four sides are marked by monumental 55 feet (16.76 m) granite arches. The building features a series of setbacks on the tower facade and is topped by an octagonal copper pyramid [36]. At street-level, granite-paved plazas frame the building on all four sides. A 2.5-acre (1 ha) park is planned adjacent to the tower as an extension of Peachtree Walk Park. Atlantic Center has been designed to serve as the focal point of the Midtown business district.

2.2 PARTIES INVOLVED IN THE PROJECT

General contractor of the project was HCB Contractors. HCB maintained a team of approximately 15 salaried employees at the site. Their prime responsibility was supervising 42

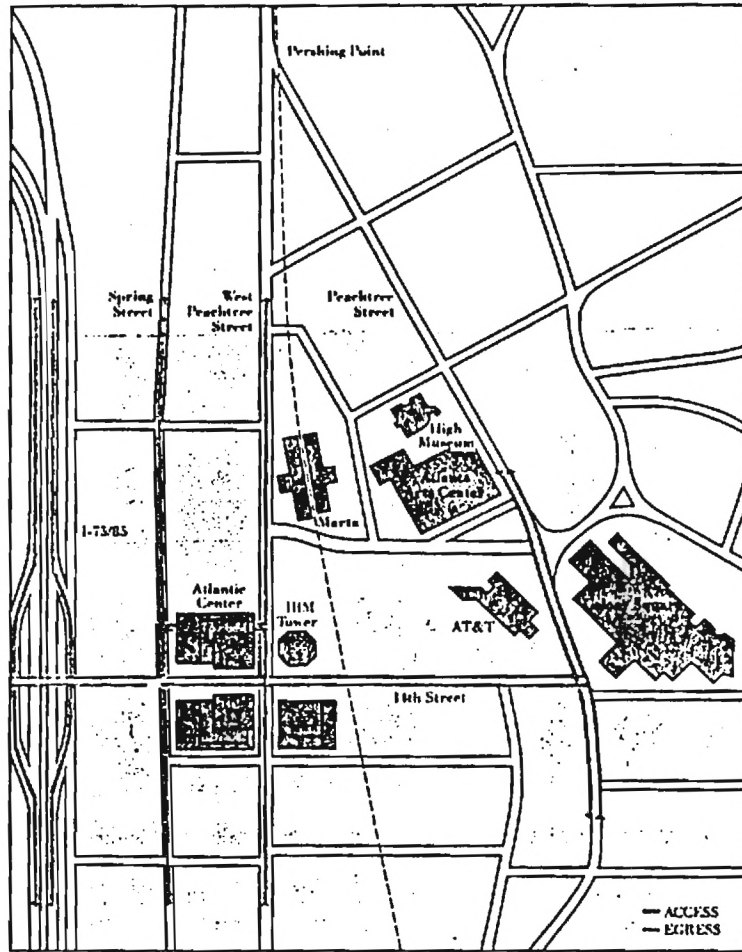


Fig. 2.1.- Location of the IBM Tower in Midtown Atlanta

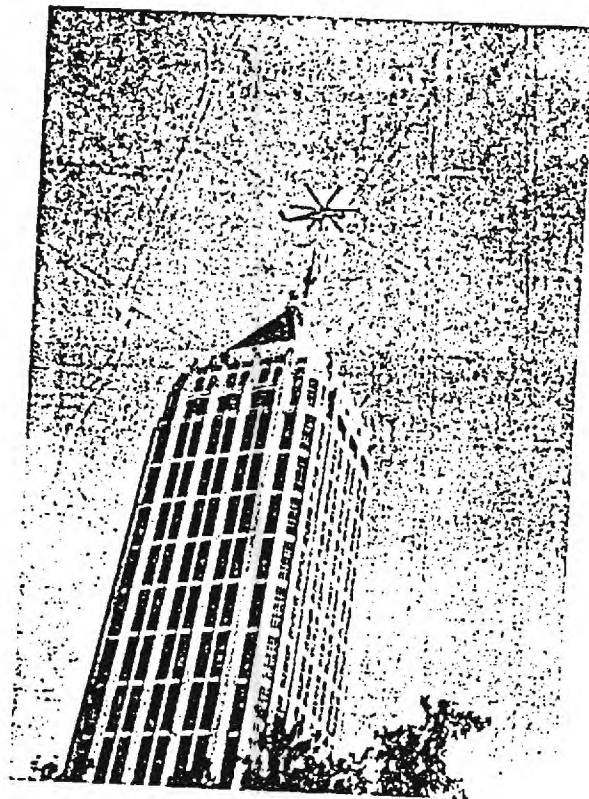


Fig. 2.2- The IBM Tower and Installation of the Cupola
by Helicopter

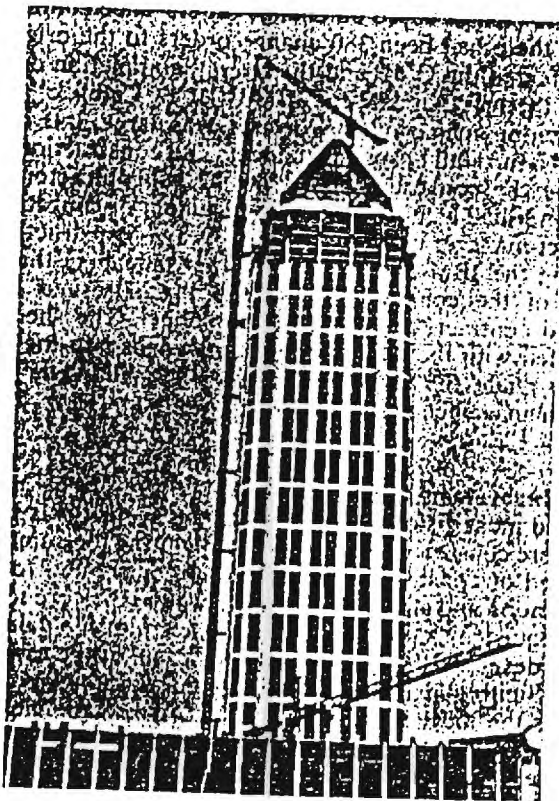


Fig. 2.3.- IBM Tower and Parking Garage in Front

subcontractors, their own personnel, materials, safety, and procedures. Also HCB monitored schedules, progress, payrolls and daily management. In concert with the owner they had the freedom to add personnel, use overtime labor, accelerate the schedule, or even reduce any of these factors if ahead of schedule.

The project is jointly owned by Cadillac Fairview Urban Development Corporation and IBM Corp. IBM did not actively participate in the management of the project. As part of their original plan, IBM wanted to gain equity without the problems of management. Cadillac Fairview Urban Development's management of the tower was broken into two separate offices: marketing, and construction. Marketing handled the development, leasing, and management of the tower's office spaces. The construction office hired the general contractor and monitored the project during construction.

Beginning in May 1985, biweekly meetings were held. Most issues arose when the architect proposed an addition to or change in the design, or when HCB or the subcontractors wanted a change because of value engineering. The design and constructability was checked by the architect, engineers, and contractors. HCB was then given a date to come up with a price for the new item. Cadillac Fairview was faced with the decision of whether to pay for the new request for proposal or settle for a less expensive alternative. If the item was critical, it would be built and negotiations would occur later.

The project was designed by John Burgee with Philip Johnson. The associate architect, Heery Architects and Engineers, Inc., acted as an on site partner for Burgee and Johnson. Heery handled all contract administration for both the tower and the garage. Part of their responsibilities included inspection of shop drawings, reviewing pay requests of HCB, delivering drawings on changes, resolving questions about documents, and solving daily field problems.

2.3 THE PROJECT LIFE CYCLE

Design plans were unveiled in May, 1985, and site preparation and demolition work started in October, 1985. The first construction phase began in January 1986, and is due to be completed in February 1988. This fast paced, 25 month total duration for the first phase is due to many of the innovations accomplished by the engineering, design, and construction team. A further scheduling factor complicating the construction project is that on October 1, 1987, IBM personnel needed to move into the tower at a rate of 3 floors

every 2 weeks. This meant that 5 months of construction was ongoing while the building was partially occupied.

2.3.1 Planning Phase

The planning phase for the construction began approximately two years prior to the groundbreaking. The construction management team was brought in very early during the planning phase and has worked very closely with owner and the design team throughout the entire project. A great deal of value engineering was undertaken pertaining to much of the construction scope, which included the second tallest slipform core in the U.S. and composite structural steel and composite exterior columns [46].

2.3.2 Construction Phase

Immediately after construction began in January 1986, the owner announced some changes in the design of the tower which included some architectural changes as well as adding 6 additional floors to the structure's height. These and other subsequent changes have lengthened the total duration of the contract. However, the October 1, 1987, tenant move-in date for IBM office spaces did not change since construction started. This factor contributed significantly to the fast pace of construction.

The contract between HCB and Cadillac Fairview was a cost plus fixed fee contract with HCB sharing savings below the Guaranteed Maximum Price (GMP) at a rate of 25% with 75% going to the owner. When construction started, the designers provided HCB with 80% structural design drawings and 60% architectural drawings and an interim guaranteed price was negotiated based on that set of drawings. When the final drawings were completed a final GMP was negotiated and has continued to change based on change orders since contract award. As of April 1987, there had been 380 change orders to the original contract. These have affected the GMP and the overall completion date, however none have changed the move-in date for IBM [4].

The organization managing the project was large and complex. The contractor had a full staff of superintendents and construction managers on site to manage the construction and the 42 subcontractors [18]. The owner had a construction management organization headed by a senior project manager who was assisted by two construction managers, one overseeing the IBM floors and the other managing the other tenant floors. Each of the construction managers was served by a staff of inspectors and contract administrative personnel. The sheer size of this project coupled with the huge number of changes, and the unique architecture have made the IBM

Tower a very challenging job from the construction management standpoint.

The construction and structural phases of the IBM Tower can be divided into three major areas: (1) Groundwork and foundation, (2) concrete core construction, and (3) steel structure.

Groundwork and Foundation

Demolition of existing structures and establishment of utilities on the future tower's site cost approximately \$1,010,000. The earthwork cost another \$2,016,000. From February through May of 1986 the underground portion of the tower's foundation was constructed. The soil retention system consisted of conventional soldier piles, wood lagging, wales, and a combination of tiebacks and rakers acting as the tension members. Soil retention added \$319,000 to the budget. A matrix of 5,000 psi (352 kg/cm²) concrete caissons resting on 150,000 psi (10,568 kg/cm²) granite bedrock were the primary load bearing structures in the foundation. Nearly 100 caissons were used, some of which are more than 30 feet (9.14 m) in length.

Fig. 2.4 shows the core foundation and basement wall forms. The core's foundation consists of caissons under a 10 foot-wide (3.05 m), 8 foot-deep (2.44 m) cap beam, both of which had a concrete strength of 5,000 psi (352 kg/cm²). The cap beam links all the piers into a single wind resisting system. The basement slab was designed as a diaphragm link between the core and the one-story, 7,000 psi (493 kg/cm²) concrete, perimeter basement wall. This created additional rigidity in the system. Tension forces at the corners of the core, resulting from the toppling affect of wind striking one or more of the approximately 130,000 square feet (12,078 m²) sides of the tower, was resisted with grouted anchors embedded 20 to 30 feet (6.10-9.14 m) into bedrock.

The foundation consumed approximately 737 tons (669 metric tons) of rebar and 4,117 cubic yards (3,446 m³) of either 5,000 or 7,000 psi (352-493 kg/cm²) concrete, at a cost of approximately \$1,217,000. This cost does not include additional site work or the specific costs quoted above.

2.4 CONSTRUCTION INNOVATION AND DIFFICULTIES

The first and most visible innovation on the project was the 725 feet (221 m) slipform core constructed by Sundt Corp. during the summer and fall of 1986. Its speed of construction significantly contributed to the project's shortened duration, and allowed steel work around the core to



Fig. 2.4.- Core Foundation and Basement Wall Forms

begin sooner in the work sequence. A great deal of study, testing, and value engineering went into the design of the core which carries all of the tower wind loads [41, and 43].

According to Sundt officials the IBM core was the most complicated slipform structure the company has ever built, primarily due to its structural design. The form moved at a rate of approximately one floor per day and upon completion was within 1.5 inches (3.81 cm) of plumb. After the slipforming operation was complete, the three level form was dismantled and removed from the structure piece by piece.

Another visible feature of the project is the pyramid roof which is 130 feet (39.62 m) tall and extends about 100 feet (30.48 m) above the core, as shown in Fig. 2.5. The height of the roof and the detailed architectural materials and requirements made this phase of work extremely difficult.

The composite exterior columns, as shown in Figs. 2.5, and 2.6 are another construction innovation which minimize column intrusions in the lower 25 floors of office space and keep lease space totally column free in the upper 25 floors. The columns are reinforced concrete poured around steel "I" beams. They are insulated and then covered with a granite exterior. The insulation was installed to minimize differential thermal expansion between the exterior columns and the core. The composite columns also minimize the differential creep and shrinkage between the core and the perimeter of the building floors. In addition, floors were constructed to slope from 0.25 to 1.25 inches (6.4 to 31.8 mm) from the core to the perimeter to further minimize the effect of the core settling less than the exterior perimeter of the building.

Another construction management problem the managers on-site faced was the construction of the underground tunnel between the parking deck and the tower. The tunnel crosses under West Peachtree Street which is a Georgia State Highway as well as an Atlanta thoroughfare. This required complex coordination between the contractor, owner, and the relevant governing bodies.

Since the IBM Tower is roofed with the pyramid architecture, there is no location on the building top for a conventional cooling tower needed for the structure's mechanical system. This required the cooling tower to be located in the parking garage across the street. This is another unique construction feature of the project. It requires a more extensive mechanical system and uses the tunnel mentioned above to carry supply and return lines to and from the cooling tower and building.

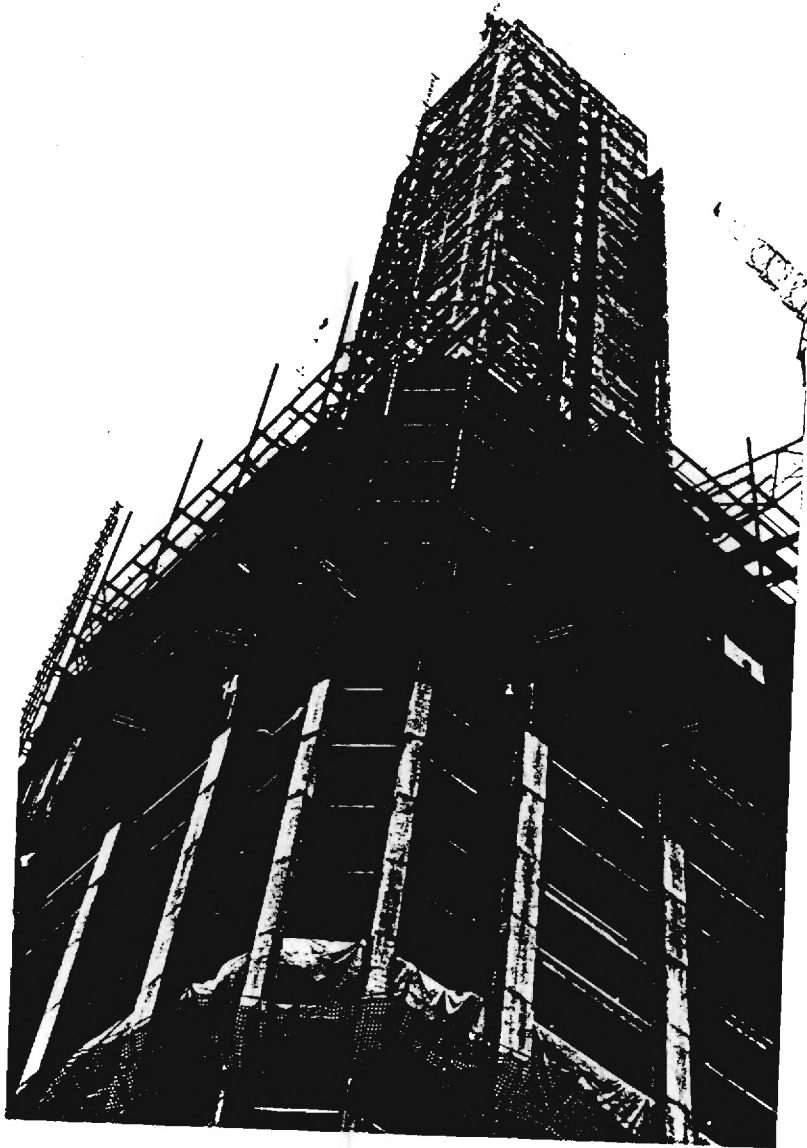


Fig. 2.5.- Core Topped out, Erection of Perimeter Steel,
Encasement of Exterior Columns

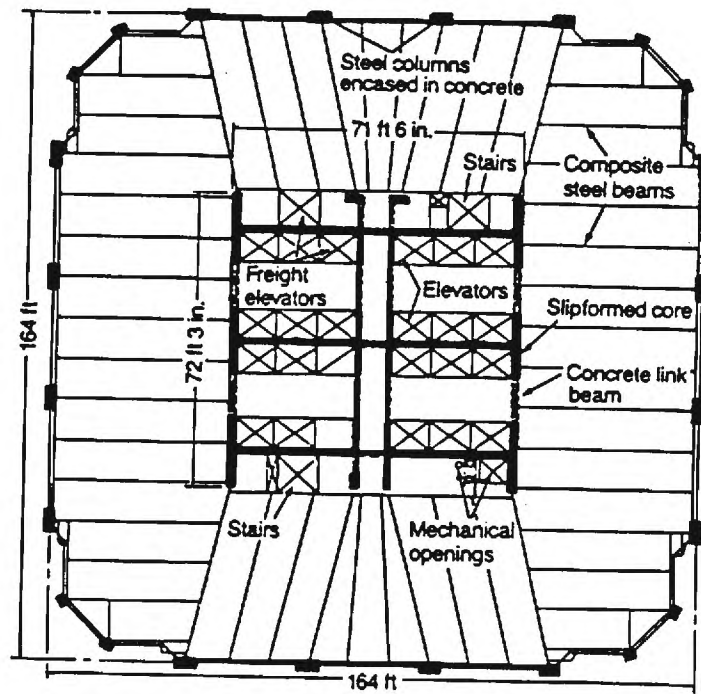


Fig. 2.6.- Typical Floor Framing System

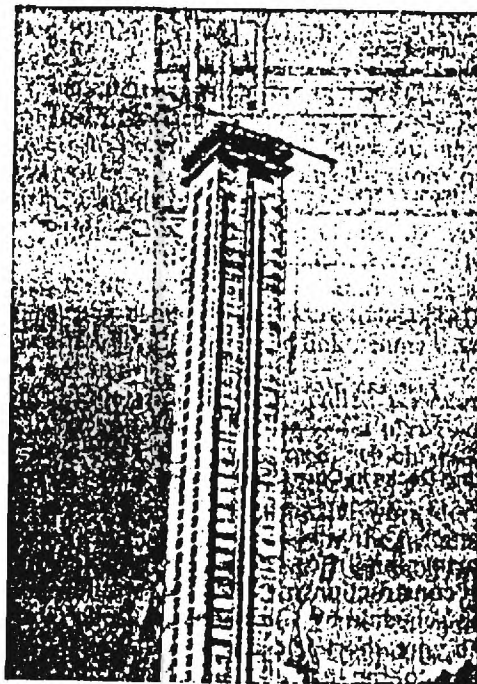


Fig. 2.7.- Overview of Concrete Core and Steel Framing in the IBM Tower

A site characteristic of the project which caused additional challenge was the strong prevailing wind from the west. This significantly affected the "steering" of the slipform during core construction as well as the pouring of concrete during the entire project.

The unique and detailed architecture of the project which incorporated five different imported marbles and imported granite from Spain, Italy, and Morocco added an international dimension to the job. This required extensive coordination. Some architectural decisions were made late in the construction phase, and therefore delayed material delivery.

Another important element of the tower's structure was the composite columns, steel beams, metal deck, and lightweight concrete fill. The decision to use composite columns was made based on time/cost tradeoff.

Accurate placement of the 3,800 steel embeds was one of the most important aspects of the core's construction. A large problem could arise if the embeds could not allow proper connection for the structural steel to the core. To help with the problem, the embed plates were designed for possible out-of-placement of 3 inches (7.62 cm) both horizontally and vertically while retaining functionality.

In conjunction with the core, the use of composite columns and large floor beams was a major factor in speed of construction and allowed virtually column-free interior spaces. The composite columns were basically steel W sections with a concrete column, including rebar, being formed and poured around the steel. The steel was first assembled like any other steel structure. The concrete encasement of the exterior columns lagged behind the steel. The steel holds the temporary load while allowing the floors to get out early. The designers stipulated that the steel could not stand alone for more than 15 floors above the concrete encasement of the columns below. Most of the dead weight is carried by the concrete in the composite columns.

The steel chased the core while it was being slipped and likewise pouring the composite columns chased the steel erection as shown in Fig. 2.5. The elevators and other core structures were also being assembled at this time. This simultaneous construction saved time but created scheduling problems with the use of cranes and interference of the 500 man work crew. For a while, the concrete and rebar was being lifted to the top of the core for slipforming, steel was being lifted for erection, the concrete, rebar, and forms for the composite columns were being assembled, and the floor decking and slabs, were all being assembled in conjunction. As was mentioned earlier, steps such as using reversible

hydraulic jacks to remove jacking rods and developing a winch and trolley system to assemble structural steel inside the core helped reduce the demand for the tower cranes.

2.5 SLIPFORMED CORE CONSTRUCTION

The concrete core of the IBM Tower is built by slipforming. The project is the tallest slipformed concrete building core ever constructed in the United States, and possibly the world. As shown in Fig. 2.7, the core is the structural "backbone" for the 50-story IBM Tower. The core contains space for the elevators, elevator machinery, stairways, rest rooms, and vertical chases for mechanical and electrical systems, as shown in Fig. 2.8. The 725 ft (221 m) high core cost approximately four and half million dollars and takes all the wind loads for the 50 story building.

Slipforming is a method of rapidly forming and placing concrete using hydraulic jacking units to raise a custom-made form at a vertical rate of approximately one floor per day. Slipforming building cores and silos -- round, square and rectangular -- is one of the specialties of Tucson, Arizona-based Sundt Corp. To date, the firm has slipformed 27 silos and cores for projects throughout the country.

Slipforming's principal advantage is speed. On the IBM Tower project, the time from commencement of "slipping" to topping out of the core was just 57 work-days. Conventional construction methods would have required an estimated 178 to 270 work-days to complete.

A concrete core's benefits to a high rise building are many, including structural stiffness, oscillation damping and fire resistance. Depending on the seismic risk and wind loading, the core can be designed to meet most or all of the anticipated lateral loads, which reduces the complexity and cost of structural steel connections. In most cases, the core also carries all of the interior vertical loads, but interior steel columns may be necessary in very large floor plans [20].

The decision to use a slipformed core must be made by the structural engineer early in the design phase of a project. On the IBM Tower, the general contractor recommended a slipformed concrete core after studying 42 different combinations of floor framing and wind framing systems. This analysis, made in association with the project's structural engineer, the Datum/Moore Partnership, showed that slipforming would cost somewhat more than other construction methods, but would shorten the project's total construction schedule by a minimum of three months.



Fig. 2.8.- Metal Decking on Roof and Garage Progress in Front

Slipforming the core shortened the overall project schedule in several ways. In addition to the actual time saved by slipforming, elevator construction was able to commence early, eliminating this important item from the critical path on the construction schedule. Also, the slipformed core permitted the early start of structural steel, stairs and other central core items. Structural steel was already to level 12 when the IBM Tower slipform topped out.

Slipforming obviously has many advantages, but obtaining a finished structure that meets the necessary critical tolerances requires extensive experience in slipform construction and operation. While each feature of the core had its own set of tolerances, the core itself had to be within 2.5 inches (6.35 cm) of plumb for proper installation of the elevators. The contract called for completion of the entire IBM Tower slipform operation in 19 weeks, with five weeks for form and structural grid assembly, twelve weeks for slipping, and two weeks for dismantling the form.

The concrete contact areas of the form were constructed in Sundt's Phoenix yard and shipped to the job site. The steel grid was fabricated in Dallas. The jacking system was supplied by Heede-Uddemann, Inc., of Connecticut.

Sundt used a form comprised of three working decks, as shown in Fig. 2.9. The upper deck, supported on a structural steel jacking grid, was 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 operation [35].

Mounted in the jacking grid were 21 hydraulic jacks, each with a capacity of 22 tons (19.8 tonnes). The jacks were mounted on three-inch-diameter (7.62 cm) jack rods, which extended down into the concrete walls. The rods acted as support columns for the slipforming operation. During slipforming, the jacks pushed up on inverted 'U' shaped structural supports called "lifting yokes", which were connected to the steel grid on the top deck.

The jacks have a maximum jacking rate of one inch (2.54 cm) every two minutes, and use two sets of teeth to clamp on to the jack rods. This safety factor allows one set of teeth to be engaged at all times during slipforming.

Larger than usual yokes were used at nine locations on the grid of the IBM Tower slipform. Called "nuclear yokes" because they were developed for the construction of nuclear power plants, the yokes were spaced 20 feet (6.10 m) apart instead of the normal six feet (1.83 m). This wider spacing accommodated placement of the massive amount of reinforcing

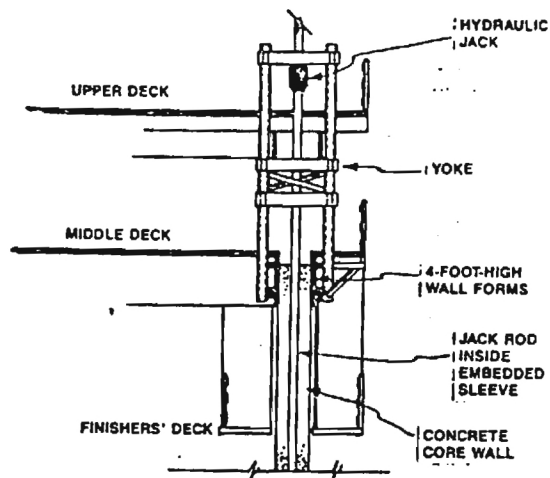


Fig. 2.9.- Three Working Decks in Core Construction (Courtesy of Concrete Construction)

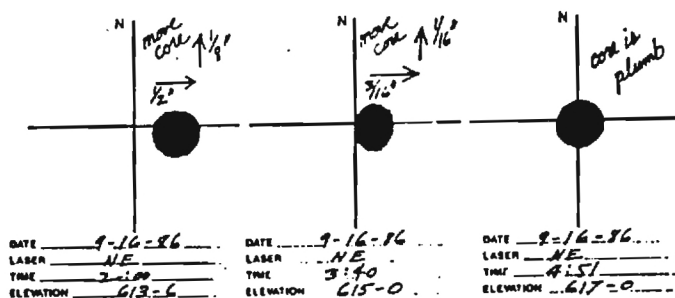


Fig. 2.10.- Monitoring Slipform Movements By Lasers (Courtesy of Concrete Construction)

steel required for very large link beams, which were to be constructed above the entry to each elevator lobby. Steel for the link beams was placed at night when the form was not in a jacking mode.

The middle level of the slipform, also called the working deck, was connected to the lifting yokes. It consisted of a plywood/structural steel floor system and the 4-foot (1.22 m) tall form, which was composed of a fiberglass reinforced plastic surface on a structural plywood substrate. At the same elevation as the top of the form, the work deck supported the distribution and placement of the concrete and installation of horizontal reinforcing steel, sleeves, block-outs, door openings, weld plates and miscellaneous hardware.

Suspended below the middle deck was the finisher's deck, where workers finished the concrete, applied curing compound, installed elevator and spreader beams, installed structural tee clips on weld plates for structural beam anchorage and removed block-outs.

Although many pitfalls are encountered on even the most simple slipform project, the principal ones are keeping the form level and the core plumb. In early days of slipforming, the only tools available for checking alignment were a transit, an inter-connected water level system, and specially-made, 45-pound (20.25 kg) plumb bobs suspended by piano wire. Sundt still uses the transits and water level system to check the level of the form and guide it during the slipforming operation, but the plumb bobs have been replaced by lasers. The IBM project utilized two vertical lasers, manufactured by Spectro-Physics, mounted in opposite corners of the core at ground level. The vertical lasers, aimed upward at targets on the work deck, permitted virtually instantaneous detection of rotation and out-of-plumb movement, as shown in Fig. 2.10.

Precise elevation measurements are also required for the proper placement of core penetrations, embed plates, etc. Again, modern laser technology was utilized. A horizontal laser was mounted on one of the jack rods and used in conjunction with an electronic distance meter to mark the base elevation for each day's concrete pour. Bands of different colored surveyor's tape were used to establish the vertical location of embeds, block-outs, sleeves, etc., on the reinforcing steel. The horizontal laser was mounted to one of the jacking rods because only the rods and the vertical reinforcing steel do not move during the slipforming operation.

A double check on the established base elevation for the day's pour was made with two steel tapes mounted in opposite

corners of the core at a set elevation. The tapes extended up to the top deck and reeled out as the form moved upward. The level of the form was also checked periodically by this method.

A total of 17,552 cubic yards (13,340 cubic meters) of 6,000 psi (420 kg/cm²) concrete was placed in the IBM Tower core, along with 2,570 tons (2313 tonnes) of reinforcing steel. The bottom levels of the core had 350 pounds of reinforcing steel per cubic yard (207 kg per cubic meter) of concrete. This record ratio of steel to concrete challenged the crew frequently during concrete placement and required the constant and careful use of air-powered vibrators.

Coordination of tower crane usage, particularly with the general contractor's third shift, was a necessity. Several techniques were adopted for the IBM Tower project that improved crane utilization during critical periods. One was to switch from pre-fabricated door block-outs to a system of slider panels and a header to form the block-out. This saved not only crane time but a significant amount of labor cost as well.

The second method of decreasing crane time involved pulling the jack rods with a reverse hydraulic pump rather than with the tower crane. The rods can be left in place, but at a cost of \$2 per lineal foot (\$6.56 per lineal meter), Sundt prefers to reuse them whenever possible.

Efficient use of the tower crane for jumping the hoist was made by scheduling this activity for the night shift, between the time that the reinforcing steel was being loaded and the trash removal operation. Also, the tower crane tie-ins were located so that the jumping of the crane took place on weekends.

A unique system for erecting the elevator lobby structural steel and exterior structural steel was employed on the project. A trolley system was mounted to the structural steel support on form's middle deck, which allowed the steel erector to install beams and decking within three levels of the finisher's deck.

Design of the IBM Tower required a large amount of wall thickness variation -- from 1'-0" to 2'-10" (30.48 to 86.36 cm). The thicker walls posed a stripping problem, which was overcome by using either tapered fiberglass block-outs for frequently repeated penetrations, or tapered wood block-outs wrapped in plastic and coated with grease for unique penetrations.

The difference in wall thickness also could have interfered with the concrete placing and jacking operations. The concrete in narrow walls sets up much faster than that in thick walls due to the heat generated by hydration. This presents the possibility of narrow walls setting up prior to being able to raise the form -- a very serious problem if it develops. To prevent that from happening, the thicker walls were poured before the narrow walls during the slipforming operation.

The concrete pour usually started at top of the lowest door block-out on the floor and proceeded to the top of the lowest door block-out on the next floor. This made it possible to install the complicated reinforcing steel and long shear plates in the link beams during the night shift.

Fortunately, the IBM Tower in Atlanta did not present any of the cold weather problems that Sundt has encountered on other projects. During the winter it is often necessary to insulate and enclose the form and a section of the core below it to keep the concrete at a proper temperature for curing. In some occasions, thermocouples were embedded in the concrete of winter-constructed slipforms to constantly monitor this critical factor for several days after the concrete has been placed.

2.5.1 The Operation of Slipforms

As the form climbs, it builds its own base as shown in Fig. 2.11. During construction, wind tends to bend the core. The sun makes it hot on one side, while the shaded side remains cooler, which tends to warp it. Sometimes the uneven rate of hardening of the concrete itself adds a torque force. Varying the forces exerted by each of the 21 jacks, and by changing the amount of steel rebar on the top deck makes it possible to steer the core straight. Top of the core is within 1.5 inches (3.81 cm) of plumb over its height of 725 feet (221 m). The allowable tolerance was 2.5 inches (6.35 cm).

In fact, the slipform was rarely in truly balanced position. Operators continually alter the elevation of the form to compensate for the different forces acting on it, sometimes actually crabbing into the wind, much like a pilot steers an airplane.

Precisely locating many different shaped penetrations for building services was one of the major problems in designing the core. A major construction problem is caused by the fact that the tolerances of the concrete core and steel frame were not compatible. One inch (2.54 cm) slip in either way at the beam connections were allowed. To reduce the misplaced embed plants, engineers designed the embed plates for 3 inches

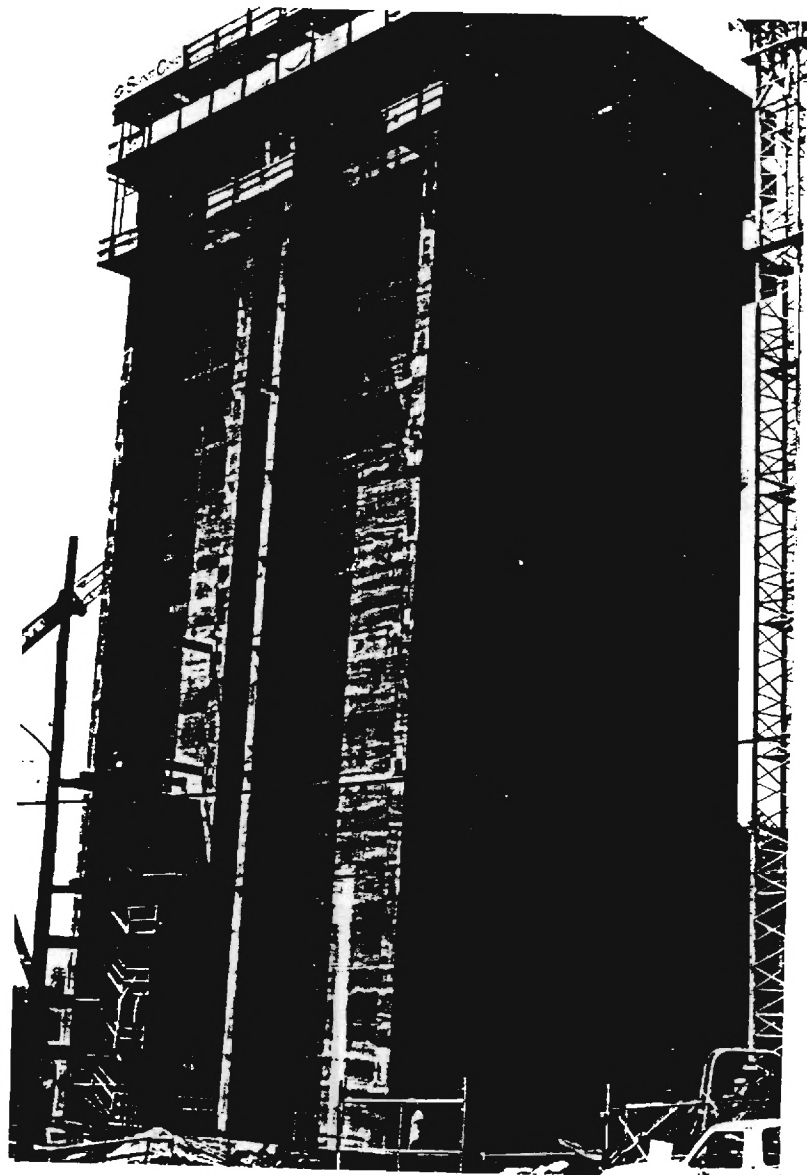


Fig. 2.11.- Core Construction and Exterior Stairways

(7.62 cm) out of placement in horizontal and vertical directions. Only 10 out of thousands of embeds were left out or had to be redone.

Placement of structural steel around the outside of the core began at ground level when the core was between the 10th and 15th floor level. The steel went up at the rate of two floors each week.

The thickness of the core walls decreased at the 34th floor level. To accomplish this, the slipform was "stepped back" while "on the fly", meaning that blocks were placed into the form at this level without having to shut down the regular pouring schedule.

Air vibrators rather than electric vibrators were used for greater reliability. The compressor for vibrators was mounted on the top level. Vibrators were lowered into freshly poured concrete to remove possible air pockets.

2.5.2 The Sequence

The form was manned on a basis of three shifts daily. There was a total of 110 to 130 men working on the form each day.

The first shift placed horizontal reinforcing steel, and placed concrete in the form using conventional concrete buggies loaded from larger hoppers which were mounted on the top level.

These hoppers were fed by a ground-mounted tower crane which climbed along with the slip form and fed concrete from trucks on the ground.

The second shift cleaned the form, stocked it with reinforcing steel and placed vertical reinforcing steel. This shift also put in place structural steel elements to be embedded in the concrete core wall and other block-outs for doors and other passages.

On the third shift, ironworkers placed structural steel "elevator spreader beams". These beams, placed in the open spaces within the finished core, formed the bracing for the elevator shafts.

Each shift included different skilled craftsmen who worked in close coordination within the relatively small work space. One man worked full-time on operating the jacks, and another man's full-time job on each shift was safety and fire prevention.

2.6 DESIGN CONSIDERATIONS

The core followed a schedule of a floor per day, after it reached about the 25th floor the perimeter steel erection was started. This involved the use of two cranes and proceeded at a rate of two floors per week. The steel erection of the IBM Tower was performed by Owen of Georgia with Williams Enterprises of Georgia as a sub-subcontractor, and was divided into three phases: (1) Erection of the concrete core and beams (elevator framing), (2) exterior columns and beam framing, and (3) pyramid roof.

2.6.1 Erection of Concrete Core and Elevator Framing

The interior elevator core was done with an electric hoist and monorail system with 1 set-up per shaft and was connected to the slipform structure. As the form rose with the pour so did all of the hoisting equipment. This made it critical that all of the interior framing to the rise of the slipform. The interior framing consisted of over 2,000 beams and 157,000 square feet (14,586 m²) of metal decking. All of this was loaded onto the core from 10:00 PM to 5:30 AM by a work crew of 20 men. This night shift was also responsible for welding the exterior seats into place so that the exterior framing could be released. This work took place on the finishers level of the slipform. As the slipform climbed, the day shift erected the steel loaded from the previous night. All of the beams and deck had to be completed during the day so that the night crew could load up the next level of framing.

Due to site accessibility, only 1 crane was present during this phase of construction. This crane was provided by HCB and was used by various subcontractors. The concrete was topped out on October 6, 1986, a mere 13 weeks after commencement; the interior framing was also on schedule. This was accomplished by using a six day work week and two 10-hour shifts per day.

Exterior Framing

On August 4 through August 15, 1986 two Favco 750 tower Kangaroo cranes were erected. The placement of the cranes required a good deal of thought and ingenuity. Again, limited space (the corner of 14th and W. Peachtree St. is very busy and congested) was a problem.

Placing the cranes outside the building presented two major concerns. One problem was the tie-off of the cranes. Since the core was the main support for the structure and not the steel, the cranes could not use the erected steel for tie-off. They had to be directly connected to the core and this distance was well over 60 feet (18.29 m). The cranes were attached by means of a three dimensional truss. Each truss

consisted of 8 tons (7.3 metric tons) of 10 inch (25.4 cm) pipe, they were 70 feet (21.34 m) long and 26 feet (7.92 m) tall. The truss was connected to the core and was jumped along with the crane every six floors.

In order to attach the truss to the core additional embeds had to be placed into the core at six story intervals and also every third floor for back-up. Sundt Corporation agreed to provide these extra embeds at no additional cost. To move the truss and allow the crane to jump up, the truss had to be disconnected from the core and lifted by the crane. Although the steel alone was not strong enough to support the crane, after the concrete floors had been poured the structure could temporarily hold the crane during the jump.

Another problem with the exterior placement of the crane was the foundation consideration. Many times a concrete footing is placed for the crane and left there after construction. However, both cranes were resting on areas that would be used later, one for a cafeteria and the other for transformers. Instead, the cranes rested on large steel beams (W 14 x 254) and were used in conjunction with the truss system.

The steel erection of the exterior framing as shown in Fig. 2.12, began on August 18, 1986 (within one week of schedule) at this time the slipform operation was at approximately the 25th floor. Since the cranes needed to reach around the core, not run into it, Kangaroo rather than standard tower cranes were used. The Kangaroo crane combines the capabilities of the tower crane with the conventional crane. The tower crane has the ability to jump and achieve great heights but its boom is not capable of moving vertically.

The conventional crane has a limited vertical reach, but the boom can move horizontally and vertically. The cranes were placed almost diagonally from one another. This resulted in each crane being responsible for an L shaped section of the building. There were some overlap area for the cranes, but accidents were avoided due to constant radio contact between crane operators and awareness on the part of the construction crew.

From the stand point of the steel erector, plumbing IBM was easier than an all steel building. With a standard steel building the steel is placed and then bolts are used to hold it in place. Before the bolts are torqued cables and turn buckles are attached to the steel. A transit was used to determine how much and in what direction the steel was leaning. The cables were then tightened or loosened until the building becomes true. The bolts were then torqued to prevent movement. The beams were fastened to the core by means of a slotted seat connection and tied into the exterior steel



Fig. 2.12.- Perimeter Steel (west side) and Illustration of Steel Joining Core

columns that would later become encased in concrete. The core was the determining factor for plumbness of the entire structure.

The slipform contractor and the HCB Contractors monitored the core daily for elevation and lateral placement. The location of the steel was determined from the location of the core. For example, if the core was leaning 1 inch (2.5 cm) too far north, the steel on the north side was shortened up by 1 inch (2.5 cm). This was done easily due to the slotted connection.

At one point during the construction the core became twisted by several inches. The correction procedure required a gradual change rather than a dramatic move. This resulted in several floors with a lateral displacement. The beams had to be shifted over in order to erect the steel.

With the use of two cranes and two separate raising gangs the erection proceeded at a rate of 2 floors per week. The use of the two distinct crews helped to speed the work by creating a friendly but competitive rivalry between them.

The weather during the structural work was normal and did not cause any serious delays, there were only 10 days lost to rain. However, some mornings construction started late due to the time required for the frost to melt. Two problems did slow down the construction and could have become major concerns. The first was the vertical transportation partly due to the sequence of construction processes.

The second potential problem was the encasement of the exterior columns. As mentioned, the steel was for framing purposes and not structural in nature and could not be depended on to support itself. The concrete poured around the steel columns would add the extra support needed. The steel erection was not to lead the composite columns by more than 15 floors. The first 5 floors of the building were not typical and somewhat complex, this slowed the subcontractor responsible for the encasement.

An additional revision was the added reinforcement of some of the floors. When bids were first called for the finished design was incomplete, the contract documents called for a floor load design of 100 lb/ft² (490 kg/m²). Later, after the steel was erected and the concrete floors poured, IBM determined which floors they would place their computers and other heavy equipment which would produce loads greater than the designed load. This added load required reinforcement of the steel beams which was done by welding steel plates to the steel beams from the floor below. Even though steel erection began 1 week behind schedule and had

some delays, the structural steel was topped out on February 16, 1987 (on time).

2.6.2 Pyramid Framing

One of the more difficult aspects of the tower was the erection of the roof structure, which was an unequal, eight sided pyramid and stood 130 feet (39.62 m) above the 50th floor as shown in Fig. 2.13. Due to its shape, little scaffolding could be used. After the center post and ring, all connections were made by scaling the 24 inch, 12 pitch hip rafters, this had to be done without any tie off ability for the ironworkers.

When construction began on the tower the roof was not yet designed. After several design changes the pyramid erection began on April 8, 1987. Part of the roof was erected using the north Favco crane and the other with Liebherr tower crane. On June 15th the Favco was taken down. The Liebherr was left in place for all hoisting needed on the project until August 30th. The Liebherr was removed by helicopter. The helicopter was then used to set the remaining five pieces (they could not be erected until the tower crane was removed from the building) and to set the cupola. The helicopter was a quick and efficient means however an expensive one. The initial cost to have the helicopter in Atlanta was \$35,000 with an additional \$1,100 per lift. The crane was dismantled, the steel and cupola set in just four hours requiring a total of 17 lifts.

2.7 KEY ELEMENTS OF SCHEDULE

The IBM Tower construction, like all modern projects, was continuously governed by a predetermined schedule which was laid out months before the construction even began. The original CPM schedule was developed in August of 1985. This was a preliminary schedule, and many updated versions were made as construction progressed. Table 2.1 shows the approximate starting dates of key elements of the project. Table 2.2 shows the durations of some of these elements.

2.7.1 Critical Path

The critical path for the tower was the sequence of events as shown in Table 2.3. The construction of the garage was simultaneously on the critical path of the project, although it was not dependent on any activities in the tower and started later than the tower. Table 2.4 shows duration (days) per floor for key elements. Table 2.5 presents the initial IBM Tower's activity path schedule.

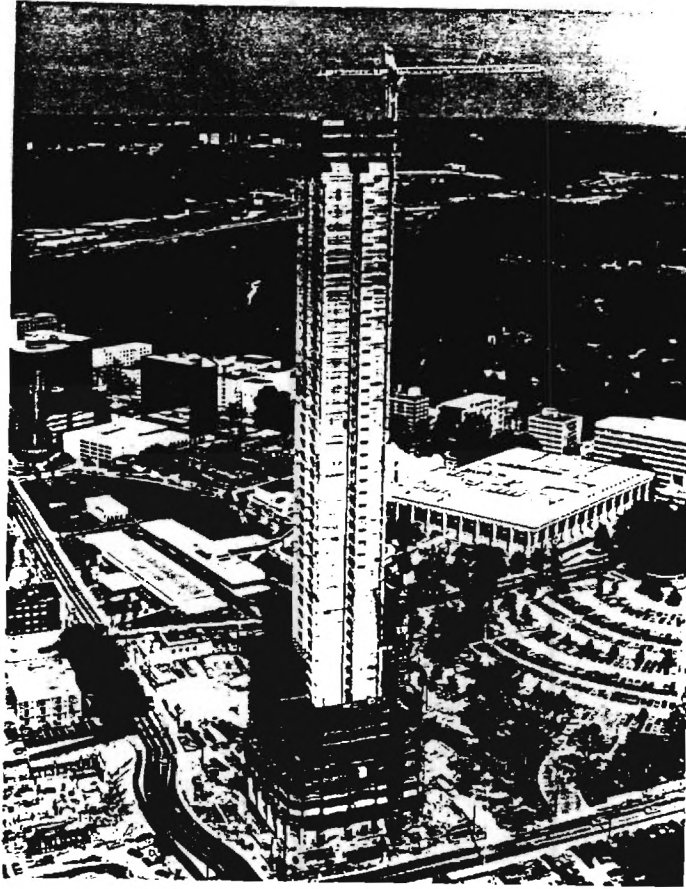


Fig. 2.13.- Core construction, Early Steel, and Composite Columns

With the IBM Tower, the deadlines imposed by Cadillac Fairview and IBM were considered by many to be the toughest part of the entire process. Without the time restrictions, not only would the pace have been considerably slower, but the slipformed core and composite beams might not have been selected. Instead, a more conventional design would have been the logical choice.

The major tenant/joint owner, IBM, was committed to move into floors four floors of the building on October 1, 1987. Nothing could affect that move-in date. After the initial occupancy, IBM would occupy through floors 29 at approximately a rate of three floors every two weeks. IBM would be completely moved in by February 17, 1988 [5].

2.7.2 Role of Slipformed Core in Schedule

The slipformed core was the major factor in allowing HCB to meet the rigid schedule. The core took 57 days to slip. More conventional construction would have taken 178 days or more [18]. The contract required that the core be slipformed in 19 weeks total. The form was assembled in 5 weeks. The slipping itself took 12 weeks. Dismantling the form was scheduled for 2 weeks. With the use of temporary roofs, the core allowed the lower level elevator banks to begin while the core was still being slipped. The slipformed core shifted the critical path off of the elevators.

2.8 SUMMARY OF PROBLEMS AND SOLUTIONS

The problems and recommended solutions associated with the design and construction of the IBM Tower are divided into three major components: (1) Design and development problems, (2) schedule and management problems, and (3) construction difficulties.

2.8.1 Design and Development Problems

The design of the core required the precise location of hundreds of odd shaped penetrations for the tower services [33, 34, and 35]. Each floor had an average of 17 blockouts and 5 pipe sleeves. To compound the problem, the link beam soffits are as close to the ceiling as possible in order to be able to use the largest beam depth as possible. This meant that, in order to reach tenant spaces, the penetrations mostly have to pass through the link beams. Datum-Moore kept the penetrations located precisely by drawing large-scale elevations of each core wall. These elevation views were passed to all members of the design team at each step in the design process thus providing standardized documentation of the penetration locations. Datum-Moore (Structural Engineer)

had a very conservative approach with the slipform finish specifications. Even small gaps and holes had to be filled in and smoothly finished.

The method used to build the tunnel (connecting the tower to garage) under West Peachtree Street caused some problems during the design phase. Being a vital link to downtown Atlanta, it seemed that either a tunnel, or combination bridge/tunnel system, would be required to allow traffic flow to continue throughout construction. As studies were made, these proposals were eliminated due to excessive costs and/or unacceptable traffic patterns. Eventually, an open cut system with earth retention was accepted. Although it was the best feasible solution, the delay during the design process caused the construction of the tunnel to coincide with the construction of the tower at probably the worst possible situation. The logistics and traffic pattern changes created by the tunnel were very problematic to the construction of the base of the Tower.

The project began with incomplete documents and were completed through Requests For Proposals (RFPs). In all, 630 RFPs occurred. Groups of approved RFPs became a change order depending on their size. The sheer size of this project, coupled with the huge number of changes and the unique architecture, have made the IBM Tower a very challenging job from the construction management standpoint.

The steel, copper, and cupola of the roof required around 20 RFPs and was considered a major challenge. Since completing the first drawings, John Burgee and Philip Johnson changed the pitch, set it back from the edge of the base, and added the various gold ornamentation [4]. Initially, the copper on the roof was to be chemically pre-weathered to a light green color at a cost of \$25,000. Very little scientific data or guarantees could be obtained on the process from the companies interested in the job. Because of the risk involved, pre-weathering was abandoned.

2.8.2 Schedule and Management Problems

With the granite skin being on the critical path, the delivery of stone was of large concern, especially since the source was outside the United States. The large, cube stock granite was sometimes behind schedule also. Several steps were taken to assure timely and quality deliveries. When the interior marble was selected from overseas, an American sculptor was hired in Italy to inspect the marble at the quarry. To keep harsh color transitions from occurring, he made sure that adjacent stone sections from the quarry were also placed in adjacent locations in the IBM Tower. Also, personnel were sent to Spain and Morocco every two to three

weeks from Atlanta to check on stone production. Most of the craftsman for the installation at the project were gathered from small towns in Tennessee where the trade is common.

In late Fall 1986, the work became behind schedule, fifteen days. The bulk of the problem involved the base of the building where the column forms and stone is unique and not repetitively constructed. Also, late decisions on the structural design had delayed the steel start.

HCB replaced on-site management approximately seven months into construction. This was mainly involved three positions. The existing senior project manager was replaced by John Monts, the project manager by Chris Gray, and the lead superintendent by Ralf Seifken.

2.8.3 Construction Difficulties

Two subcontractors on the tower especially created problems. Universal Stairs, the prefabricated steel stairs installer, went bankrupt during the project and their bonding agent finished the job. The supplier of ornamental metal billed HCB for cost overruns even though they had given HCB a hard bid. It was taken to court, but settled out of court.

From the contractors point of view, the composite columns were a nightmare for construction and maintaining schedule. Floors 1 through 5 were slow due to each section being somewhat unique. The remaining floors had uniform forms.

The \$1,073,000 tunnel under West Peachtree Street provided quite a construction challenge. The Georgia Department of Transportation (DOT) required that the road remain open at all times and that a time restraint be placed on how long tunneling operations could take place. When it was decided to use an open excavation instead of a tunnel, it became necessary to convince the DOT that rerouting the traffic in phases around the excavation could be accomplished without causing tremendous traffic problems. HCB designed supports to span the 50 foot (15.24 m) width of the tunnel which would support the utilities running under the road. Because most of the utilities were over 60 years old, very little deflection could be tolerated. HCB was responsible for any damage during construction. One telephone conduit cable held the transmissions for two television networks. The cost for down time was thousands of dollars per minute per network.

Keeping the core level and plumb took a combination of innovative methods. As the slipform advances, the sun's effect on differential curing, the twisting because of the crane attached to the side, the forces exerted by wind, and the imperfect balance of the entire mass cause the core to

divert from a straight course. The core had to be steered straight by varying the force exerted by each of the 21 jacks and by varying the amount and location of the steel rebar that is stored on the top deck. Because of the unusually large amount of rebar, the core reacted stiffer than others had in the past. It was impossible to steer in the early stages, but eventually was directed.

To monitor the relative position of the core, a combination of lasers and old-fashioned plumb bobs were used. Specifications required that a 1.5 inch (3.8 cm) tolerance from plumb was required up to the twentieth floor and a 2.5 inch (6.4 cm) tolerance at the top. This stipulation was mainly necessary for the installation of the elevators. Vertical lasers were set on the ground in the northeast and southwest corners of the core. They were aimed at clear plastic targets set in holes cut in the middle work deck. The jacking operators could tell whether the core was rotating or out of plumb by watching where the lasers hit the target. Approximately every two hours, a piece of paper was placed over the plastic target and the spot where the laser hit was recorded. For precaution and redundancy, a combination of transits, 45 pound (20.5 kg) plumb bobs suspended by piano wire, and a water-level system was also used to check the lasers results.

The core had an average of 17 blockouts and 5 pipe sleeves per floor. To provide a base elevation for each day's pour and to determine the vertical location of embeds, blockouts, and sleeves, a horizontal laser was used in conjunction with an electronic distance meter. Getting precise elevation measurements for the various core elements was necessary for their proper placement. A rotating horizontal laser was placed on one of the jack rods above the upper deck. It created a level plane of light that struck all vertical rebars at the same elevation. An Electronic Distance Meter (EDM) was mounted on another jack rod. The EDM was pointed at the ground and measured its own elevation. With a tape, field engineers measured the vertical distance between the EDM and the laser to determine the elevation of the laser. The slab elevation at various locations could be measured by measuring down with tape from where the laser hit the vertical rebar. A piece of red tape was used to mark the slab elevations. A vertical steel channel was embedded in the face of the core to permanently record slab elevations at casting time. To double-check the established base elevation for the day's pour and the levelness, two steel tapes were mounted in opposite corners as the lasers. They were anchored at the base of the core and pulled up by the slipform [19].

The thickness of the IBM Tower's wall varied from 12 to 34 inches (30.5-86.4 cm). The greatest variation the

subcontractor had ever experienced [43]. Thin concrete walls sets much faster than thick walls. As the concrete sets, the friction between the wall and the slipform increases. The friction that developed between the thin walls and the form walls as the thick walls set could tear the slipform walls apart. To prevent this from occurring, the thick walls were placed before the thin walls and careful attention was given to the placing rate. The core is stepped inward 6 inches (15.2 cm) at the 33rd floor to reduce wall thickness. During the slipforming of the core, the delivery of concrete had to be scheduled around the traffic patterns of the busy intersection.

Minimizing crane usage on the project was imperative since there were many concurrent activities requiring the crane's use. The blockouts were small and light so that they could be installed and removed by hand from the middle work deck. The reusable jack rods were removed with reverse a hydraulic pump instead of a crane. The winch and trolley system in each quadrant of the core minimized the tower crane's role in erecting steel for the elevators. The crane added sections to the personnel hoist tower at night when the crane wasn't in as much demand. Also, sections were added to the crane itself during the weekends.

The roof provided a number of challenges. Because of its pyramid shape, very little scaffolding could be used in its erection. After the center post and ring, all connections were made by scaling the 24 in 12 pitch hip rafters without the luxury of being tied off. The tower crane, erected on the core to help maintain schedule, protruded through the area where one hip rafter was to be erected. This area was left open and temporarily supported until the crane was removed [18]. A helicopter was used to dismantle the crane. A plan was established to bring down the crane and place the last elements of the roof in a quick and coordinated procedure. The gold-leafed cupola weighs in excess of 20,000 pounds (9,091 kg) and is 45 feet (13.72 m) high. This was too tall to set with the tower crane and too heavy to lift with the crane. Instead, the cupola was reduced to three pieces. The first two pieces were set by the crane. The 7,500 pound (3,409 kg) roof of the cupola was set with the helicopter, making the tower the tallest building in the southeast at 825 feet 8 inches (251.62 m).

2.9 VALUE ENGINEERING

This part of the paper describes the selection process for the structural framing system. The final selection was made by the owner at the end of a comprehensive, three-phased value engineering study.

In Phase I, eleven floor framing systems and eight wind framing systems (which in combinations gave forty-two possible schemes for the structure) were developed by Datum-Moore. Schematic information consisting of member sizes for each scheme was provided. These schemes were then reviewed by the design team for functional requirements, and by the contractor from a construction viewpoint. In this review, nineteen schemes were determined as unsuitable, and were eliminated.

In Phase II, pricing information in the form of psf of rebar or structural steel was developed for the remaining twenty-three schemes. The Contractor transformed this information into relative costs for a typical floor of each of the schemes. The time of construction of a typical floor, a factor directly related to the cost of interim financing, was estimated for each scheme as shown in Table 2.1. Based on economic feasibility, the owner selected the following four schemes for further development:

- Scheme I: Composite steel floor beams at 10'-0" o.c. (3.05 m), composite exterior columns, and slip-formed core.
- Scheme II: Post-tension floor beams at 30'-0" o.c. (9.15 m), with joists between beams, concrete exterior columns, and concrete core.
- Scheme III: Post-tension floor beams at 30'-0" o.c. (9.15 m), with joists between beams, exterior moment resisting tube.
- Scheme IV: Same as Scheme III, except use haunch girder in lieu of post-tension beams.

The third and final phase consisted of the development of beam, column, and shear wall schedules for the above four schemes. A typical floor and columns and wind resisting elements for the entire height were designed. Using this information, the unit (per square foot) cost of structure and the total construction time for Schemes I, II, and III were developed by the contractor, which are presented in Table 2.2. No cost data for Scheme IV is available.

Scheme II was first to be eliminated due to its excessive construction time. Schemes I and III were considered very close in overall economic feasibility. Scheme I had a premium of \$0.58 per square foot ($16.06 + 1.56 - 15.58 - 1.46 = 0.58$); (\$6.24 per square meter), but saved ten weeks in construction time in comparison with Scheme III. The owner selected Scheme I at an estimated structural cost of \$16.06

per square foot (\$172.87 per square meter), and \$1.56 per square foot (\$16.79 per square meter) cost of foundation with a 104 week of construction time; due to the benefits of the shorter construction schedule. The slip-form core in Scheme I was further optimized by studying five possible core layouts for functional, structural and economic factors [7].

2.10 OVERALL VIEWS

The IBM Tower in Atlanta is a fascinating example of architectural, engineering, and construction innovation and practice. The owner has acted as the construction manager, coordinating the design and construction between the architectural and engineering teams, and the general contractor. This team approach has resulted in a maximum amount of quality construction being accomplished in minimum time, and the project being completed within a tightly controlled schedule.

Due to the complexity of its design, it required a unique form of construction - slipforming. The utilization of this construction process enabled the contractor to keep construction time on the building to just 25 months. Using a slipformed core kept lease space totally column free.

The engineer designed the structure so that exterior composite columns pass wind loads through the building's composite floors to the core. Tension forces resulting from wind loads are resisted by core anchors embedded 20 to 30 feet (6.10 to 9.14 m) into rock. The core foundation consists of drilled piers under ten foot (3.05 m) wide, eight foot (2.44 m) deep cap beam that links all the piers into a single wind resisting system. Value engineering study considered 42 different of floor framing and wind framing systems. Slipformed concrete core with structured steel floor framing and composite exterior columns was selected. The analysis showed that slipforming would cost somewhat more than other construction methods, but would shorten the project's total construction schedule by a minimum of three months.

Table 2.6 presents general statistics for the IBM Atlantic Center Tower. Table 2.7 shows the IBM Tower's building shell construction cost.

TABLE 2.1.- Relative Costs of a Typical Floor of the Phase II Framing Schemes

SCHEME (PLAN REF.)	RELATIVE STRUCTURE COST PER FLOOR	TOTAL RELATIVE COST PER FLOOR	ESTIMATED CONSTR. TIME PER FLOOR
SPR-1	\$377,701	\$412,344	3-4 DAYS
SPR-1 ALT.*	389,837	400,285	4
SPR-2	385,151	425,180	4
SPR-2 ALT.	408,428	423,792	4
SPR-3	376,404	408,407	5
SPR-3 ALT.	387,371	395,809	5
SPR-4	314,966	327,650	6
SPR-5*	308,300	309,886	6
SPR-5 ALT.	312,610	314,196	6-6.5
SPR-6	280,966	293,650	7-8
SPR-7*	280,248	281,894	7-8
SPR-7 ALT.*	284,111	285,697	8
SPR-8	511,680	546,323	6
SPR-8 ALT.	449,840	460,288	6
SPR-9	501,809	541,838	5
SPR-9 ALT.	441,341	456,705	5
SPR-10	523,143	555,146	6.5
SPR-10 ALT.	448,403	456,841	6.5
SPR-11	506,484	541,127	4-5
SPR-11	484,943	495,391	4-5
SPR-12	514,304	546,307	5-5.5
SPR-12 ALT.	474,294	482,732	5-5.5
SPR-13	367,045	371,587	6

* Selected for further development in Phase III

TABLE 2.2.- Cost Comparisons of the Phase III Framing Schemes

SCHEME (PLAN REF.)	STRUCTURE COST PER SQ. FT.	FOUNDATION AND SITE EXCAVATION COST PER SQ. FT.	CONSTRUCTION TIME
SCHEME I* (SPR-1 ALT.)	\$16.06	\$1.56	104 WEEKS
SCHEME II (SPR-5)	15.34	1.63	128
SCHEME III (SPR-7)	15.58	1.46	114

* Selected as the final scheme.

TABLE 2.3.- Approximate Starting Dates for Key Elements

Milestone	Date
Start Network	August 15, 1985
45% Drawings	August 30, 1985
Award Elevator Contract	September 12, 1985
Award Foundation Contract	September 27, 1985
Award Concrete Core Contract	September 27, 1985
Granite Drawings	October 1, 1985
Award Granite Contract	October 28, 1985
90% Drawings	November 1, 1985
Award Steel Contract	December 2, 1985
Award Window Wall Contract	December 2, 1985
Award Contract	December 16, 1985
Start Tower Construction	December 16, 1985
Excavation & Shoring	December 16, 1985
Garage Construction	April 15, 1986
Slipform Core	April 15, 1986
Begin IBM Tenant Work Drawings	May 20, 1986
Start Speculative Tenant- Work Drawings	May 20, 1986
Structural Steel	June, 1986
Elevators	June, 1986
Column & Slab Pours	July 15, 1986
Rough In	August 15, 1986
Precast Granite	September, 1986
Window Wall	September, 1986
17th Floor Temporary Roof	November 20, 1986
Finishes	December, 1986
37th Floor Temporary Roof	March 30, 1987
Garage Complete	September 15, 1987
6 Floors Ready For IBM Move In	September 15, 1987
Construction Complete	February 18, 1988

TABLE 2.4.- Days per Floor for Key Elements

Element	Floor	Duration (days/floor)
Structural Steel	Basement	5
	Lobby	8
	Lobby Mezzanine	8
	3-4	8
	5-6	4
	7-50	2.5
Column & Slab Pours	Lobby Mezzanine	8
	3-4	4
	5-50	3.5
Handset Granite	Base	70
	Top	30
Precast Granite	3-21	4
	22-41	4.5
	42-50	5
Window Wall	3-50	4
Rough In	3-50	14 *
Finishes	3-50	14 *
Elevators	Low	250
	Mid-Low	265
	Mid-High	305
	High	285
	1st Service	100
	2nd Service	260
Core	Foundation-10	23
	11-17	7
	18-28	11
	29-37	9
	38-Top Out	20

* Stairstep: 8 days on two floors, begin next two floors, then finish first two floors in 20 days.

TABLE 2.5.- Initial Tower CPM Path in Schedule

Code	Event	Duration	Dependency
A	Excavation Part A	20	-
B	Excavation Part B	10	-
C	Shoring	20	-
D	Complete Rebar Data	5	-
E	Complete Slipform Data	10	-
F	Rakers	10	A & C
G	Shop Drawings	15	D
H	Slipform Design	20	E
I	Fabricate & Deliver Pier Rebar	10	G
J	Central Core Drilled Piers	10	G
K	Fabricate & Deliver Footing Rebar	15	G
L	Fabricate Slipform Offsite	30	E
M	Core Footings	15	G
N	Assemble Slipform	25	L & M
O	Slipform Concrete Core, Foundation - 10th Floor	23	N & *
P	Structural Steel: Basement - 4th Floor	37	O & *
Q	Column & Slab Pours: Lobby - 8th Floor	30	P
R	Precast Granite: Floors 3rd - 47th	192	Q
S	Hand Set Granite at Top of Building	30	R
T	Complete Roof & Flashing	10	S
U	Speculative Tenant Work: Top Six Floors	100	T
V	Remainder of Tenant Work	67	*
W	Punch List	25	U & V
X	Final Acceptance	20	W

* Indicates a prerequisite activity not on the critical path

TABLE 2.6.- GENERAL STATISTICS FOR THE IBM ATLANTIC CENTER TOWER

TONS OF REINFORCING STEEL:

Rebar in Foundation:	737 tons (663.3 tonnes)
Rebar in Core:	2,435 tons (2191.5 tonnes)
Rebar Balance:	1,316 tons (1184.4 tonnes), projected
Total:	4,488 tons (4039.2 tonnes), projected

TONS OF STRUCTURAL STEEL:

Perimeter:	Approximately 5,046 tons (4541.4 tonnes); 45,174 pieces
Core:	Approximately 591 tons (531.9 tonnes); 23,530 pieces
Total:	5,637 tons (5,073.3 tonnes)

CUBIC YARDS OF CONCRETE:

Foundation:	4,117 cy (3129 cubic meter)
Core:	17,552 cy (13,340 cubic meter)
Balance:	30,850 cy (23,446 cubic meter)
Total:	52,519 cy (39,915 cubic meter); projected

CONCRETE TYPES:

Floors:	3,000 psi (210 kg/cm ²)
Piers, Grade Beam, Slab-On-Grade:	5,000 psi (350 kg/cm ²)
Columns:	7,000, 6,000, 5,000 psi (490, 420, 350 kg/cm ²) as noted
Core:	6,000 psi (420 kg/cm ²)
Basement Walls:	7,000 psi (490 kg/cm ²)
All Else:	4,000 psi (280 kg/cm ²)

FLOOR DECK:

Metal Deck:	18 ga. (68 lit.) with 3" (7.62 cm) ribs
Concrete Thickness:	3.5" + 3" = 6.5" (16.51 cm)

TABLE 2.6.- GENERAL STATISTICS (Cont.)

GRANITE:

Type:	Spanish Pink Imported from Spain
Number of Pieces of Precast:	2,076 through level 4
Number of Pieces of Precast:	852 above level 46
Number of Pieces of Handset:	8,852 (estimate)

CURTAIN WALL SYSTEM:

Glass:	1" (2.54 cm) insulated PPG Solar Gray
Reflective Quality:	Translucent natural glass reflection
Metal System:	Inside glazed custom pressure wall system

MARBLE:

Main Lobby:	
* Walls	Lido - Morocco Calacata - Italy Nero Portora - Italy
* Floors	Negro Marquina - Italy Acqua Bianca - Italy

MECHANICAL SYSTEM:

Type:	Forced air, water cooled, electric heat
Zones per Floor:	8 interior and 12 exterior
Tons of Cooling:	(3) 1,240 ton (1,116 tonnes) chillers, 3,720 tons (3348 tonnes) total.

TABLE 2.7.- IBM Tower Building Shell Construction Cost

ACTIVITY	COST (\$)
Demolition and Site Utilities	1,010,000
Earthwork	2,016,000
Retention System	319,000
Sitework	3,195,000
Foundations	1,217,000
Concrete Work	23,876,000
Masonry	946,000
Granite	11,250,000
Lobby Allowances	4,515,000
Structural Steel and Metal Deck	11,469,000
Carpentry	95,000
Waterproofing and Damproofing	646,000
Roof Feature	2,382,000
Tunnel	1,073,000
Doors, Frames and Hardware	583,000
Metal Screens	611,000
Glass, Glazing, and Curtainwall	5,471,000
Lath and Plaster	249,000
Drywall and Acoustical	4,371,000
Ceramic Tile/Toilet Marble	655,000
Resilient Floor and Base	7,000
Painting/Vinyl Wall Covering	348,000
Toilet Partitions & Accessories	237,000
Miscellaneous Accessories	265,000
Window Washing Equipment	215,000
Elevators	7,366,000
Mechanical	10,199,000
Fire Protection	1,401,000
Electrical	4,996,000
TOTAL	\$100,983,000

Time: February 1, 1986 to Substantial Completion October 1, 1987.

Final Completion Feb. 29, 1988

CHAPTER 3

PROBLEMS, SOLUTIONS, AND LIMITATIONS

Since the inception of slipforming, it has been employed successfully and economically. However, there are also many problems that should be explored. These problems are principally due to alignment, wall thickness, form removal, concrete handling, organization /coordination, steel placing, blockouts, crane use, jack rods and weather. This chapter discusses how these problems were overcome in particular instances and the limitations that emerged.

3.1 ALIGNMENT

Sideways displacement of the core structure and the tendency for the form arrangement to spiral leading to unevenness of the wall cross-section as the slipforming progresses have been inherent problems. In the early days, visual checks on transit plumb lines suspended within shafts and towers and damped by suspending the bob in oil at set positions on the base plus water-level system maintained perpendicular alignment to the ground. Recently, laser beams have been used to provide an available permanent datum at any point throughout the slide. A typical project in which the old and the new techniques were used successfully is the IBM building in Atlanta, GA.

In the IBM building, transits and water-level system were used to check the level of the form while the plumb bobs were replaced by lasers. Two vertical lasers were mounted in the opposite corners of the core at the ground level. The vertical lasers were aimed upward at respective targets on the work deck and this allowed instantaneously a practical detection of spiral and out-of-plumb movement.

Again, to achieve exact elevation measurements needed for the proper placement of core penetrations and embedded plates, a horizontal laser was secured to one of the jack rods and with the help of an electronic distance meter, the base elevation was marked for a day's concrete placement. To locate the vertical position of embeds, block-outs etc. on the reinforcing steel, bands of different-colored surveyors' tape were utilized. The securing of the horizontal laser to the jack rods was for a practical reason. The vertical reinforcing steel and the jack rods were the only elements that did not move during the slipforming operation. Two steel tapes had to be mounted in opposite corners of the core at a set elevation to ensure a double check for the day's pour.

The tapes hung from the top deck and as the form moved up, they also reeled out.

Irrespective of laser beam introduction, there is always a perpendicular deviation of +1" (25 mm) in height of structures [15]. In the IBM project, the slipform was hardly in any true balanced position. The operators had to continually change the elevation of the form as a compensation for the different forces acting on it, greatly due to wind effects. Actually the top of the core was within 1.5" (3.81 cm) of plumb over its total height of 725 ft (221 m). This was within the allowable tolerance of 2.5" (6.35 cm).

As a rule of thumb, total deviation of any point on the slipform should not exceed 1 in/50 ft. of height. The laser technology has also created a new labor skill needed for constant monitoring unlike the plumb line and water-level-system which is thoroughly known by all crew members. More importantly, the laser technology has also been patented by Spectra-Physics, a sure limitation on its use without involving the manufacturer.

3.2 WALL THICKNESS

Uniform cross-section design through-out height to eliminate the need for modification of the forms with attendance of expense and delay is a necessary condition for concrete slipforming. J. Dough Pruitt [34, and 44] describes it in this way, "Walls can start or stop at any elevation and wall thickness can be changed, but if the advantages of speed and economy of slipforming are to be fully realized, the designer must minimize changes in the horizontal cross section of the concrete core". But in actual practice, the thickness of the core walls quite often changes. And to compensate for the decrease to follow the regular pouring schedule, fillers are inserted into the form at the level of change. In the IBM building, there was a decrease in thickness of the core walls at the 34th-floor level and the slipform was "stepped back" while "on the fly", indicating that blocks were placed in the form at that level to enable the regular pouring schedule to continue without any shut down. Again thicker walls were poured before the narrow walls. This was to prevent narrow walls setting before the raise of the form.

The complexity and five wall thickness decreases in the 483-ft core of the Dallas Tower, Dallas, TX, called for a multistage form slips spanning a street as illustrated schematically in Fig. 3.1 [15, and 44]. The slipforming took five stages with incredible time consumption.

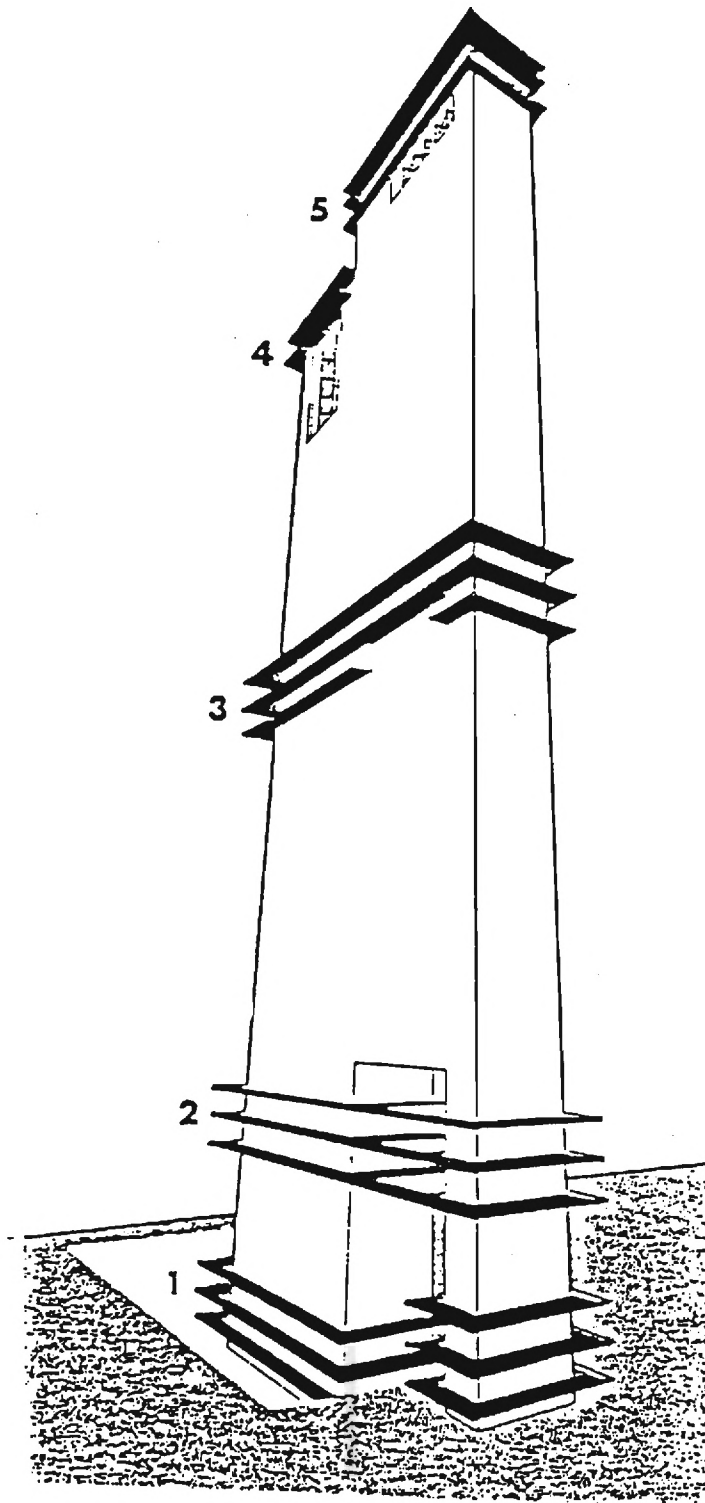


Fig. 3.1.- Wall Thickness - Changing Form:
(1) Lift Off, (2) Link Up,
(3) Adaptive, (4) Separated,
(5) Topped Out, Courtesy of Sundt Co.

Stage One: Named the lift-off mode by Sundt, consisted of slipping the 90 x 32-ft "leg" of the core on one side of the street, starting 22 ft below grade. Assembly alone took 28 days [15, and 44].

Stage Two: Called the linked-up mode, consisted of lining and attaching the 90-ft-wide section to a 10 x 32-ft "leg" for a stair tower 50-ft across the street. The forms were tied into one unit to keep them level, but blocked out the opening over the street. The linked-up mode lasted seven days and during that period the form had reached the top of what would become the garage, leaving a 50 x 85-ft opening over the street.

Stage Three: Called adaptive mode, started above 85-ft when workers started pouring concrete for the entire 150 x 32-ft core. Within walls for three levels directly above the street, deep post-tensioned "beams" of 3 ft thick, 5 ft deep and about 65 ft long were created.

Stage Four: Named the separation mode, started at 42 ft. A major section of the form had to be disassembled, leaving just enough in place for workers to walk between the two sections. This was partly to reduce the weight at the upper levels, and the form slipped the core in two sections. The sections had major blockouts and one section ended several levels lower than the other since the roof has a vertical offset [15, and 44].

Stage Five: Called the topped out mode, consisted of removing the form. That consumed nine days according to Sundt Co.

According to Pruitt [34], M.M.Sundt Construction Co. currently has contracts for structures with the following specified tolerances:

Wall Thickness:

+3/8" (9.5 mm) for walls to 8" (203 mm); +1/2" (12.7 mm) for wall over 8" (203 mm):

- a) Shall not exceed + 1/2" (12.7 mm) in any story.
- b) Shall not exceed + 2" (50.8 mm) overall up to 500 ft.
- c) Either a or b above, whichever is smaller.
- d) Deviation in horizontal location of weld plates +2" (50.8 mm).

- e) Deviation in vertical location of weld plates +2" (50.8 mm).
- f) Plumb tolerance of weld plates is maximum 1" (25.4 mm) face of wall.
- g) Mechanical openings should be oversized 1/2" (38 mm) all around.
- h) Door openings should be oversized 1" (25.4 mm) at each jamb, 3" (76.2 mm) at head and 1" (25.4 mm) at bottom of door.
- i) Variation in size and location of sleeve + 2" (50.8 mm).

3.3 BLOCKOUTS

With openings like door/window ways and other passages, blockouts slightly greater than frames' dimensions for later installation are inserted in the wall during the slipforming operation. Nevertheless, thicker walls pose some stripping problems. In the IBM project (Atlanta), tapered fiberglass blockouts or tapered wood blockouts wrapped in plastic and coated with grease for unique penetration and early removal were employed to overcome the difficulty. Yet with abnormal openings as discussed earlier on in the case of Dallas Tower, the work on blockouts was too much extensive with its attendance cost in days spent.

3.4 THE FORM SYSTEM

The adoption of the slipform construction method is also for safety. The form, built as a semi-permanent structure with scaffolds, work decks, ladders, handrails, is not normally dismantled and reassembled for each floor construction cycle, but move upward as a unit. Yet individual components had some problems.

3.4.1 Sheathing or Formwork

Originally the sheathing panels were of timber boards and plywood which offered a higher friction drag on the concrete. But with the introduction of steel or glass fibre as panels, the friction was dramatically reduced. Nowadays a very rigid form panel with a fiber glass reinforced plastic surface on a structural plywood substrate is being used. All the same in a particular project, Westbury Condominium, Honolulu, Hawaii, another problem arose. There was abrasion resistance during form cleaning. The plywood had 0.02" polyethylene skin bonded to the concrete contact face. Delamination in the

wood placed behind the polyethylene skin became a problem. The burges in the polyethylene form face had to be removed and patched with a moisture compatible epoxy putty. The problem arose because there was no detailed investigation of the quality of the plywood [19, and 20]. This led to a new panel made from a higher quality plywood 0.1" polyethylene skin now available in the market. In addition, the polyethylene has "oily" surface texture.

Initially, the sheathing usually was 3 1/2' to 4' even high and materials fell from the form to the ground, posing dangerous situations for those on the ground. So, to prevent concrete and other materials from falling from the form, the outside form is now 6" higher to act as a splash board.

3.4.2 The Jacks, Jack Rods, and Yokes

Experience has shown that the 3-ton jacks could not offer proper lifting force for massive cores slipforming. So 22-ton hydraulic jacks were designed for massive cores. These jacks are mounted on 3" (7.62 cm) diameter rods which also extends into the concrete walls. The rods perform supporting columns functions for the slipforming operation. The forms move up at approximately 1" for each jack stroke [14].

In the IBM project, the jacks used two sets of teeth secured to the jack rods. This was a safety measure to allow one set of teeth to be engaged at all times during slipforming.

In the past, some systems depended on "lost" bars upon which the jacks climbed, the lifting effort having been transmitted via yokes to the form. But nowadays, for more economic reasons than anything else, the jack rods are retrieved for reuse. The rods are installed with steel sleeves that form holes for easy recovery. Quite often the tower crane is used to pull the jack rods, the operation being expensive. But in the IBM Tower, an innovative technique called "a reverse hydraulic pump" was used. It is worth noting that each rod would have cost \$ 2/lineal foot to the slipforming subcontractor if left in place.

The more massive a core structure is, the larger than usual the yokes have to be. In the IBM project slipform, larger yokes were demanded. Named "nuclear yokes" after those used for the construction of nuclear power plants, the yokes were positioned 20 ft (6.10 m) apart instead of the normal 6 ft (1.83 m). The spacing of the yoke was conducive for the placement of massive amount of reinforced steel needed for very large link beams.

3.5 STEEL PLACING

As stated earlier, reinforced-steel design should be kept to an absolute minimum because large concentrations of steel make it difficult to place the steel while the slip is in progress. Yet, because of massive cores of structures being common in high rise buildings, this rule of thumb is hardly achieved since massive cores require massive beams for structural soundness. For instance, the bottom levels of the IBM Tower core had 350 lb. of reinforcing steel per cu. yd (207 Kg/m³) of concrete. This high ratio of steel to concrete made it very difficult during concrete placement and air-powered vibrators had to be used constantly and carefully for good and reliable concrete consolidation. In the same project too, wider spacing of unusual yoke sizes had to be restored to, in order to accommodate placement of the massive amount of reinforcing steel needed for very large beams above the entry to each elevator lobby.

Moreover, another rule of thumb for steel placing is to have all items having tolerance to ensure proper fit. Again, a major construction problem that arose in the IBM Tower was that the tolerances of the concrete core and the steel frame were incompatible. To cut down misplaced embed plates, the structural engineers, with correct foresightedness, designed the embed plates for 3" (7.62 cm) out of placement both horizontally and vertically, knowing that there would be differential thermal expansion between the exterior columns and the core in addition to also differential settlement between the core and the exterior perimeter of the building. Only 10 out of thousands of embeds fell out of place and had to be redone.

3.6 NATURE OF SITE

The nature of site has great effects on slipforming operations. Sites with easy access allow activities to be performed without unnecessary interference. Tight sites slow down speed of performance and thus make coordination very difficult.

A typical project example is the Olympia and York Office Tower in Dallas. The massiveness of this 483-ft-tall complex core, measuring 150 x 32 ft, spans 50 ft over a city street that cuts through the base of the building. The 280 x 120-ft building fills its 284 x 135-ft site around which is heavily developed as pictured in Fig. 3.2. "Scheduling the job was like choreographing a gala performance - each subcontractor had to be careful not to step on another's toes. There was almost no storage. Materials had to be delivered and used

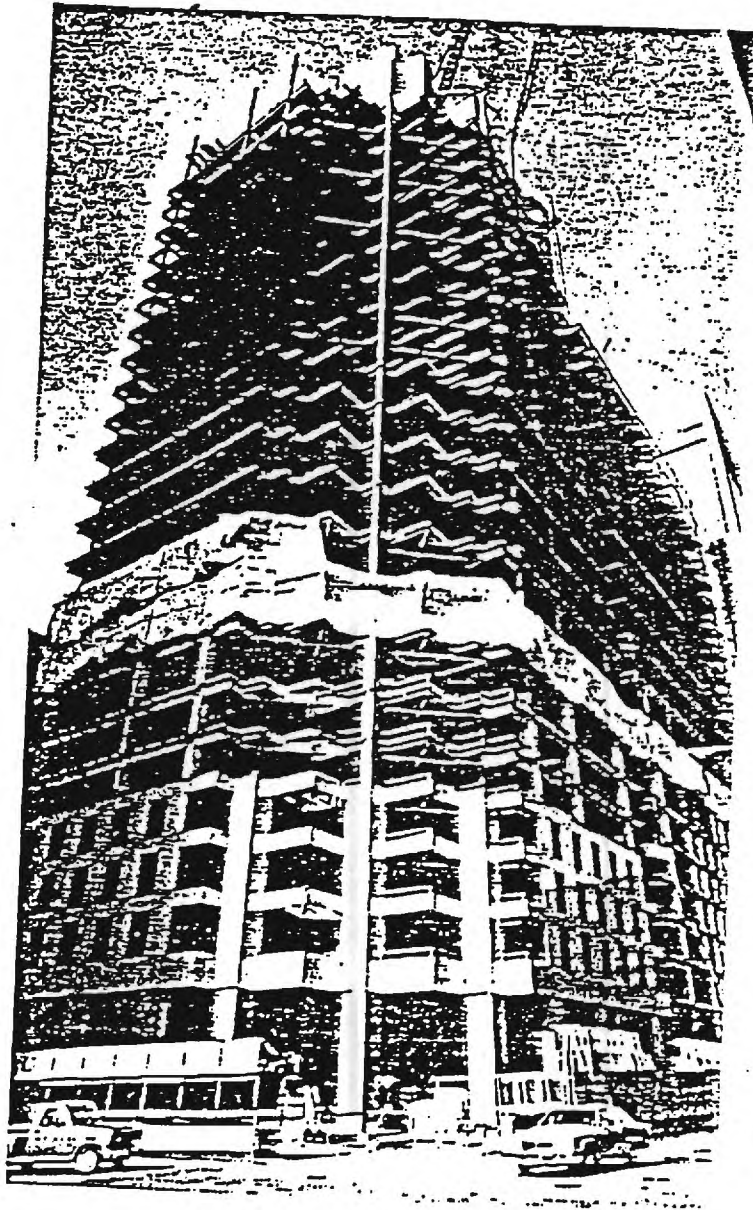


Fig. 3.2.- Congested Site of Olympia and York Office Tower, Dallas. Courtesy of Sundt Co.

quickly", says P. Cadenhead, Asst. Project Manager for the developer [11, 12, and 13].

There was so much tremendous initial delay that, the slipform contractor, M.M.Sundt Co. could not start soon enough to top out the core before it was time for the steel erector to begin work. Scheduling concrete deliveries became extremely critical during the slipforming since little could be stored on site [15, and 44]. Downtown traffic congestion hindered timely arrivals, and standby cost due to late deliveries of concrete soared. Instead of electric vibrator, Sundt used air vibrators for consolidating the concrete. Air had to be piped in an overhead loop around the form and 8 to 10-ft-long hose connections excluded the danger of hoses strewn along the form's decks. According to Sundt Co, the air system produces better quality work and reduces down time. Even though the compressor occupies more space, the "air was needed anyway for the cleanup work" [15].

Another example is The Westbury Condominium Project, Honolulu, Hawaii. The project is in a difficult site in a heavily developed area. It became imperative to "jump" the tower crane every four floors, which took one working day, retarding the overall progress rate from the normal 1 working day per floor to 1.25 working days per floor [11, 12, 13, and 20].

3.7 CRANE USE

The crane plays a major role in slipforming and it is a time saving machinery. A single crane could be enough to provide required materials to keep the operation going, yet because of possible breakdowns, two or more small cranes are quite often used. Larger projects, however, demand fixed or mobile cranes in addition to powered man cage lifts.

In projects with tight space, the use of crane becomes very difficult. And it became necessary to "jump" the tower crane after few floors, requiring usually one working day as in the case of The Westbury Condominium, Honolulu, Hawaii.

In other projects with less restrictive site spaces, many techniques are used to improve upon crane use during critical periods. For instance in the IBM Tower (Atlanta), one technique was a switch from prefabricated door blockouts to the use of slider panels and a header to form the blockout, saving crane time and also amount of labor cost. Another technique was to shift the activity of the tower crane jumping the hoist to the night shift period. Furthermore, the tie-ins of the tower crane were so located that the jumping of the crane occurred during the weekends.

3.8 ORGANIZATIONAL/COORDINATION

"Coordination is the key to the successful completion of any slipform project" writes J.D. Pruitt [34]. The coordination input is the responsibility of the owner, architect, engineer, general contractor and the slipform subcontractor during the preliminary phase of the project. This effort should be contributed equally by all involved contractors during the design and construction of the core. Thus, all the various trades must be organized and coordinated into one another with minimum conflict. The planning and scheduling therefore become much more critical than normal if the full economic benefits from the slipform are to be optimized.

Nevertheless, difficult sites with massive complex cores breed congestion and its allied consequences of late deliveries of materials, standby costs, idle workers and inefficient use of crane. In the case of Westbury Condominium, Honolulu, all these adverse effects emerged because of a difficult site. The contractor, however, tried to solve the problem. Time-lapse film analysis and video on-the-spot observation were used to streamline the tower construction operation and optimize the number of people in the various crews.

The limitation in this measure is that once the crews become aware that they are being filmed, they resort to all funny acts of excitement, causing distraction on work.

3.9 WEATHER

There are problems involved in both hot and cold weather concreting. In hot weather, there is an increased rate of evaporation from the fresh mix, particularly in the case of large masses of concrete, the difference between a temperature rise and fall due to the heat of hydration of cement, with its concomitant restrained volume changes, leads to possible cracking. In cold weather, too, the adverse effects of frost damage in fresh concrete leading to development of inadequate strength is a problem.

At any rate, it is the cold weather (low temperature) that has been posing problems for slipforming. Thermometers or thermocouples are used to monitor the temperature of the concrete.

In the Dallas' Union Project, Dallas, Sundt Co. had to use heated water in the cold weather to keep concrete in the mid - 60 F degree temperature range for uniformity in coloration and setting [15, and 44].

In another project, The ARCO Tower building in Denver, Colorado State, the Sundt Co. used high strength concrete mix for the job during a special cold weather. To achieve the design strength, between 50 F and 70 F curing temperatures had to be maintained. Corrugated fibre glass panels were used to enclosed the bottom two decks as shown in Fig. 3.3. Electric heaters and propane heaters were also additionally installed on the third or bottom deck as seen in Figs. 3.4 and 3.5. And 25 ft below the bottom deck, concrete insulation blankets made of foam with fire - retardant canvas covers were used to enclose the whole form. All these measures made it possible for Sundt to maintain its one floor per day pace. But there was a limitation. Any time, the outside temperature fell below 10 F on many occasions in January and February, all work had to be stopped since curling temperatures inside the slipform could not be maintained.

In The Olympic and York Tower Project, Dallas, total of 17 working days were lost because of heavy rain which rendered many equipments malfunction and created dangerous working environment [20].

Another aspect of the weather is wind forces. In the IBM building, Atlanta, the adverse effect of strong prevailing western wind on the "steering" of the slipform made it very difficult to set the form correctly. The wind forces also disturbed the pouring of the concrete.

In the Reunion Tower in Dallas, too, wind forces disturbed the cable through which electricity was being fed from the ground to a transformer at the top platform station for the crane operation. And the cable had to be braced occasionally.

3.10 CONCRETE HANDLING

The speed at which the forms are lifted depends upon the average temperature and the quality and workability of the concrete mix, that is the concrete should remain cohesive and should not segregate. Concrete can be brought to site by many means, but so far truck-deliveries are the most common means for slipforming in the United States. The concrete is then distributed through chutes or through direct discharge from crane buckets.

3.10.1 Placing And Compacting

The operations of placing and of compacting are independent and are carried out almost simultaneously. To avoid segregation and air pockets or voids which are common

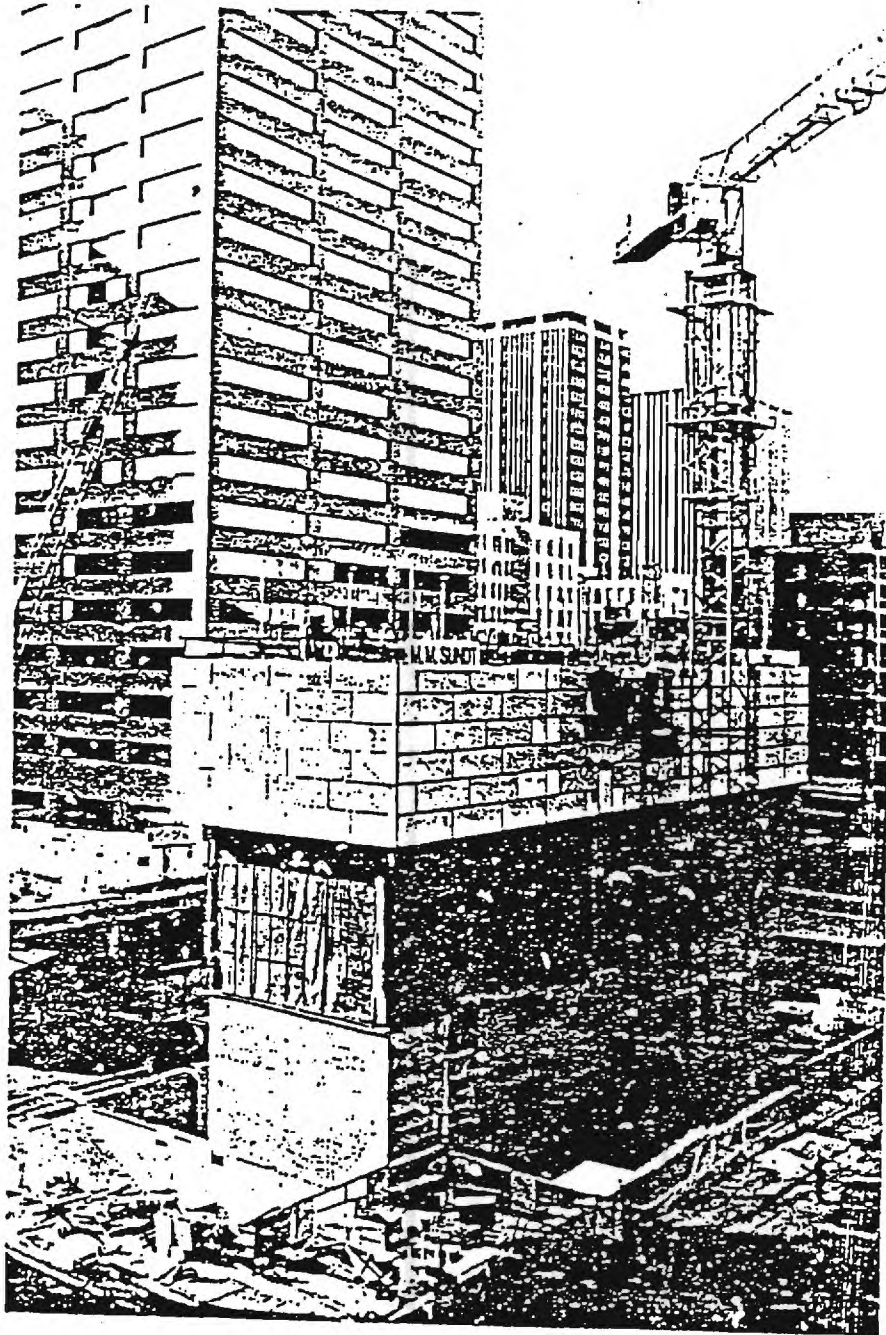
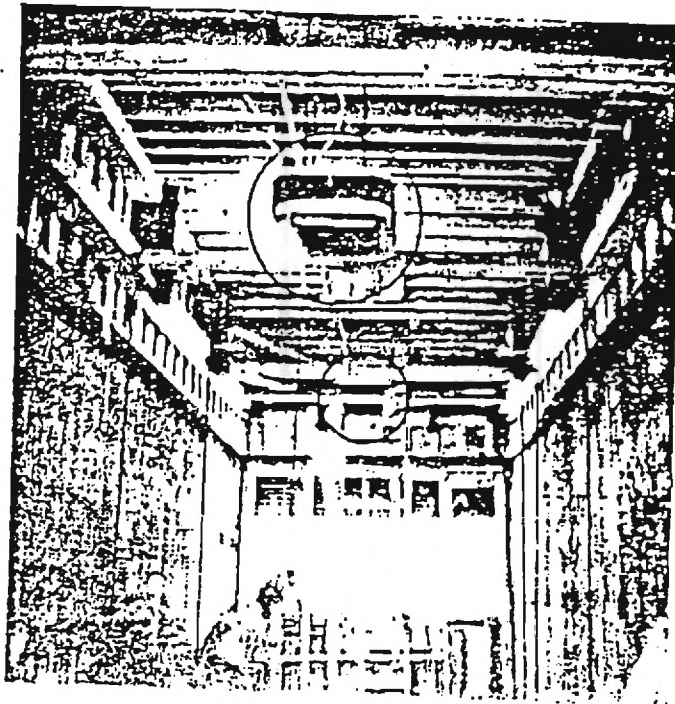
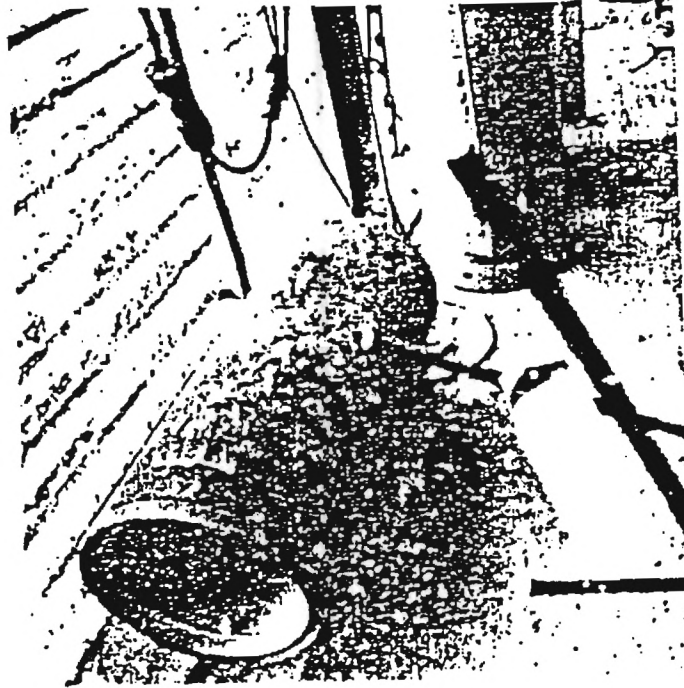


Fig. 3.3.- Blanket Drapped Below Lower Deck and Enclosed Lower Deck for Cold Winter Operations, Courtesy of Rocky Mountain Construction



Ceiling-Mounted Electric Heaters on the Third Deck

Fig. 3.4.- Maintaining Concrete Curing Temperatures in Cold Weather, Courtesy of Rocky Mt. Construction



Propane Heaters on the Third Deck

Fig. 3.5.- Maintaining Concrete Curing Temperatures in Cold Weather, Courtesy of Rocky Mt. Construction

problems in these activities, the following measures must be heeded to:

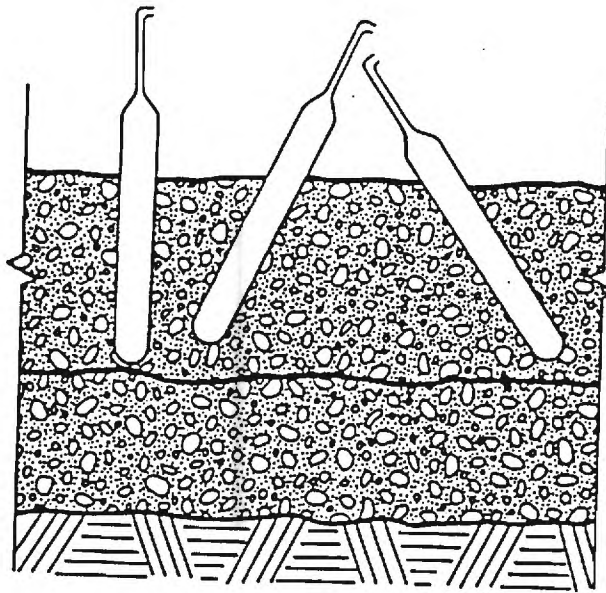
- a) The concrete should be placed in uniform layers, not in large heaps or sloping layers.
- b) The thickness of a layer should be compatible with the method of vibration so that entrapped air can be removed from the bottom of each layer.
- c) The rates of placing and of compaction should be equal.
- d) While a good finish and uniform color are required on columns and walls, the forms should be filled at a rate of at least 6 ft (2 m) per hour, avoiding delays - Long delays can result in the formation of cold joints;
- e) Each layer should be fully compacted before placing the next one, and each subsequent layer should be placed whilst the underlying layer is still plastic so that monolithic construction is achieved [25].

In the IBM Tower project, the ratio of steel to concrete was unusually high, which posed challenging problems to the crew during concrete placement. Air vibrators had to be used constantly and carefully (not electric vibrators) for greater reliability to remove any possible air pockets, although the compressor required larger space.

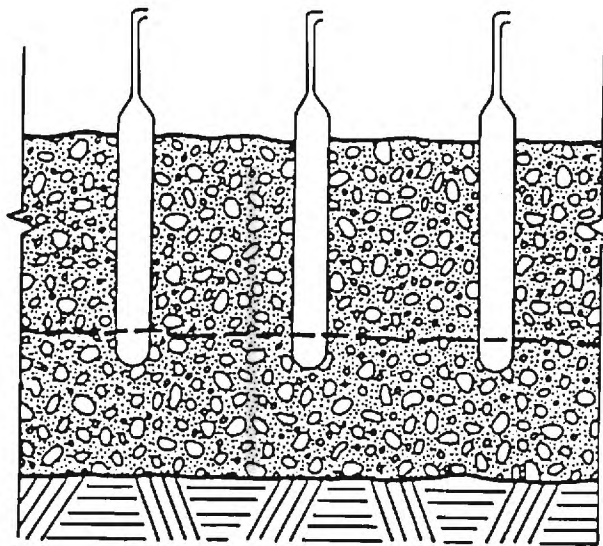
As a caution, the internal vibrators should be immersed quickly through the entire depth of the freshly deposited concrete and into the layer below if this is still plastic or can be made plastic as shown in Fig. 3.6. In this way, monolithic concrete is obtained and thus avoiding a plane of weakness at the junction of the two layers, possible settlement cracks, and the internal effects of bleeding. The major problem here is that with a lift greater than about 2 ft (0.5 m), the immersion vibrators may not be fully effective in expelling air from the lower part of the layer. Again, immersion vibrators will not expel air from the form boundary so that "slicing" along the form by means of a flat plate on edge is necessary. The use of absorptive linings to the form is helpful in this case but expensive [25].

3.10.2 Concrete Set Control

The setting time of concrete required to meet the rate of rise of a slipform depends upon the supply, handling and placing operations to be faced in a specific project. Once the nature of a specific project is known, the correct concrete mix supply can be met to match the intended rate of



(a) Wrong



(b) Correct

Fig. 3.6.- Placing of Poker Vibrators, Courtesy of ACI Manual of Concrete Practice

rise. Variations in the rate of rise can be predicted at any time in the slipforming to allow slowdowns where inserts, special steel or special situations need it, and also to speedup where conditions are optimum, requiring straightforward operations.

The variable rates of rise can be introduced upon thorough understanding of the following conditions:

- a) Correlation between concrete setting time and concrete slipping time.
- b) Correlation of concrete setting time and form height to rate of rise of slipforming operation.
- c) Mix proportional components and principles [14].

The problem being discussed here is that sometimes large concentrations of horizontal steel (especially in earthquake zones) make it necessary to delay the slip or, in some cases, stop the slip in order to place the steel properly. And if the forms stop, or rise too slowly, friction will be increased between the concrete and the form face leading to overload of the jacking system and possibly causing the partly-set concrete to lift with the forms. Again if the underlying concrete layer is allowed to set, then the necessary continuous monolithic construction will not be achieved. Therefore, concrete set control is the important factor here.

3.10.2.1 Correlation between Concrete Setting Time and Concrete Slipping Time

Upon a number of experiments with empirical data to establish the optimum range of set correlating the effects of various degrees of set on such factors as ease of slipping, ease of finishing and where problems such as "scoring", or "sagging" occurred, G.H. Fisher [14] came to the following conclusions:

- a) Concrete can be slipped at any time after the concrete has reached a measurable degree of set between 25 and 100 psi (1.75 and 7.0 Kgf/cm²), although the range should be considered subjective, he emphasized (see Fig. 3.7).
- b) Concrete slipped below 15 psi (1.05 Kg/cm²) sagged or fell out beneath the trailing edges of the slipform.
- c) Concrete that was slipped in the setting time range of 100 to 500 psi (7.0 to 35 Kgf/cm²) presented minor difficulties.

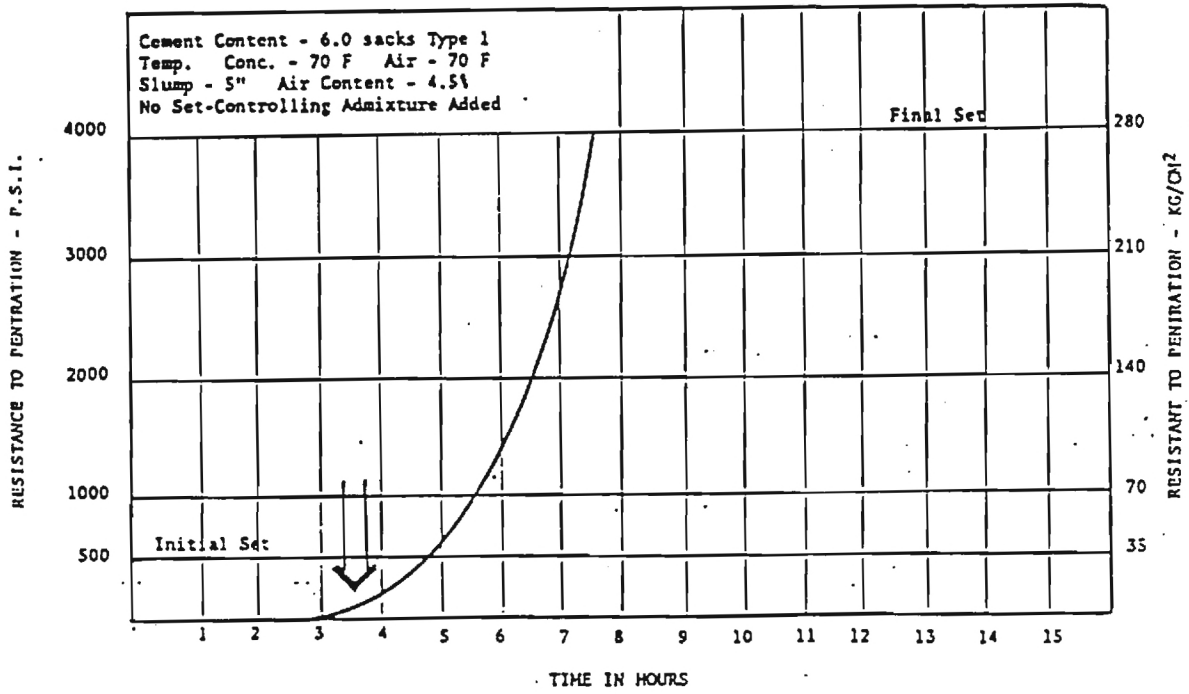


Fig. 3.7.- Setting Time Chart for Plain Concrete Mix, Arrow Shows Optimum Time for Slipping, Courtesy of American Concrete Institute

- d) Concrete slipped above 500 psi (35 Kg/cm²), which is defined as initial set under penetration resistance method, showed scoring of the wall surfaces, difficulty in slipping and was not generally favorable to those methods of slipforming where dimensional changes in wall thickness or diameter of the slipform were being introduced.

G.H. Fisher cautions that concrete can be slipped at higher degrees of set, especially where steel forms are used. He also emphasizes that the optimum range of degree of set - between 25 and 100 psi (1.75 to 7.0 Kg/cm²) - is well below the initial set of concrete, and that must be clearly understood.

3.10.2.2 Correlation of Concrete Setting Time and Form Height to Rate of Rise of Slipforming Operations

To determine the time at which the slipform passes the concrete, divide the required rate of rise into the slipform height [14]. For example, concrete entering a form of height H moving at a rate of R per hour comes out of the form in H/R hr.

Within the range of degree of concrete set - 25 to 100 psi (1.75 to 7.0 Kg/cm²) - by the resistance method, a high quality of concrete can be achieved. A technician can obtain different setting times by varying the proportions of retarders on trial mixes at the job site when using the chart of Fig. 3.8 [14]. The following measures must also additionally be taken into consideration:

- a) The changes should be supplied while the slipform is reaching the desired height.
- b) The mix proportions need to be incorporated, usually 2 to 3 hrs, prior to the desired predicted rate of rise.
- c) If several changes are desirable, they should be incorporated in gradual steps to eliminate any possible drastic changes in the concrete setting time.

With empirical data, Fisher has developed the information in Table 3.1 for final set of concrete as against the predicted rate of rise of slipform.

3.10.2.3 Mix Proportional Components

Based upon practical experience, H.G. Fisher [14] highly recommends the following factors to be taken into

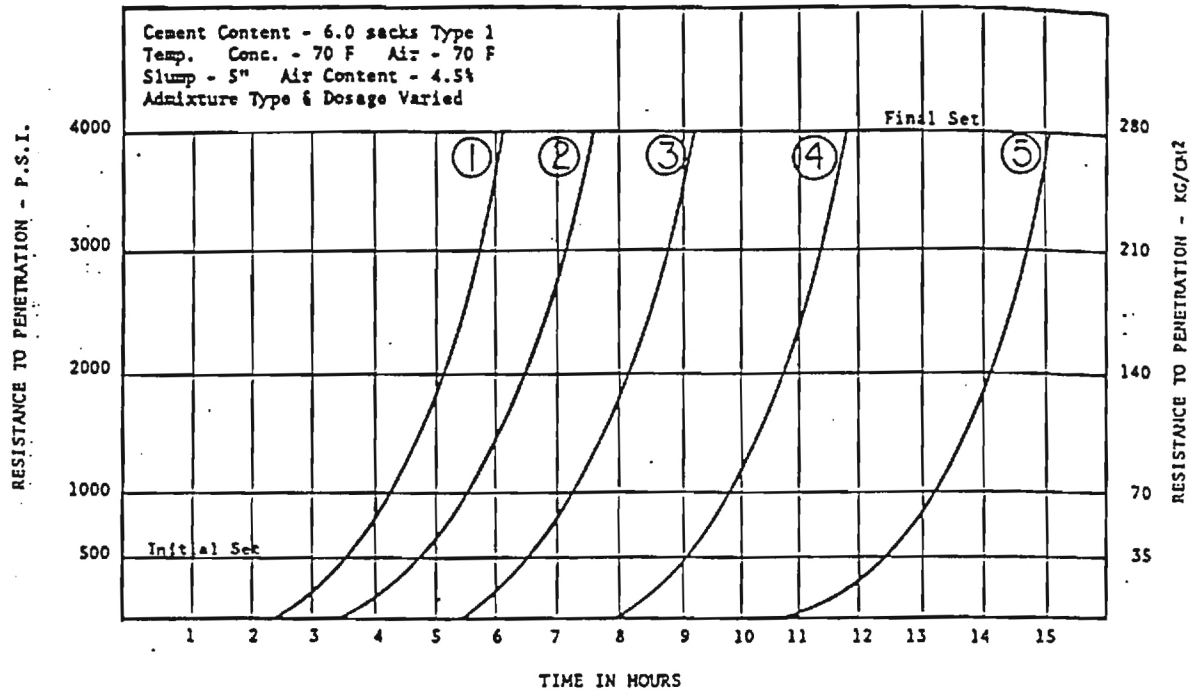


Fig. 3.8.- Determining Effect of Admixtures on Setting Time of Concrete, Courtesy of American Concrete Institute

consideration in the formulation of the mix proportions:

- a) Minimum cement factor should be 6.0 sacks (564 lb = 255 Kg).
- b) To compensate for variations in setting time caused by daily temperature changes, Fisher recommends that Table 3.2 has been extremely useful in changing the admixture dosage to a constant rate of rise.
- c) The use of admixtures should take place at the concrete batching plant and incorporated into the mixing water for thorough dispersion through the mix.
- d) If possible, the concrete batching plant must be close to the project. Again if complete supervision of the mixing trucks is not practical, the delivery sheets must be time-stamped on leaving the batching plant and also at the start of delivery.
- e) The placement of each lift should be completed around the entire slipform before the next starts and the form should be kept filled. Furthermore, the rate of filling the slipform should be timed to match the expected rate of rise.
- f) It should be noted that the first movement of the slipform (jacking) cannot start until a period of time equal to the optimum slip time has elapsed after the placement of the first lift of concrete. But the first movement of the slipform can be quickened by placing a faster setting mix in the first lift (7 to 10 in.) of concrete or by adding an extra bag of cement to the mix proportion. This technique used occasionally applies when concreting under cold weather conditions since the foundation is generally massive and acts as a heat sink.

TABLE 3.1.- Predicted Rate of Rise Versus Final Set of Concrete

Final Set of Concrete HR.	Predicted Rate of Rise Inch (cm) Slipform per HR.
5	18 (46 cm)
6	14 - 17 (40 cm)
8	10 - 12 (28 cm)
10	7 - 9 (20 cm)
14	5 - 6 (14 cm)
18	3 - 4 (9 cm)

TABLE 3.2.- Admixture Dosage Changes to Compensate for Daily Temperature Changes

Time Period	Winter Accelerator	Summer Accelerator
12 AM-10 AM	High dosage	Low dosage
10 AM- 2 PM	Medium dosage	Medium dosage
2 PM- 8 PM	Low dosage	High dosage
8 PM-12 PM	Medium dosage	Medium dosage

CHAPTER 4

OVERVIEW OF SLIPFORMING OPERATION

4.1 HISTORICAL DEVELOPMENT

The objective of this chapter is to provide the reader with a historical background about slipforming operation. This part has not been within the focus of this research, however, it was felt that this background is necessary for those who have know little about slipforming. The information in this chapter has been obtained from Batterham [3].

According to him, the first slipforming application occurred in 1885 when a Texan built a small concrete shaft with the principle. And no further development occurred until 1903 when in America, a screw jack was first used to propel the formwork for the first true slipforming system. It was then manually operated and so it showed many inherent problems of concrete such as vibration, fallouts, honey combing, wall buckling which had to be studied to finalize the concept.

It was not until the 1940's that a Swedish manufacturer developed the present standard hydraulic equipment that the slipforming system has been used successfully on a wider scale to the present time. Before then its application was limited to silos and simple chimneys.

The screw-jack method is illustrated in Fig. 4.1., as used in a simple chimney construction. Curved inner and outer formwork faces were built from manufactured tongue-and-grooved boards fastened to timber ribs. Timber yokes supported the arrangement which was raised together resting on climbing tubes inserted in the structures concrete footings. Notably there was no concrete kicker to start the structure on its upward movements. Yet to prevent the initial significant grout from falling underneath the shatters, damp sand was placed around the base of the formwork. More importantly, alternate jacks used a left-hand thread for each to counterbalance the horizontal movement of its neighbor. This was a measure to prevent the whole system from rotating as a result of the horizontal force applied to the jack handle.

Batterham describes that at this time a number of people did manually the lifting operating, each responsible for an assigned number of marked wrapped jacks. At the blow of a whistle, the jacks were rotated a quarter of revolution to raise the whole structure uniformly, and the color coding ensured that no jack was missed. Larger contracts demanded a permanent hut on the uppermost deck, from which levels could

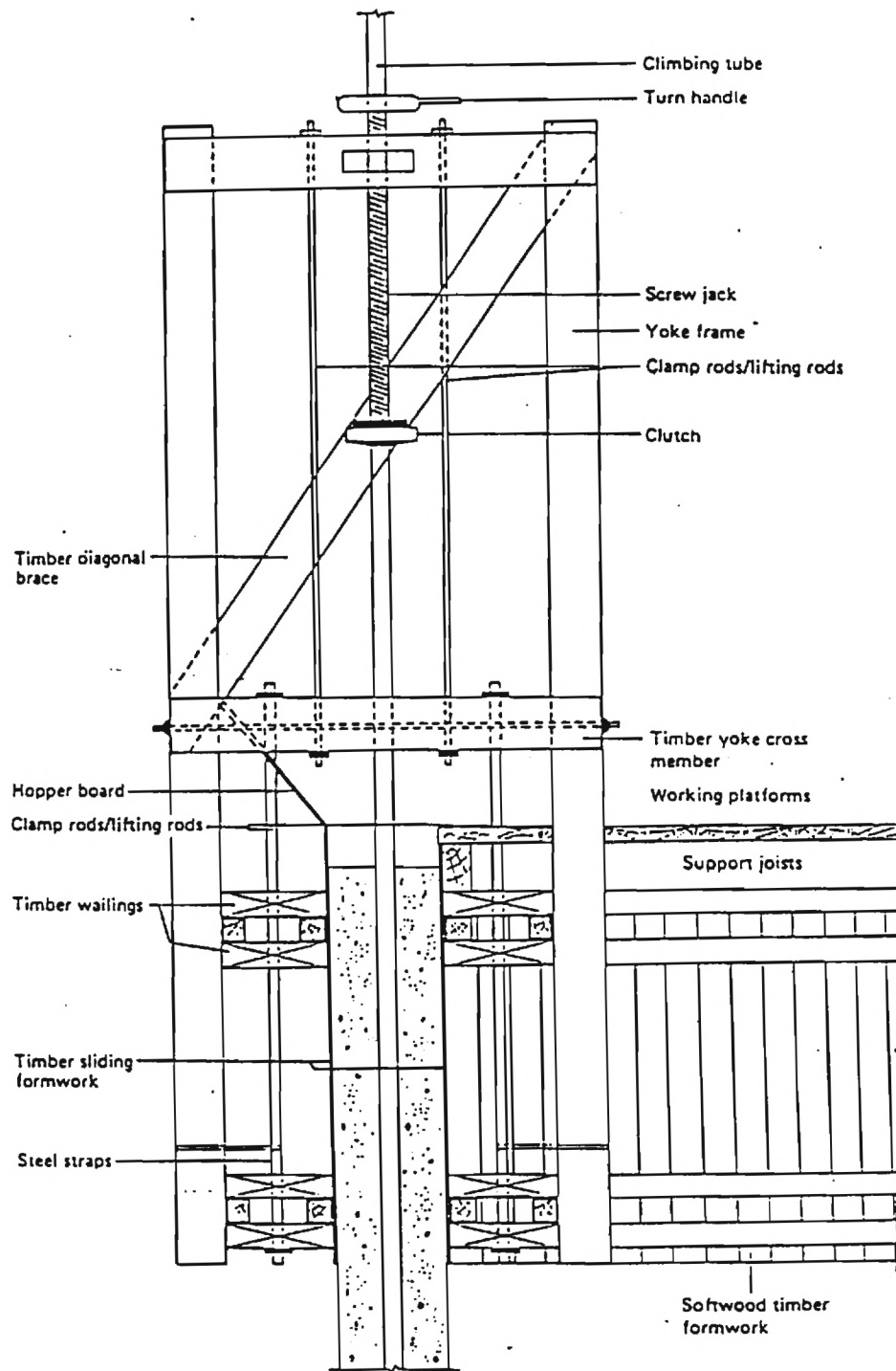


Fig. 4.1.- Section Through Screw Jack Sliding Formwork System
 Courtesy of Batterham [3]

be often checked. At the completion of sliding, the formwork was secured to the walls in order to offer greater stability for the dismantling stage.

According to Batterham: "Even at this stage of slipform's history it was discovered that it was best not to incorporate a concrete kicker to start the structure on its way". In order to prevent the bleeding (initial grout to escape underneath the shutters) the formwork base was sealed with damp sand. To prevent the whole system from rotating, due to the horizontal force applied to the jack handle, alternate left-hand thread jacks were installed in order to balance the horizontal force of its neighbor. It is important to notice that at that time, the forms were lifted manually by a number of people. A color code was used, in which each operator was responsible for a certain number of colored jacks. The level of the forms was controlled by rotating each jack a quarter of revolution, assuring that the whole structure was lifted uniformly. On larger contracts, a permanent leveling place was located in the uppermost deck, from which levels could be frequently checked. Once the sliding was completed, the forms were pinned to the walls, assuring great stability during the dismantling phase.

4.2 HISTORY OF SLIPFORMING FORMS

The forms in slipforming operation consist of the following seven principal components:

- 1) Sheathing or formwork
- 2) Wales or Ribs
- 3) Yokes
- 4) Working platform or deck
- 5) Suspended scaffolding
- 6) Lifting jacks
- 7) Spiders

The following sections describe each of these components, and stage of their development.

4.2.1 Sheathing or Formwork

Two sets of sheathing are needed for structures that include walls with inner and outer surfaces. The sheathing may be made of D and M number, such as 1" (25 mm) by 4" (100 mm) or 1" (25 mm) by 6" (150 mm) boards installed vertically, 3/4" (18.75 mm) plywood with the grained installed vertically or sheet steel.

At first, the actual face was built from a series of tongue-and-grooved boards which helped in controlling any lateral

movement due to their constant contact with wet concrete. Moreover, expansion gaps were incorporated within the sheathing face purposely for controlled movement as shown in Fig. 4.2.

Originally the sheathing panels were suspended by long steel rods from yokes of about 6' (1.8 m) apart, depending upon the panel size. And the system needed an excessive degree of bracing. But with the introduction of steel or glass fibre as panels, the panels are now secured directly to the yokes.

Steel or glass fibre has a longer life and a lower friction drag on the concrete than boards or plywood. The sheathing usually varies in height from 3'6" (1.050 m) to 5'0" (1.5 m), and a height of 4'0" (1.2 m) is commonly used. The opposite faces of the sheathing should be about 1/4" (6.25 mm) wider at the bottom than at the top to reduce the possibility of the concrete sticking to the forms.

Initially formwork configurations were made up of a variety of timbers, typically 1" (25mm) thick and 4 feet (1.2 m) in height. The face was constructed with a series of tongue-and-grooved boards, which also prevented any lateral bend or swelling due to the constant contact with the wet concrete. It can be seen in Fig. 4.2 a detailed of how this board was assembled.

These forms are shop fabricated, which is not only faster and more economical because of the specialization of the labor and equipment employed, but also because of the better control over details and dimensional tolerances that could be obtained.

The formwork panels were suspended by long steel tubes from yokes about 6 feet (1.8 m) apart; but this system required a lot of bracing and today the panels are directly attached to the yokes. Instead of the boards, above mentioned for the form surface, fiberglass or steel panels are currently used; they are expensive but can be used repeatedly and give a good degree of finish.

4.2.2 Wales or Ribs

Traditionally wales have been made from timber but escalating costs favor the use of steel which can be used repeatedly. As illustrated in Fig. 4.2., the sheathing is usually held in alignment by two rows of wales or ribs each side. Steel wales are generally used when steel sheathing is in use.

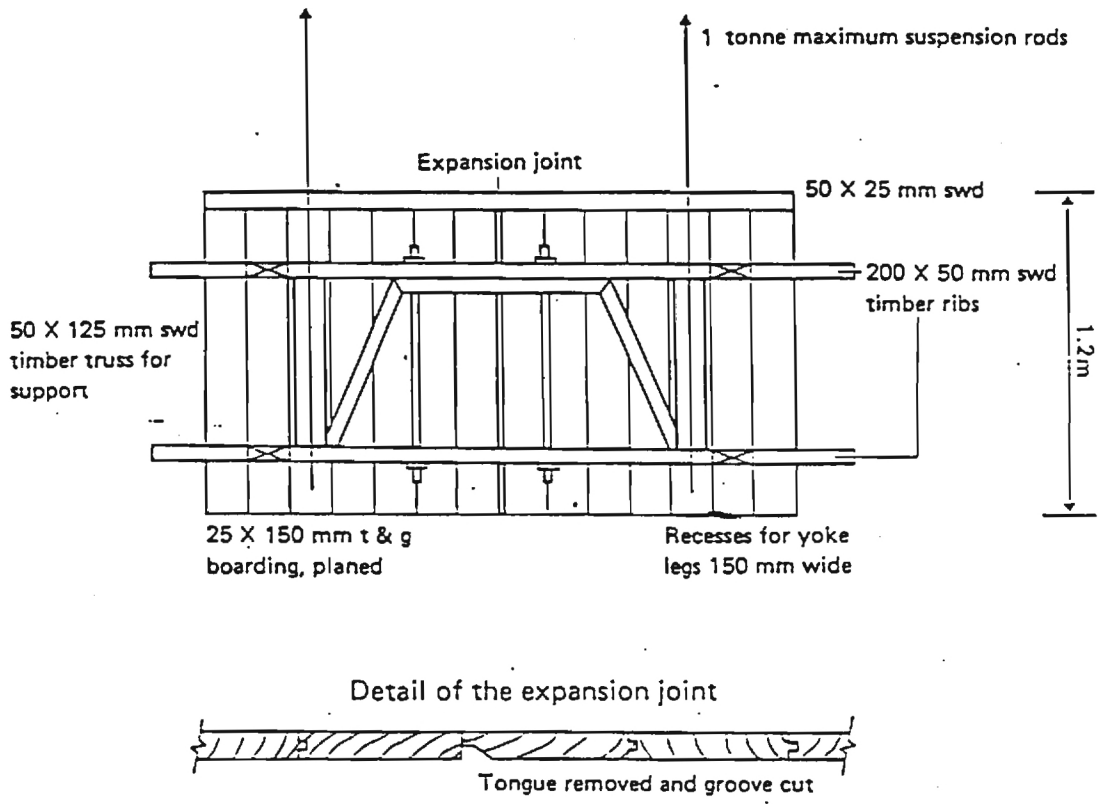


Fig. 4.2.- A Typical Timber Formwork Panel Structure Detail,
 Courtesy of Batterham [3]

The wales or ribs serve the following functions:

- a) They support and hold the sheathing in position.
- b) They support the working platform.
- c) They support the suspended scaffolding.
- d) They transmit the lifting force from the yokes to the form system.

Traditionally these have been made from wood but now they have changed to adjustable steel ribs that can be reused for many times. Usually two rows were assembled and braced together, forming a whole structure that transmitted the loads directly to the yokes. Fig. 4.2 illustrates the ribs situation. The steel ribs accomplish the following functions:

- a) Support and keep the panel forms in place.
- b) Support the working or central deck.
- c) Support the lowest working deck.
- d) Transmit the lifting forces from the yokes to the panel forms.

4.2.3 Yokes

Each yoke comprises a horizontal cross member connected to a jack, plus a yoke leg for each set of sheathing and wales. As illustrated in Fig. 4.3., the top of each leg is attached to the cross member while the lower end is attached to the bottom wale or rib.

The yokes serve two purposes:

- a) They transmit the lifting forces from the jacks to the wales or ribs.
- b) The yoke legs hold the sheathing or formwork in the required positions.

Attached to the forms at the ribs, at calculated intervals are jakes, which in essence are two vertical members with a horizontal tie above and across the slipform top. The jacks are placed on the horizontal member of the yokes.

The main function of the yokes are:

- a) Transmit lifting forces from the jack to the ribs.
- b) Maintain the whole system together in a given pattern.

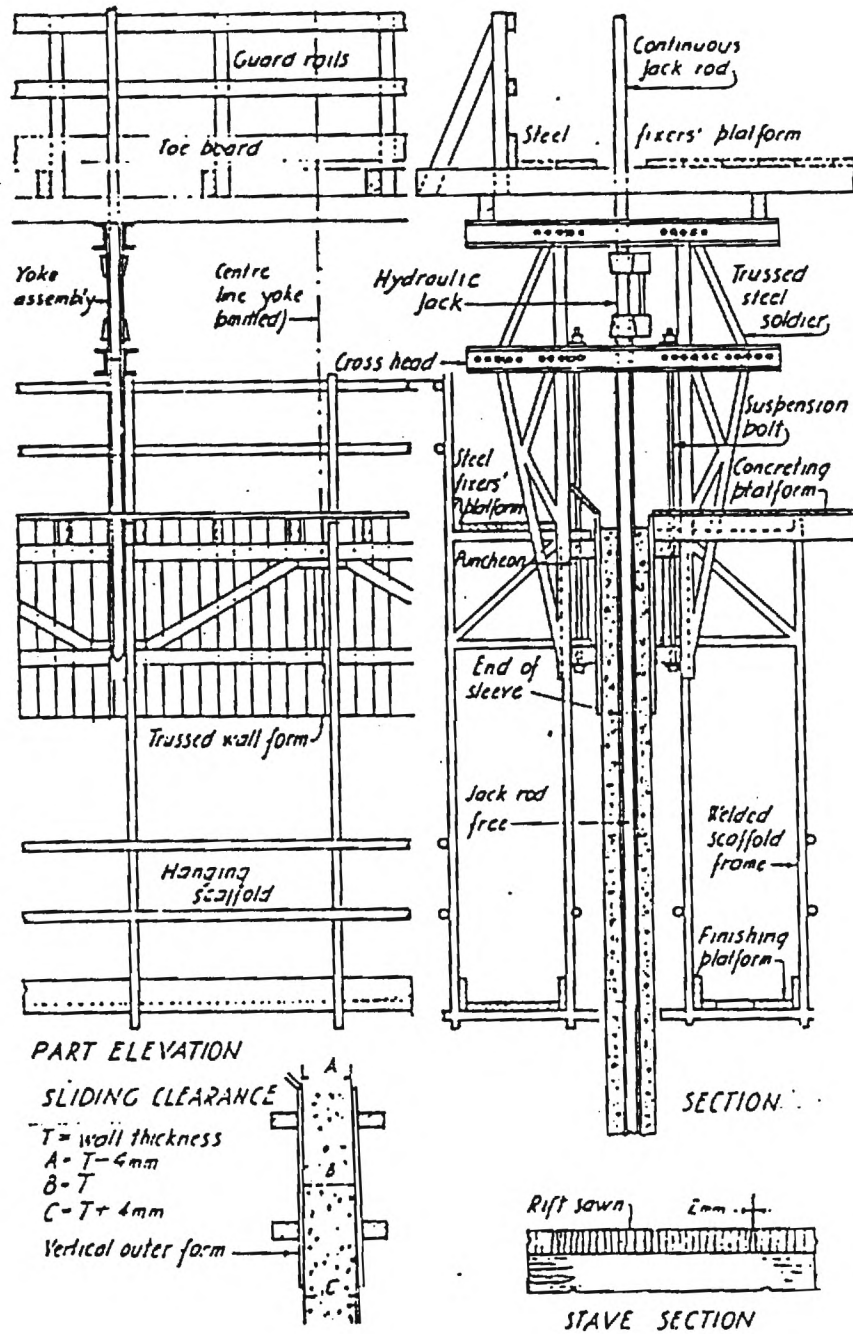


Fig. 4.3.- Slip Form Construction, Courtesy of Austin [2]

4.2.4 Working Platform or Deck

The working platform or deck usually consists of 1" (25 mm) thick boards or 3/4" (18.75 mm) thick plywood, supported by joists. The joists may be supported at the ends only by the wales (ribs) or for long spans, they may require intermediate supports by wood or steel trusses, with the steel joists or steel beams attached to the wales (ribs) as shown in Fig. 4.4.

Initially the slipform system started with two working platforms or decks - the top one for working and storage and the lower one for finishing touches to the concrete as emerged from the sheathing or formwork. Later on because of overcrowding for storage and working purposes, a third deck came to existence. The three decks of today are shown in Fig. 4.3. The topmost platform or deck is for storage and fixers while the central one is for concreting workers. The lowest one is for finishers.

If the structure is to be finished with a concrete roof or cap, the working platform (the topmost one) may be used as a form to support the concrete. For this function, pointed steel pins are driven through the sheathing into the concrete wall under the wales (ribs), and the yokes are removed.

The working platforms are still made from wood timbers which offer, so far, the most versatility. The early phase of slipform systems, started with two decks, the top one functioned as a working deck and at the same time was used to store materials like rebar. In the lower deck the concrete was finished once the forms had gone up. Soon it was realized that the working deck did not have room enough for both storage and working purposes then another deck was added. In this deck, which is in the top of the form structure, materials were stored and it was also used to unload concrete from the crane. Figure 4.3 gives a section and elevation of the whole structure. The weight of the material that is being carried in the upper deck must be checked frequently, since excessive weight will cause forces on the yoke structures that may move the form out of alignment.

4.2.5 Suspended Scaffolding

Scaffolding is suspended under the forms to allow finishers to have access to the concrete surfaces as illustrated in Fig. 4.3., which usually need some finishing dressing.

The scaffolding is assembled in sections before placement of the concrete starts. After the concreting has progressed

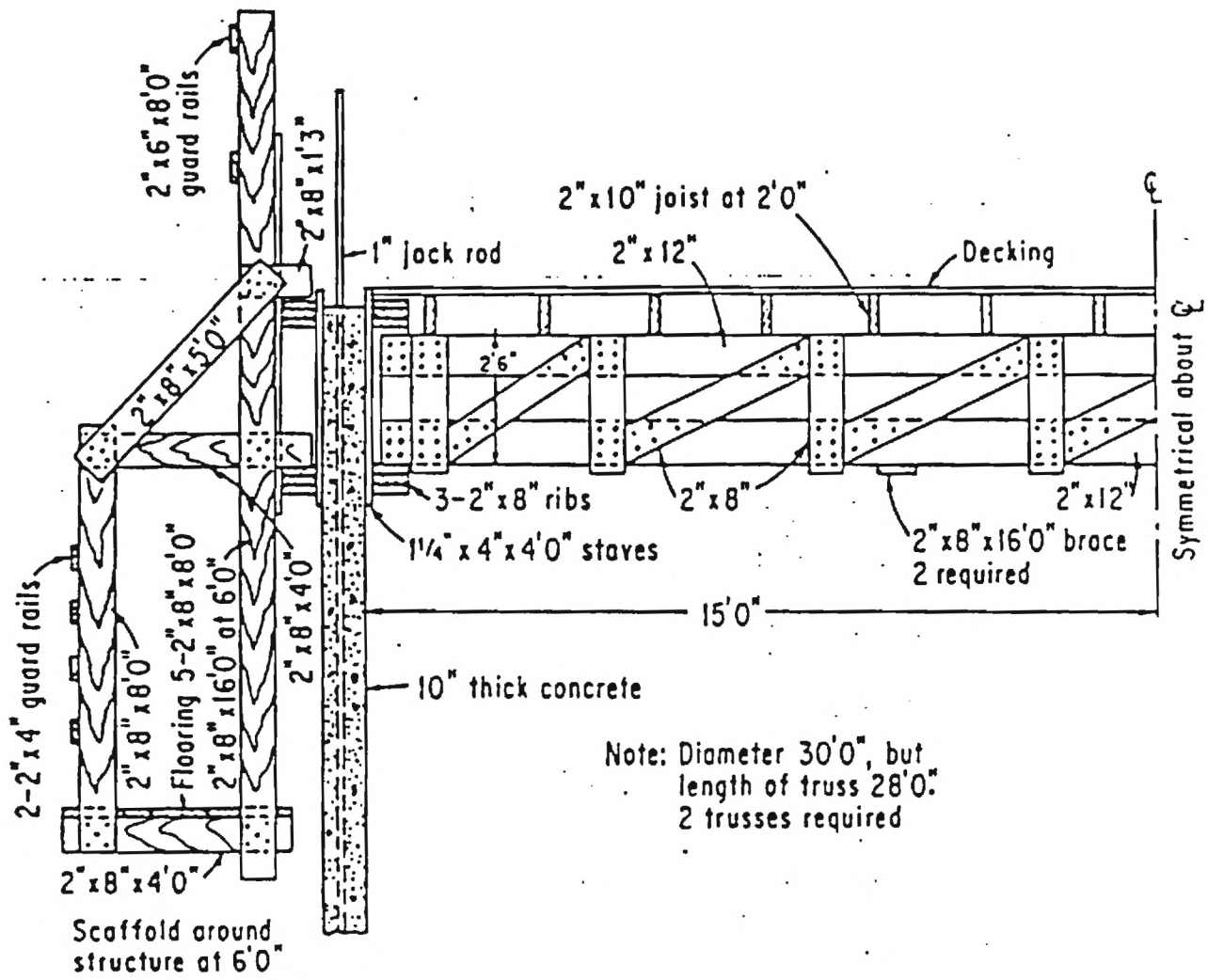


Fig. 4.4.- Structural Detail of Working Platform, Courtesy of B.M. Heede [19]

sufficiently, the raising of the forms is stopped temporarily and the scaffolding is attached to the forms.

4.2.6 Lifting Jacks

There are three types of jacks that are used to lift the forms, namely, screw, hydraulic and pneumatic. The jacks provide the forces needed to raise the forms as the concrete is placed. Normally the jacks are spaced from 6' (1.8 m) to 8' (2.4 m) apart along a wall.

Nowadays a hydraulic jack is the most common used. A smooth steel jack rod, its lower in the concrete, passes upwards through the hollow jack, which is attached to a yoke. When pressure is applied to a jack, one element of it grips the jack rod and another element moves upward, lifting the yoke with it. The jack resets itself automatically for another upward movement when the pressure is released temporarily. All the jacks are interconnected to a centrally located pump. This makes the oil pressure on each jack the same, assuring uniform upward movements. It must, however, be noted that any given jack can be operated individually or taken out of operation if so desired to bring sections of the forms to uniform elevations.

There are three different types of climbing jacks available: screw, hydraulic, and pneumatic. The last two operate by anchoring the extended head of the jack to the climbing tube (or bar) and then by pulling up from the anchorage raise the jacks. Once the jack movement has gotten to the head of the jack, this must be repositioned further up the climbing tube. Generally a clutch is used to do this operation. The climbing tube can be withdrawn or cast in the concrete. It depends on the cost of the tube, thickness of the wall (thin walls could be damaged during the withdrawal), reinforcement of the wall and the time factor.

Every contractor should design the formwork structure and assure that the number and location of the jacks is enough to lift the system formwork structure; if they occur, the uniform movement will not be guaranteed and distortion surfaces may be obtained.

The load that each jack is going to carry is mainly determined by three factors:

- a) Dead weight of the whole structure.
- b) Friction between the forms and concrete.
- c) Area of working platforms and live loads carried by them.

According to Batterham: "With timber-based systems, cross sections of the formwork area one jack may lift are as follows:

Small circular silos	5.6 m ²
12.2 m diameter silos	5.1 m ²
Awkward shaped plan	3.7-4.2 m ²
Single faced formwork only	2.0 m ²
General situations	3.1-7.3 m ²

The approximate load hydraulic jacks can lift without undue concern is two tons, a figure confirmed by years of experience". The steel climbing tube is generally 48 or 30 mm and passes through the center of the jack. Hydraulic pressure is applied to a series of grips and when they are activated they clamp onto the climbing tube. In order to obtain a uniform movement all the jacks are connected to a central hydraulic pump; the system also has hand operated valves located at certain strategic points in the pipework to allow individual operations or repairs. Each lift of the jacks moves the formwork 70mm, so the system moves in a series of steps instead of a continuous sliding action. This have some effect on the surface of the concrete and some attempts have been made to smooth the process by incorporating electrical motors to the jacks, but several problems have been encountered like:

- a) Synchronization of the motor speed.
- b) Sensitivity to overloading.
- c) Rough handling of the motors.

4.2.7 Spiders

Early slipform systems used spiders which interlaced the internal ribs of the formwork to provide rigidity to the structure, that today is considered of an excessive degree. Complicated formwork often requires the spider system and sometimes a second spider may be needed to transmit forces within the three deck system.

CHAPTER 5
BUILDING CORES

5.1 FACTORS OF CONSIDERATION

Slipforming in building construction has been almost exclusively limited to the "core" of buildings or that portion which generally contains the elevators, stairs, toilet rooms, etc. If the design of the building is for bearing-wall construction, then all the vertical elements can be slipformed. The ultimate approach to slipform all vertical concrete elements makes the slipform the primary operation controlling the other phases of construction. The elevators, for instance, are usually eliminated from the critical path when slipforming is used. Since slipforming is a faster method of construction than the conventional forming, an earlier completion date is achieved. This translates into an earlier return on the owner's invested capital and thus a reduction on cost of interests on permanent loan for construction. To the contractor, an earlier completion date means lower overhead costs and more jobs that can be completed with his organization in a given period of time. However, to develop an economical and efficient slipform, some necessary factors must be in order.

5.1.1 Design Requirement

There should be a layout that remains typical from floor to floor. This helps a form to be built that will not have to be modified to any great extent as the slips progress. If possible, there should be uniform wall thicknesses throughout their full height, even though walls can be narrowed by inserting filler panel in the form if necessary. It should be noted that sometimes the saving in concrete is more than offset by the additional labor spent in modifying the form, not to mention the time lost [26].

Reinforced-steel design should be kept to an absolute minimum because large concentrations of steel make it difficult to place the steel while the slip is in progress.

All items to be installed within or connecting to the slipformed walls should have tolerances in their design to ensure proper fit. This calls for careful incorporation of architectural details into structural details. The difficulty of setting work to an exact position from a moving deck accents this importance.

5.1.2 Finishing

The type of required concrete finish is another basic consideration in setting up a slipform. If the finish is going to be applied to the wet surface of the concrete as the slip progresses, then a finishers' platform suspended below the form is needed for the crew. On the other hand, if the finish is to be applied "dry" after the slipping operation is completed full height, then usually the finishers' scaffold is omitted. Thus, the cost of fabricating and installing a finishers' platform is saved and can be applied to the higher unit cost of applying the finish in this manner.

5.1.3 Elevators

The most important thing to take into consideration is the alignment of the shafts because once the rail line for the first segment is established, it is necessary to continue this line for segments above. This makes the elevator-front design more important than ever.

5.1.4 Jacking Systems

Selection of a jacking system to be used is an important factor for a smooth slipform operation. The hydraulic and the pneumatic systems seem to be the commonest and they are all patented. The selection leads to the patented company coming in early in the planning stage to advise on lifting capacities necessary to get the job done on schedule.

5.1.5 Form Design

Closely allied to jack system selection is the form design. Given all parameters available, the chosen patented company, can flexibly decide on the type of form and where to fabricate them, taking costs into consideration to get the work done smoothly.

5.1.6 Thorough Planning

The last major part of slipforming to be considered is the actual operation of the form during and between the slip. The quality of this portion of the work is a function of the proper preparation of the details prior to starting to slip, scheduling of material to be delivered to the job primarily concrete, coordination of subcontractors, and a thorough knowledge of the slipform work including all details of all work to be incorporated into the slip.

5.2 TECHNIQUES

Slipforming is considered a specialist area of construction, and several major national and international companies undertake the operation involved as specialist sub-contractors. In the United States, Sundt Construction Co. (based at Phoenix and Tucson in Arizona), Heede-Uddemann Inc. (in San Francisco, CA and Mt. Prospect, IL.), and Patent Scaffolding Co., a Fort Lee, New Jersey based company are the leading contractors in the slipforming of concrete building cores.

5.2.1 3 to 6 and 22 Metric Tons Jack

This slipforming system is used by Sundt Construction Co., and Heede-Uddemann, Inc. 3 to 6 ton-jacks are only suitable for grain silos work. So for large core work in high rise buildings, large hydraulic jacks of 22 metric tons are now used for greater lifting capacity.

Briefly, the sequence of operation consists of: after a set of slipforms is completely assembled on a concrete base, the forms are filled slowly with concrete. When the concrete in the bottom of the forms has gained sufficient rigidity, the upward movement of the forms is started and continued at a speed that is controlled by the rate at which the concrete set. Reinforced steel is placed as the forms move upwards. Figs. 5.1-5.9 show typical "core" details. One-floor-per day pace is the normal rate of slipforming.

If the general contractor is the same entity handling the slipforming, then the core construction and the erection of the structural steel are done simultaneously, and that requires 3 shifts of work. On the other hand, if the core construction is subcontracted, the two activities become independent processes, even though the structural steel erection will be done on the third shift in each case.

The major tasks performed on each shift on a typical day are as follows:

First Shift:

- a) Place horizontal rebar, and place concrete in the form, using buggies loaded from larger hoppers (mounted on the top level), and the hoppers being fed from a ground-mounted tower crane that climb along with the slipform, and the crane too being fed with concrete from trucks on the ground.
- b) Finish concrete in exposed areas.

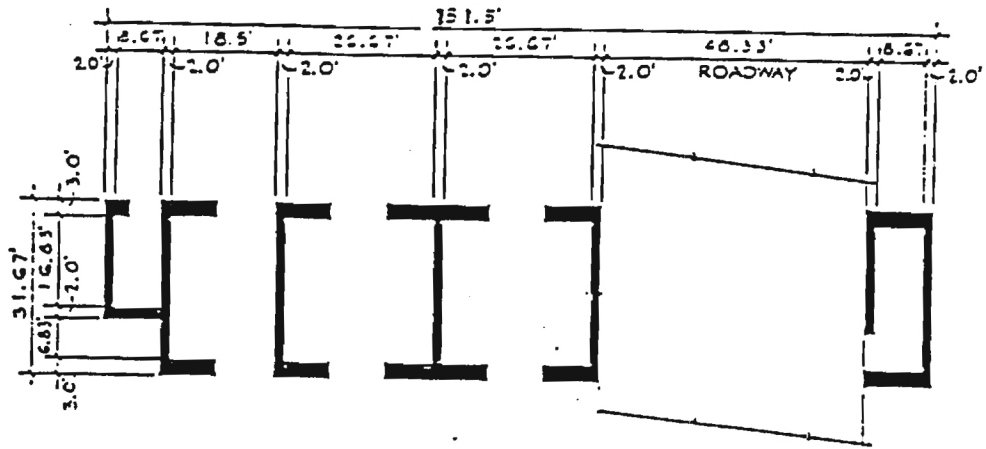


Fig. 5.1.- Plan View, Core at Foundation

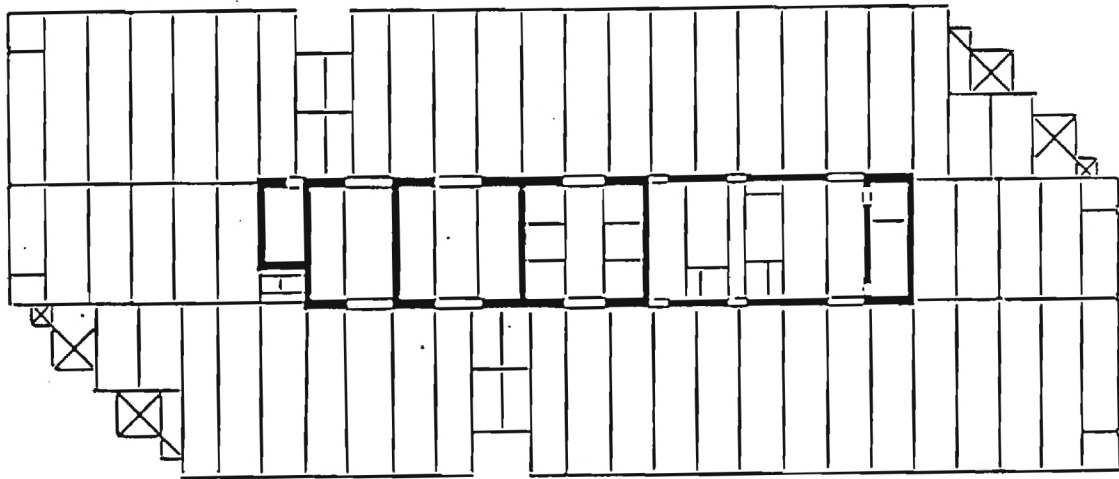


Fig. 5.2.- Plan View of Core at Typical Floor

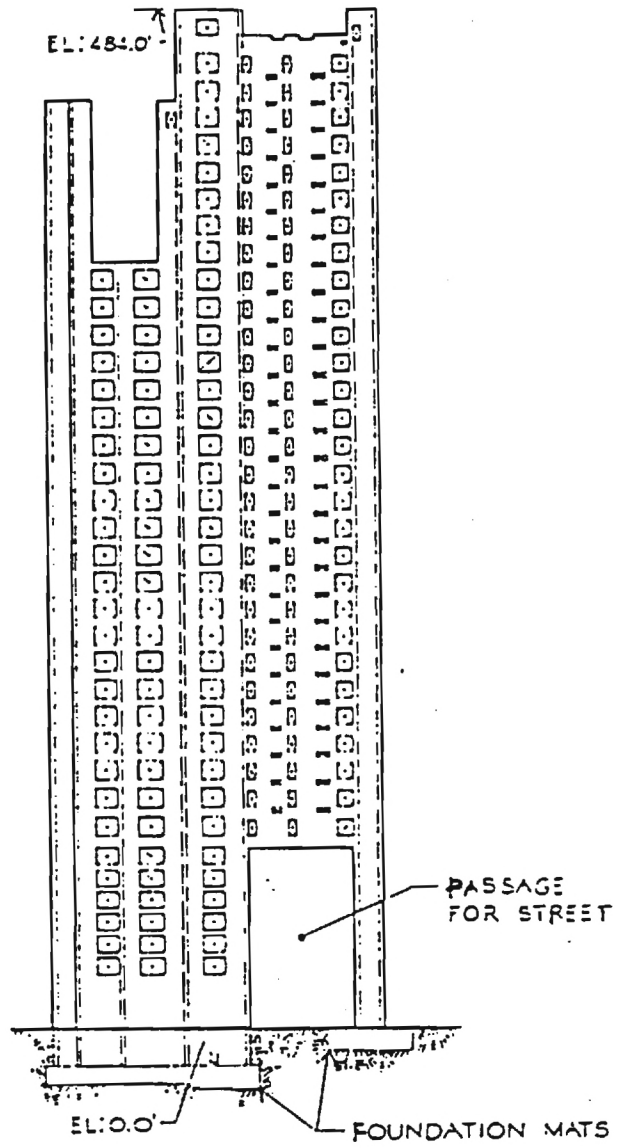


Fig. 5.3.- Elevation View of The Core

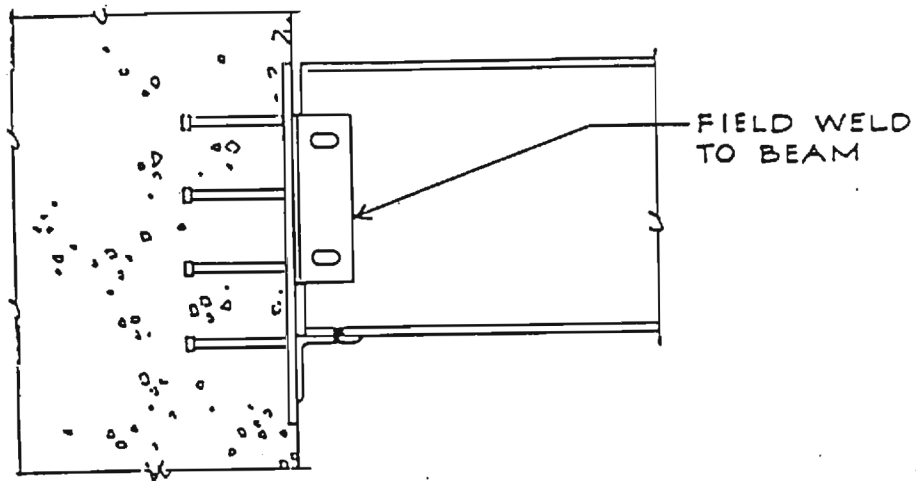


Fig. 5.4.- Vertical Cross-Section of Typical Floor Beam Anchorage to the Core

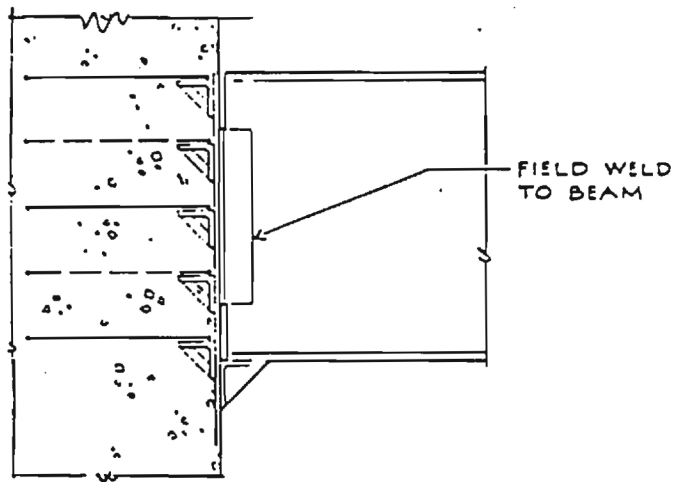


Fig. 5.5.- Vertical Cross-Section Loaded Girder Connection to the Core

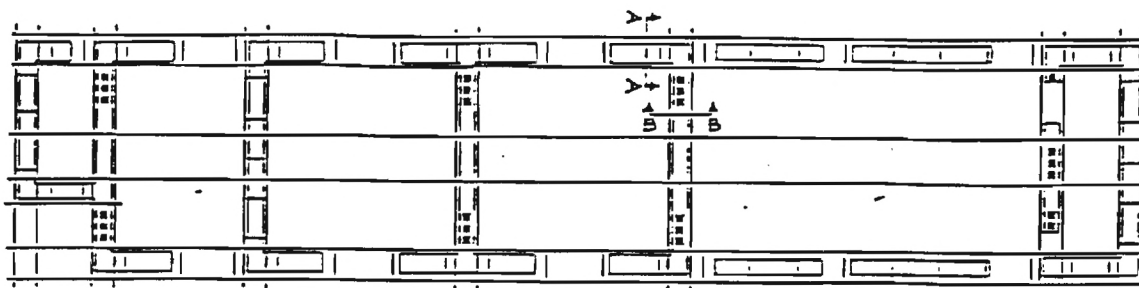


Fig. 5.6.- Plan View of Jacking Grid and Jack Locations

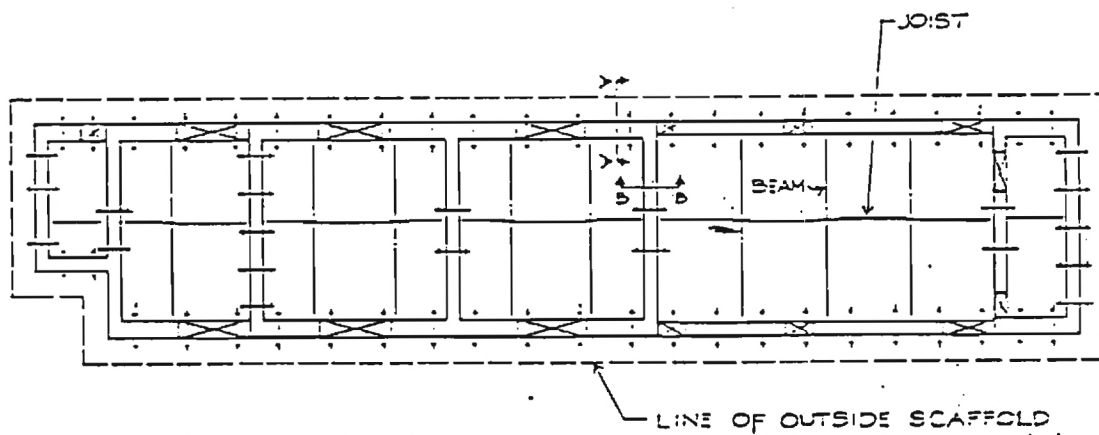


Fig. 5.7.- Plan View of Slipform at the Work Deck

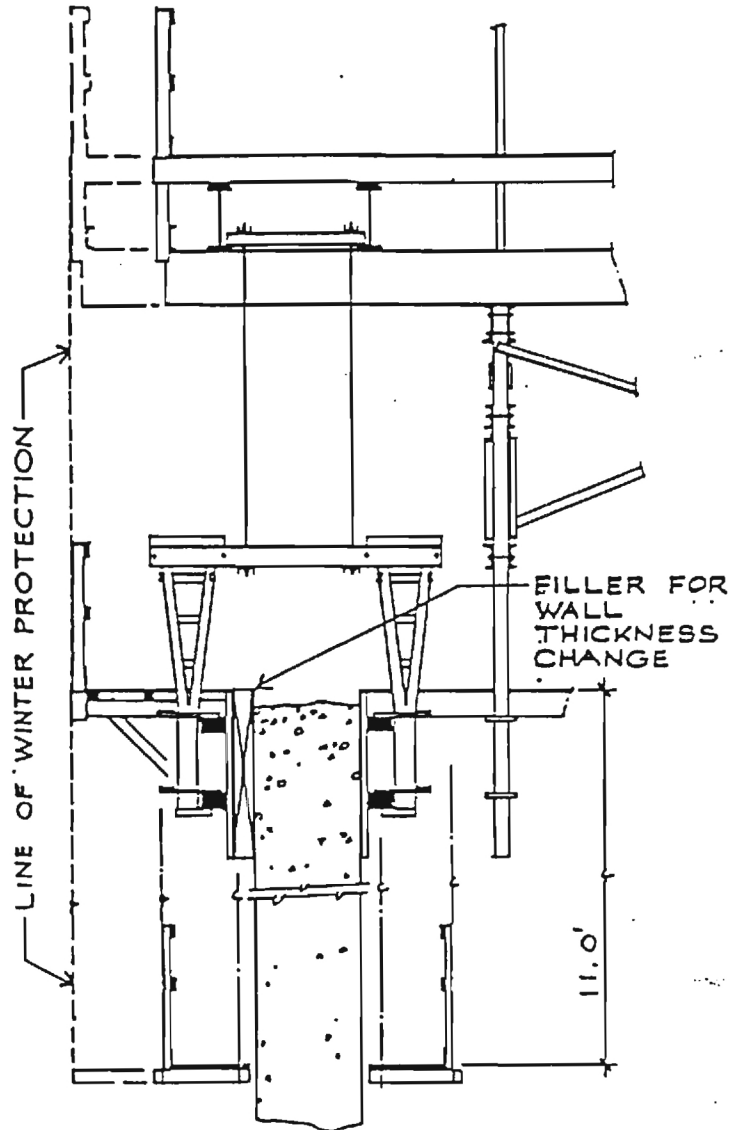


Fig. 5.8.- Section A: Typical Section Exterior Wall

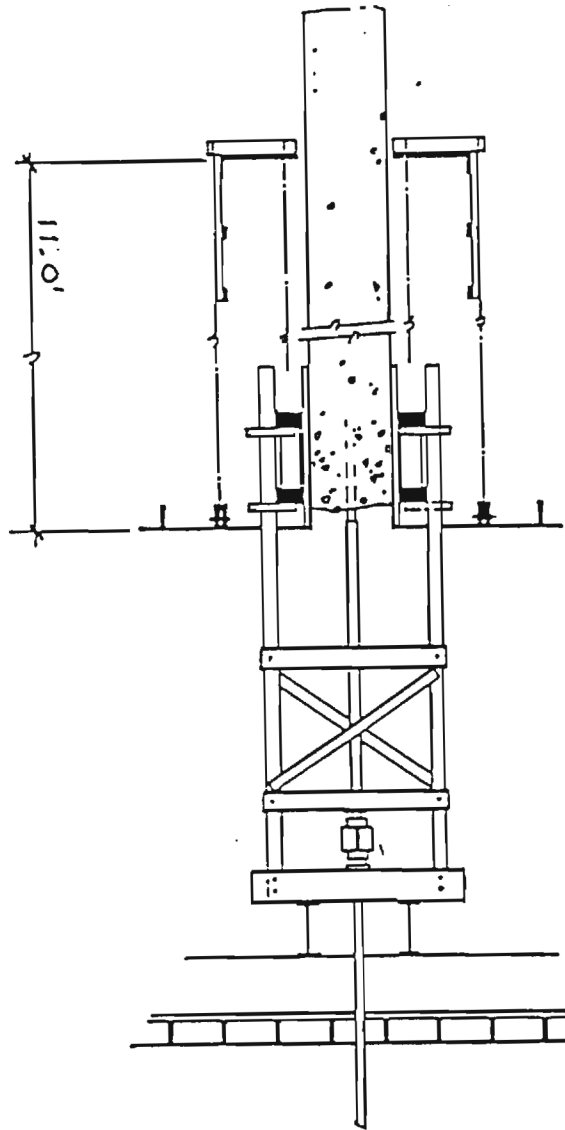


Fig. 5.9.- Section B: Typical Jack Installation, Courtesy of M.M. Sundt Construction Co.

Second Shift:

- a) Clean form and decks.
- b) Distribute and place vertical rebar.
- c) Distribute horizontal rebar for placement in the next slip.
- d) Install other structural elements to the core wall and the block outs for doors and other passages.

Third Shift: Iron workers place structural steel.

It is worth noting that one man work full-time on operating the jacks and another person, full-time job also on each shift for safety and fire prevention. The typical tasks performed at each level are detailed as follows:

Upper Deck:

- a) Control and operation of the jacks.
- b) Installation of the jack rod.
- c) Landing, sorting and placement of the vertical rebar.
- d) Distribution of concrete to hoppers or directly into the form below.
- e) Storage of utility items.

Working Deck:

- a) Distribution, placement and consolidation of the concrete.
- b) Placement of horizontal rebar.
- c) Vertical rebar splices.
- d) Installation of doorway forms, pipe sleeves, duct sleeves and the like.
- e) Placement of keyway and dowel anchors for slab to core connections.
- f) Monitoring of laser target for steering input.
- g) Installation of the structural steel beam anchorage assemblies.

Finishing Boards:

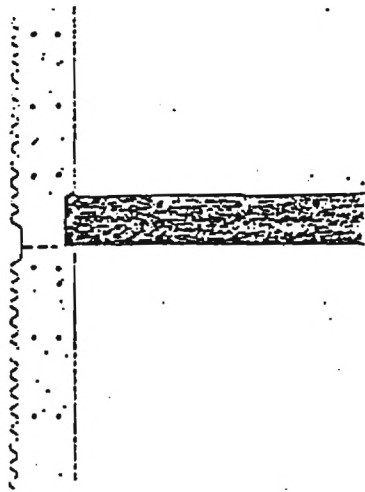
- a) Finishing the concrete where exposed in the completed building.
- b) Patching the concrete when necessary.
- c) Stripping of the forms for keyways.
- d) Installation and welding of beam bearing brackets and attachment tees.
- e) Installation of elevator lobby floor beams.
- f) Application of sprayed curing compounds.

5.2.2 Self-Climbing Wall System

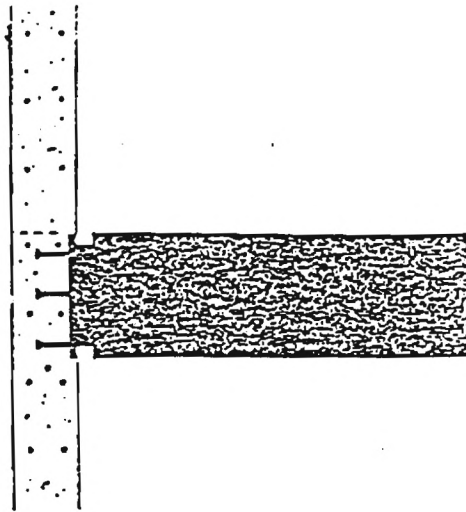
This is another quick forming system for high rise building concrete cores, and it was introduced by Pattent Scaffolding Company of New Jersey.

The system has the following unique features:

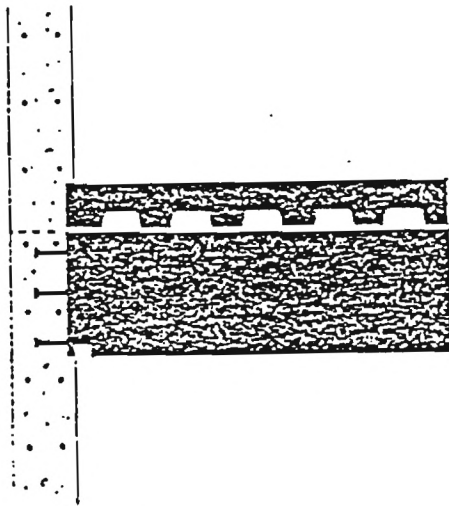
- i) It has no limit in the core dimensions and can also handle a single cell or numerous elevator shafts.
- ii) Its adaptability to any shape is superb, being rectangular, triangular, curved or cores with wing walls. Fig. 5.10 shows the different systems that can be used in conjunction with the concrete core: a) shows a poured in place concrete frame, b) is a combination of concrete core and steel frame, c) indicates a composite steel frame and concrete deck, and d) represents a precast concrete frame.
- iii) It is relatively easy for contractors to assemble and operate the system by. Their own concrete forming crews, since many of the tasks are familiar to experienced crew.
- iv) The weather does not pose much problem in the operation of the system because the top platform serves as a roof in a rainy time. Moreover in a cold weather, the system can be easily enclosed and equipped with heaters, ensuring normal construction continuity.



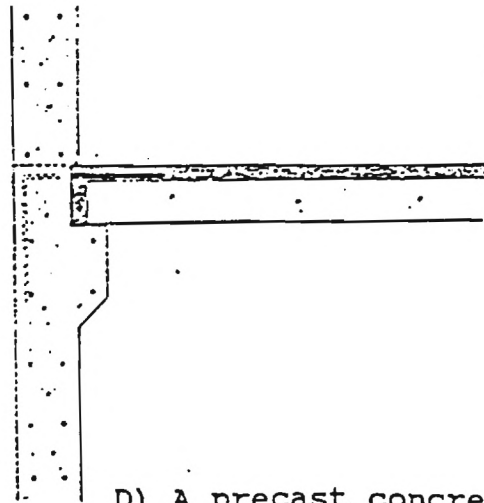
A) A Poured in place concrete frame



B) A combination of concrete core and steel frame



C) A composite steel frame and concrete deck



D) A precast concrete frame

Fig. 5.10.- Various Structural Assemblies, Courtesy of Patent Scaffolding

5.2.2.1 Different Approaches

Self-climbing construction offers different approaches:

Separate Core Pour: With a very large core, the self-climber can be manipulated into two independent operating assemblies for reduction in both crew and pour size.

Floor Levels: Preferably the core and the floor slab constructions can proceed at the same pace, that is, concrete is placed in the wall form just after the pour of the floor slab.

A Unit for Two Cores: If two or more individual cores are close to one another, one self-climber unit can be used to form the cores, leading to elimination of a second control booth or separate work crews as shown in Figs. 5.11, and 5.12)

5.2.2.2 Components

Superstructure: Lateral and transverse beams constitute the backbone of the self-climber. They give locational support to the gang forms and the heavy work platform. The superstructure with all the forming and platform areas is raised to the next level with hydraulic jacks [28].

Forms: The forms, designed to be compatible with any common floor height, hang from the superstructure on a trolley system to enhance easy opening and closing. Fig. 5.13 shows a cross-section of the whole system. The forms are plywood-sheet faced for a smooth finish, and they can be overlaid with form liners or rustic scripts for any desired special finishes.

Platforms: Two platforms are contained in the system; one is the level scaffolding platform which hangs below the forms to create perfect working spaces, and the other is at the top of the superstructure for a work deck from which concrete is poured, also serving as a storage area for reinforced steel and other equipments. All the platforms moves with the forms when a lifting force is applied. As the core's height increases, there is no dismantlement between raises, which increases safety.

Jacks: The readily accessible jacks are all mounted behind the forms. Each jack, being self-contained, has its own pump and reservoir system for an individual concrete during a raise, even though not all the jacks are needed for the operation because of each powerful lifting capacity.

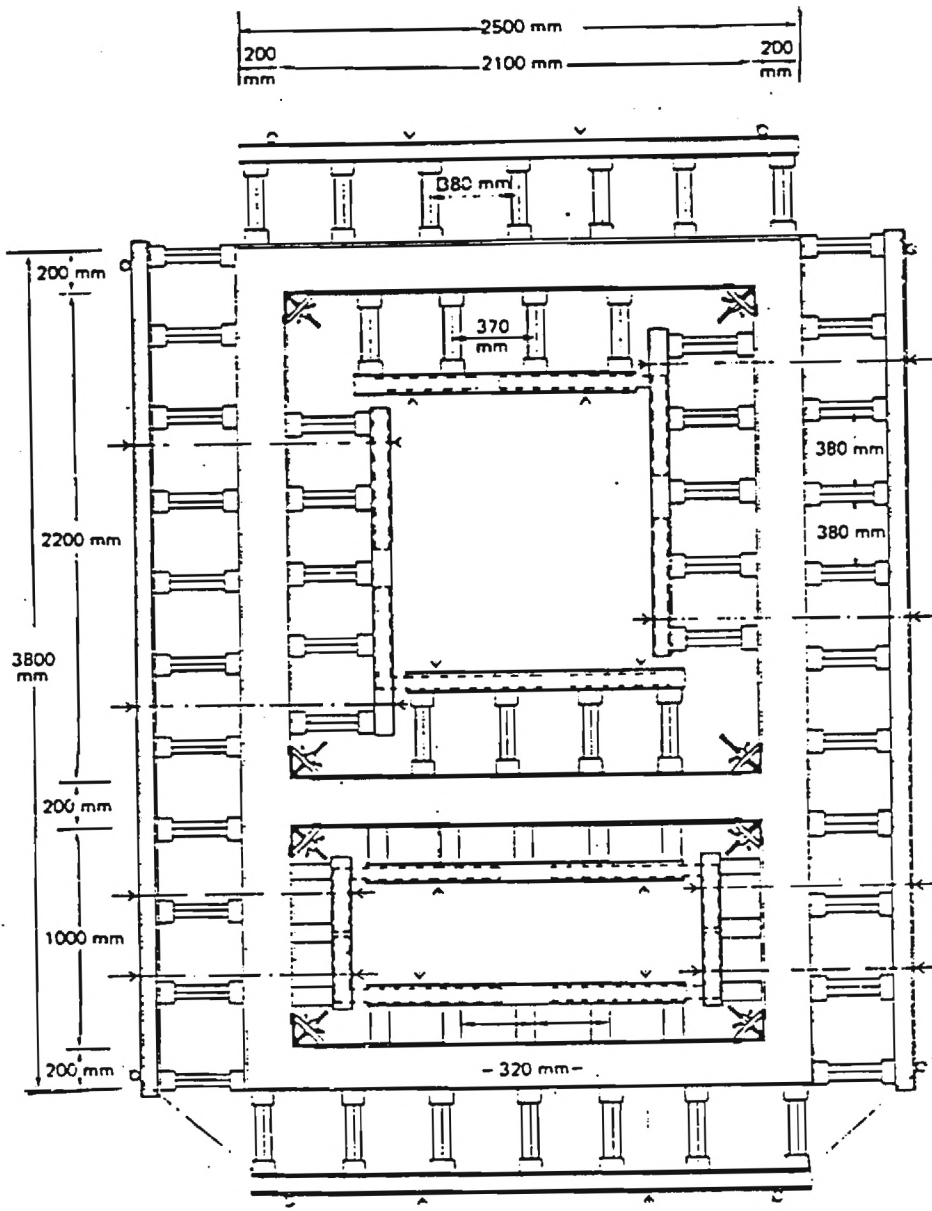
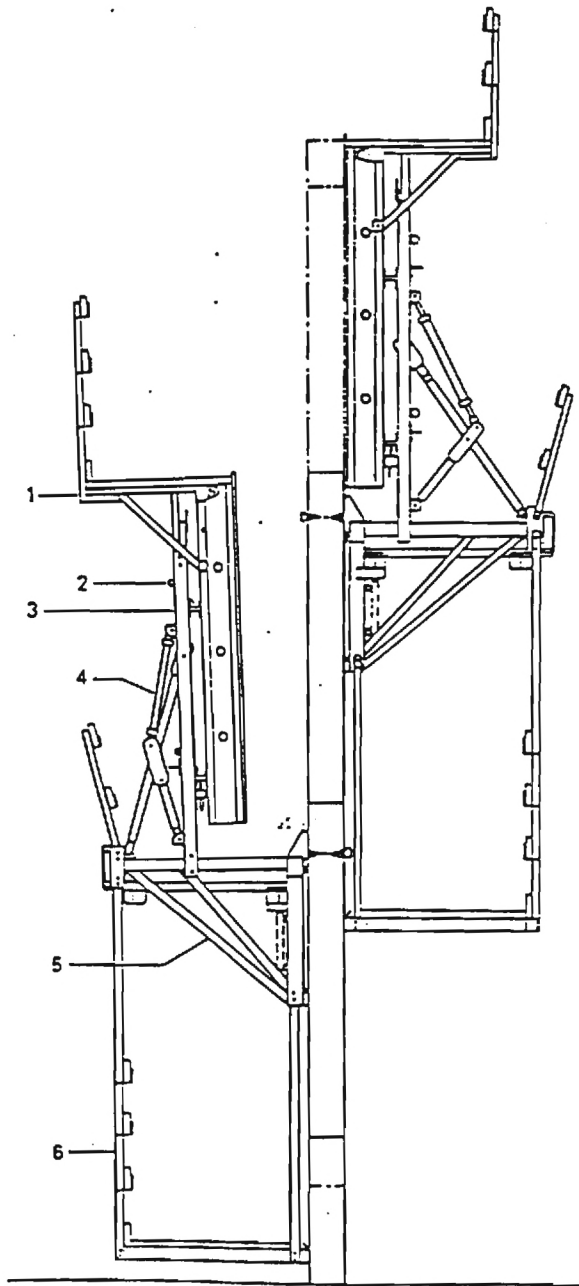


Fig. 5.11.- Multiple Core with Lifting Service Shaft



1. Universal Bracket
2. Wailing-to-Bracket Holder
3. Vertical Wailing
4. Scissor-Action Spindle
5. The Climbing Bracket
6. The Lower Platform

Fig. 5.12.- Doka Self-Climbing Formwork for Multiple Core,
Courtesy of Doka Inc.

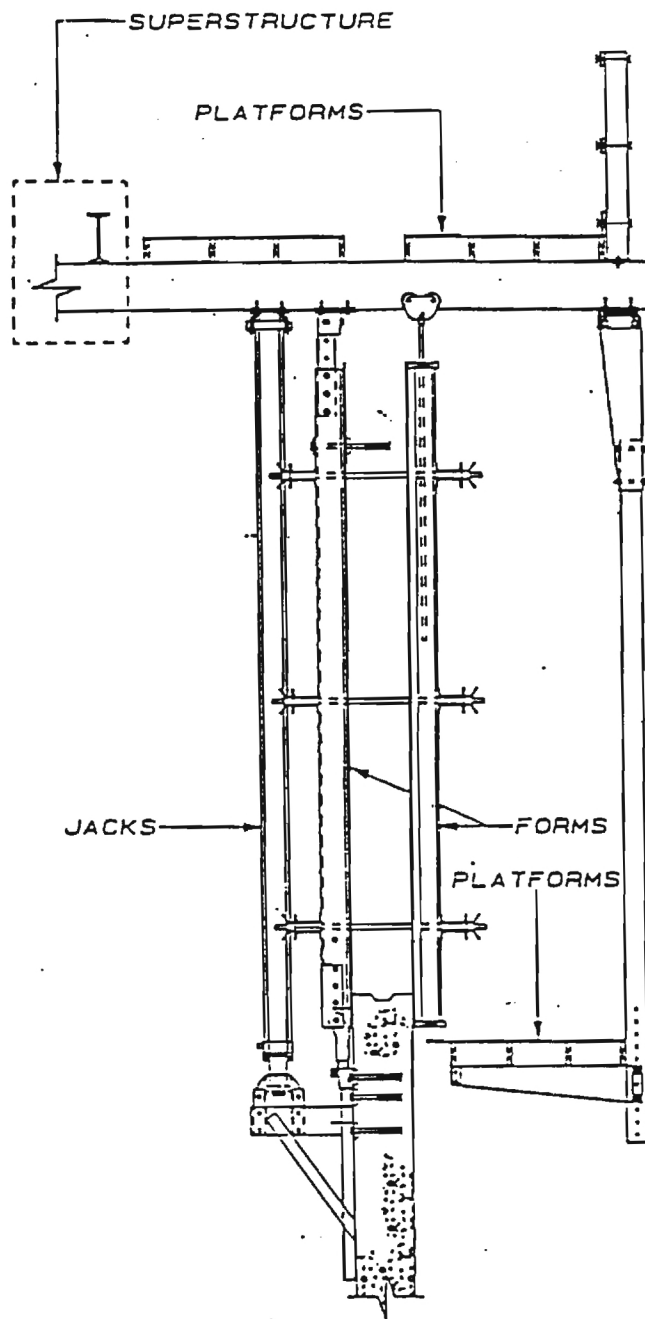


Fig. 5.13.- Cross-Section of Self-Climber Wall System, Courtesy of Patent Scaffolding

5.2.2.3 Typical Cycle

The day after pouring, a new cycle begins and Fig. 5.14 illustrates the system at this stage. As follows, workers, removing the ties, roll back the outside forms and the inside forms are released. Any connections to the form faces are removed as well.

Fig. 5.15 shows the start of the lifting. The hydraulic jacks are activated by the operator from a central point on the platform, and the whole self-climber starts moving up to the next level. Individually jack speeds are manipulated while monitoring also the water levels to keep the system level during the raise. With the bottom of the forms overlapping the new cast wall, the raise ends. The levelling and the overlapping ensure alignment for the next pour.

With the forms at the new position, preparation for the next pour begins. The crew members then clean and oil the form face and install all needed box-outs as shown in Fig. 5.16. Then follow the placing and tying of the reinforced steel. At the finish of each section, the workers roll the form in. Some crew members check the vertical alignment and the adjustable screw jacks at the form support bracket are repositioned.

The entire system ready for pouring is indicated in Fig. 5.17. Generally the forms are designed to take a full liquid head, meaning the concrete can be placed as rapid as availability allows [28].

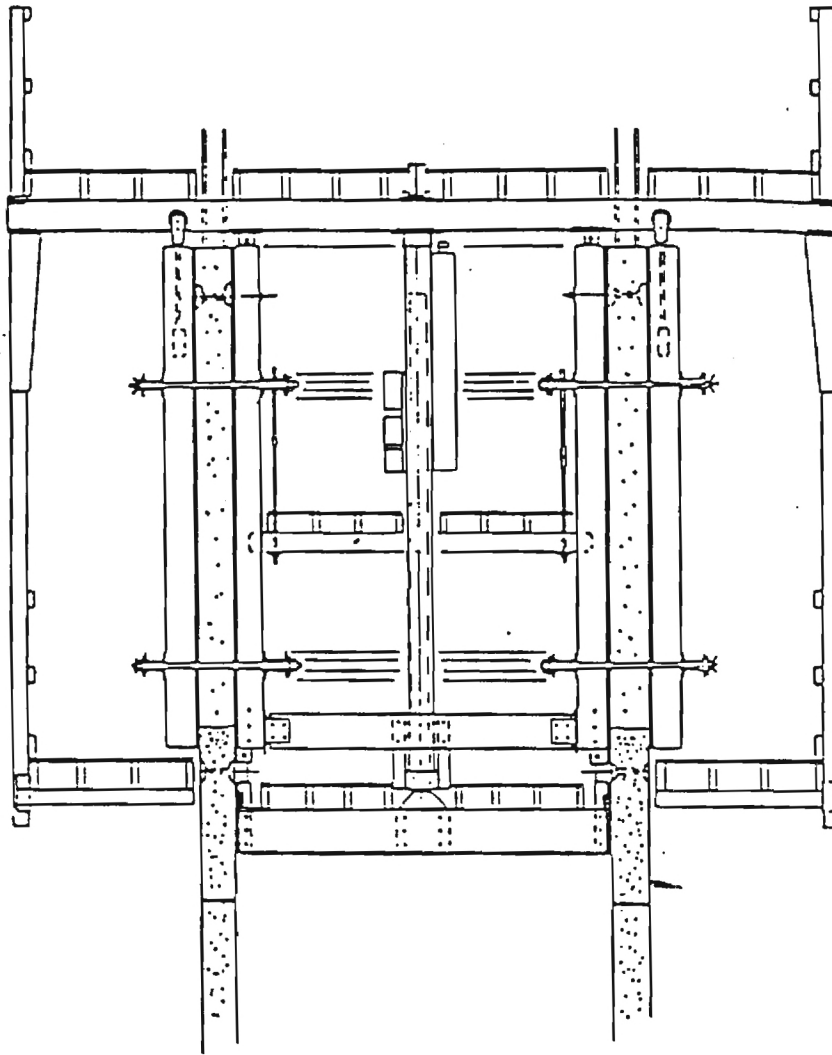


Fig. 5.14.- The Day after Pouring for a Typical Cycle, Courtesy of Patent Scaffolding

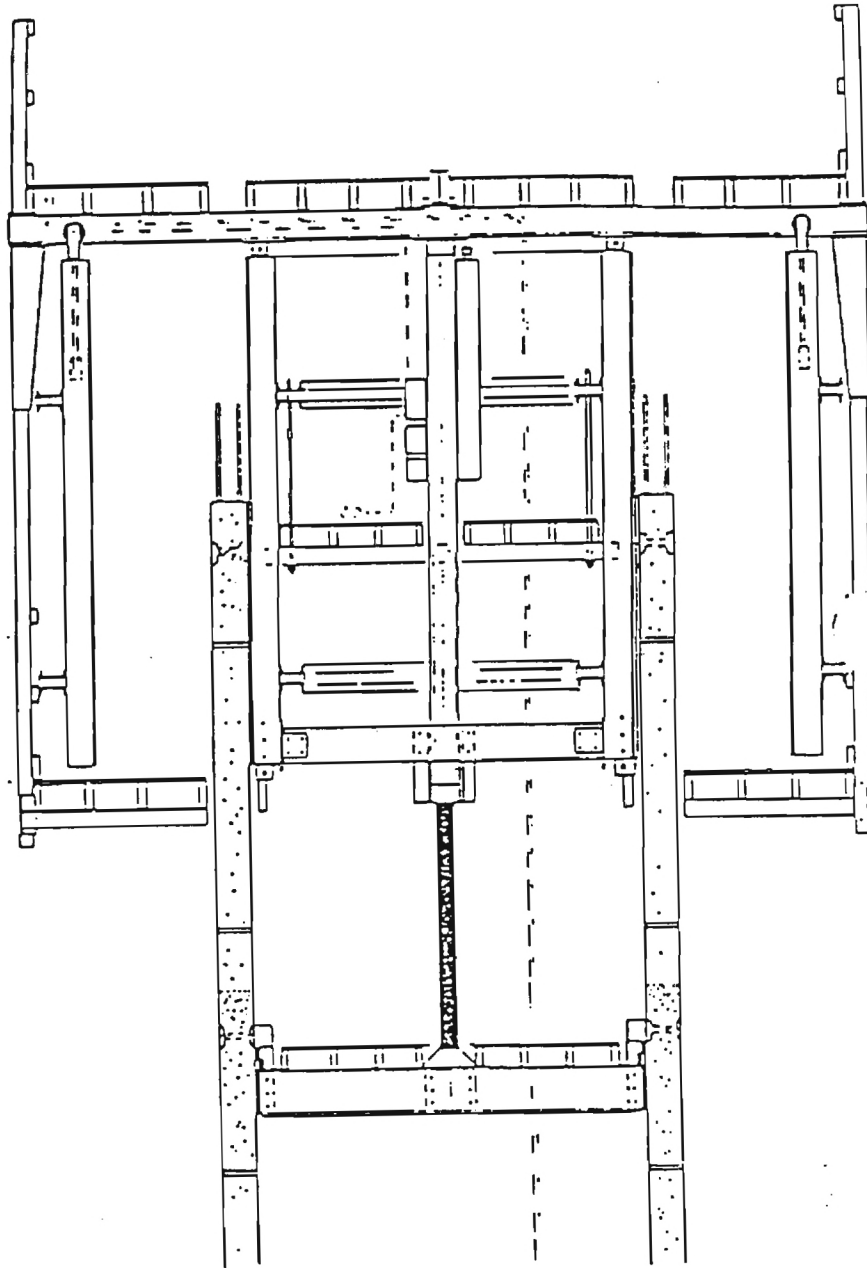


Fig. 5.15.- Beginning of the Lift for Typical Cycle, Courtesy of Patent Scaffolding

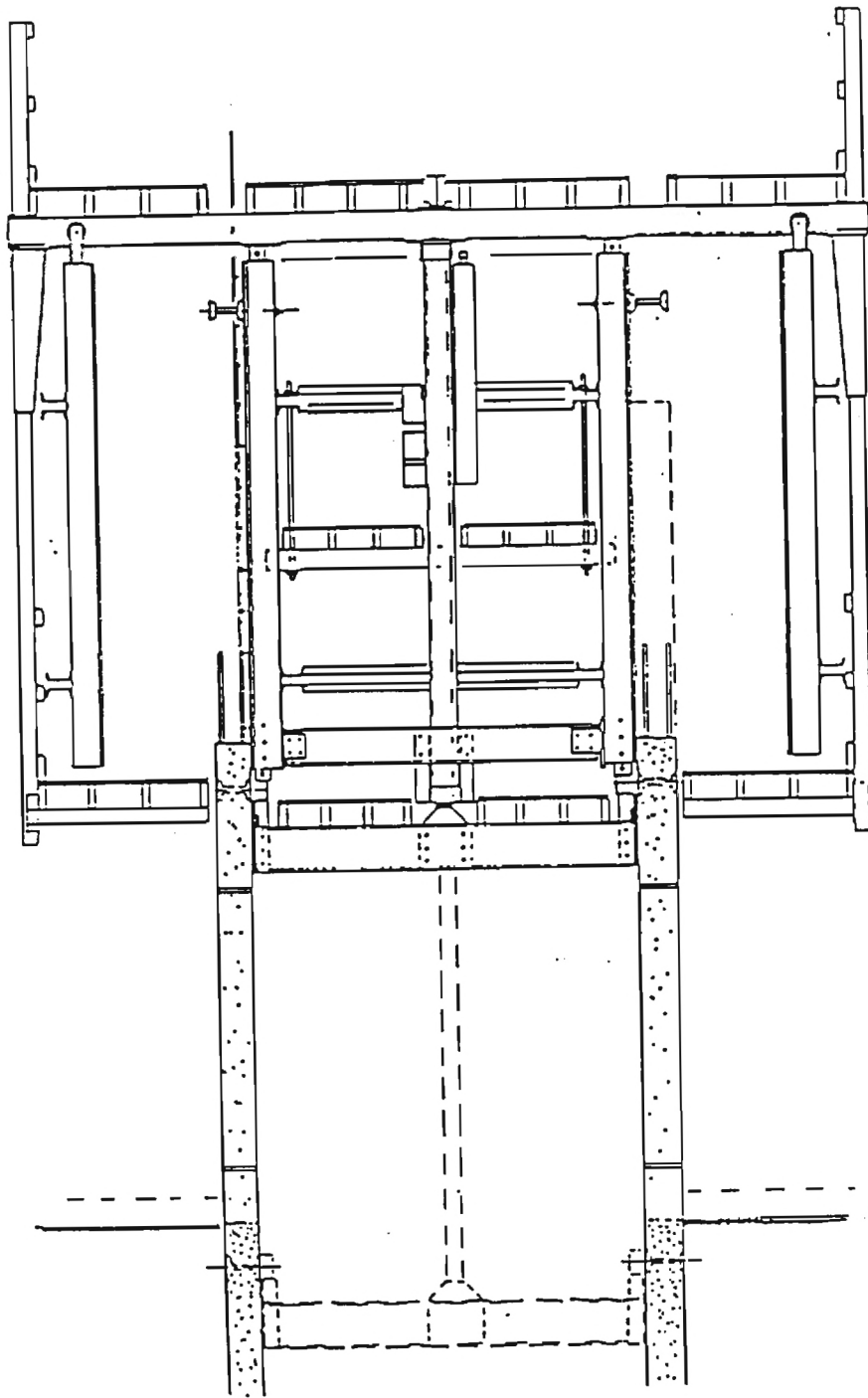


Fig. 5.16.- Next Pour Preparation of Typical Cycle, Courtesy of Patent Scaffolding

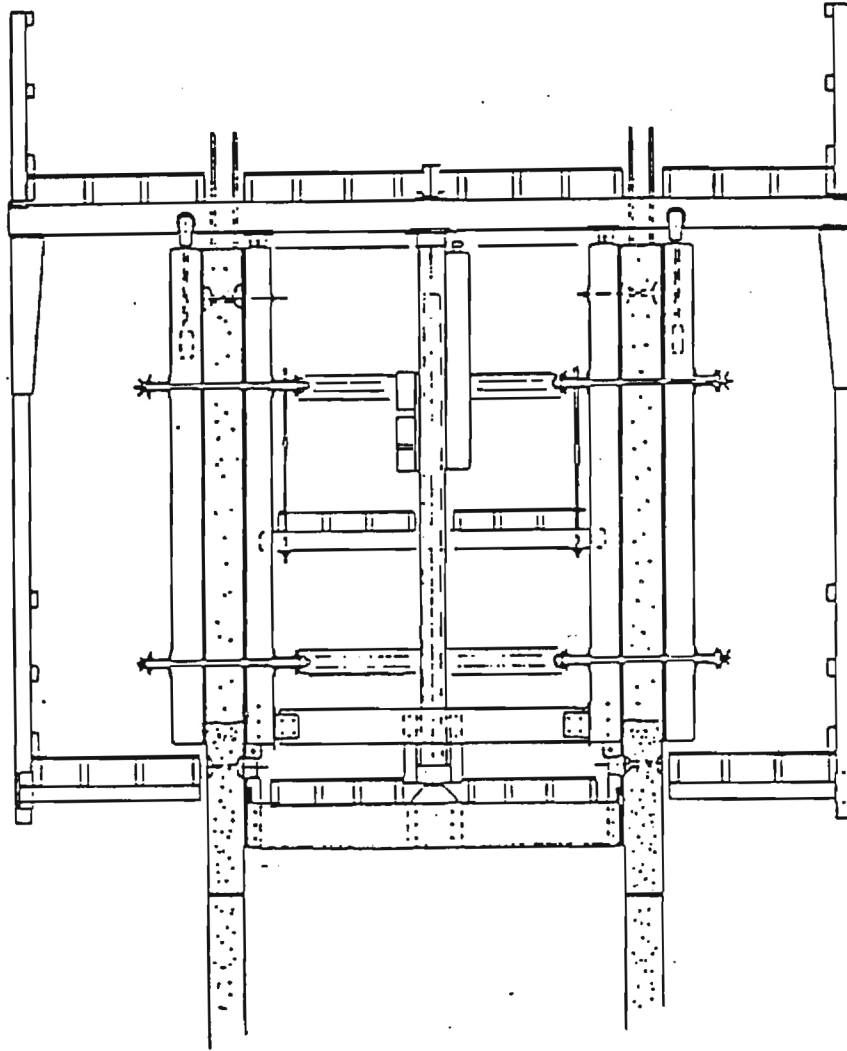


Fig. 5.17.- Forms in Ready State for Pouring of Typical Cycle
Courtesy of Patent Scaffolding

CHAPTER 6

METHODS DEVELOPED IN SLIPFORMING

Slipforming is a specialized method of construction, and because of that, each new contract has to face the perpetual problem of technical ignorance throughout the whole strata of the site staff. To overcome this problem, the specialist equipment suppliers also provide experts who can help not only in the necessary supervision but also in the operation of the equipment. Slipforming could be taken as a subcontract or alternatively the equipment can be rented in a contract on a time basis.

One of the leading contractors in the slipforming of concrete building cores in the United States is M.M. Sundt Construction Co., with bases in Phoenix and Tucson, Arizona. This firm has slipformed more than 27 structures across the country to date. This chapter will describe the method employed by them, and describes a different approach to the system, as employed by Pattent Scaffolding Co., called Self-Climbing Wall Forming System.

6.1 METHOD DEVELOPED BY SUNDT

6.1.1. Concrete Core and Structural Steel Frame

The current trend in structural systems for high rise office buildings in the United States is the combination of a concrete core with concrete on composite steel deck floor slabs on a structural steel frame. Some of the main reasons for using this combination are:

- a) With suitable foundation conditions, including a concrete core in a structural steel building is an economical way to provide structural stiffness and conveniently located mass for damping oscillations due to wind or seismic forces.
- b) The safety of the building is highly increased due to the fire and explosion resistance of the structural concrete. All fire stairs and distribution headers can be located inside the core. The possibility of a fire advancing to a higher floor is decreased if vertical ducts and chases are inside a concrete core.
- c) The economic aspects of using the concrete core are:
 - The core suppresses a substantial amount of structural steel.

- Sometimes, it is possible to reduce the required sizes of the remaining structural steel members.
- Since a major percentage of the lateral loads are carried by the core, it may be possible to reduce the complexity of the structural steel connections.
- This combination scheme lends itself to reduce the time necessary to construct the structure. With an experienced management and coordination, 3 to 5 months have been saved in buildings in the 30 to 45 stories range, when compare to competing schemes [33].

Generally the geometry and height of those cores made them good candidates for the slipforming system. Experience has shown that this system gives very good records in terms of reduced in-place construction costs, speed, and quality of construction for the structure.

6.1.2. Structure Details

The core usually contains the elevator shaft and lobby spaces, utility rooms, vertical mechanical ducts and chases, stairways and also may include restrooms. Fig. 6.1 gives a plan view of the core at the foundation. Fig. 6.2, and 6.3 illustrate details of connection between core and structural steel structures.

Generally, the thickness of the core perimeter walls is reduced at some intermediate height and also segments of the core are normally discontinued at the intermediate elevator shaft. As Mr. Pruitt states: "if the advantages of speed and economy of slipforming are to be fully realized, the designer must minimize changes in the horizontal cross-section of the concrete" [34]. The core is usually symmetrically centered in the lower levels but could become asymmetrical in the upper levels.

The slipforming system for concrete cores used by Sundt is different to the system used to construct storage silos, and they do not operate on a 24-hour per day continuous schedule. The major differences are:

- a) Sundt uses a very rigid form panel with a fiberglass reinforced plastic surface on a structural plywood substrate.
- b) A structural steel jacking grid about 10 feet above the slipform.

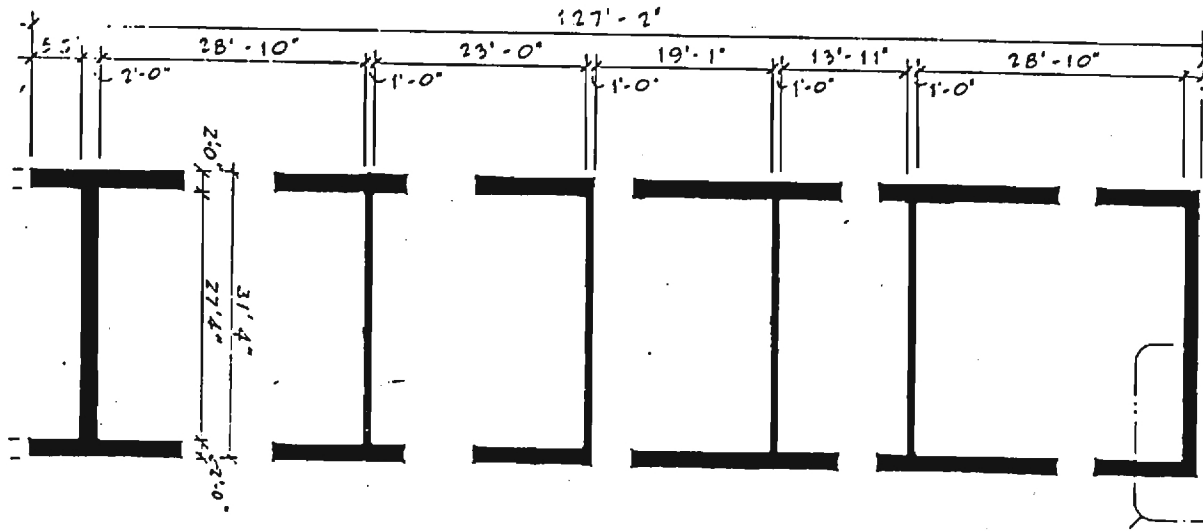


Fig. 6.1.- Plan View of a Typical Core at the Foundation
 Courtesy of Pruitt and Henry.

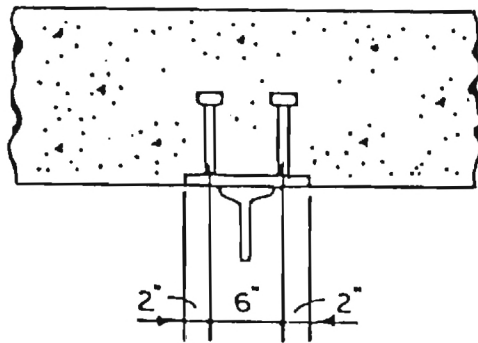
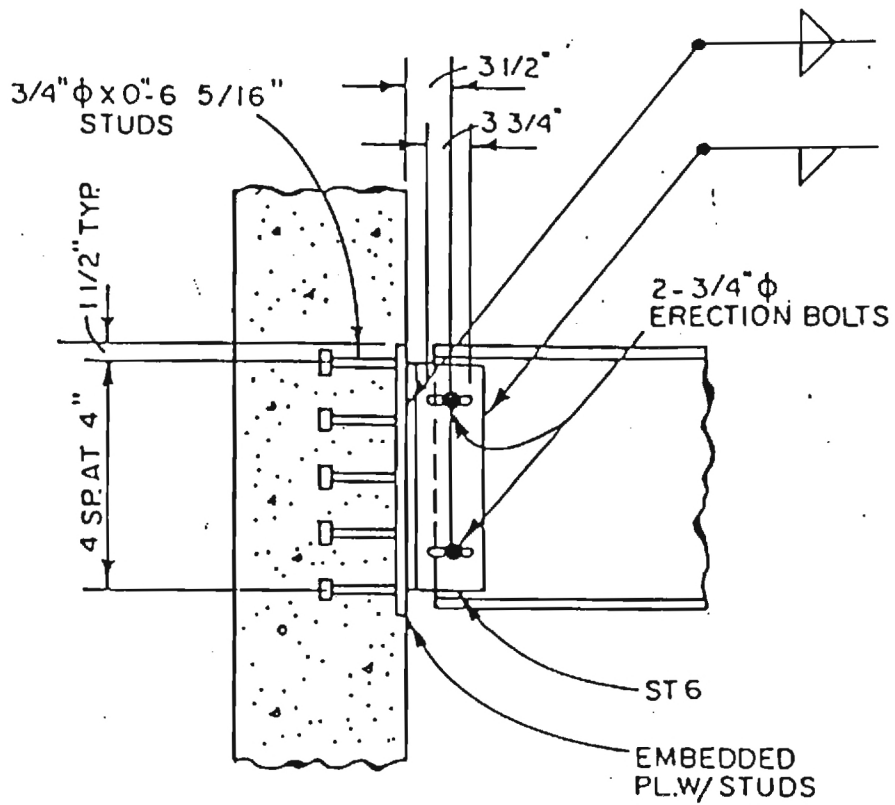


Fig. 6.2.- Typical Beam to Core - Wall Connection, Courtesy of Sundt Corporation

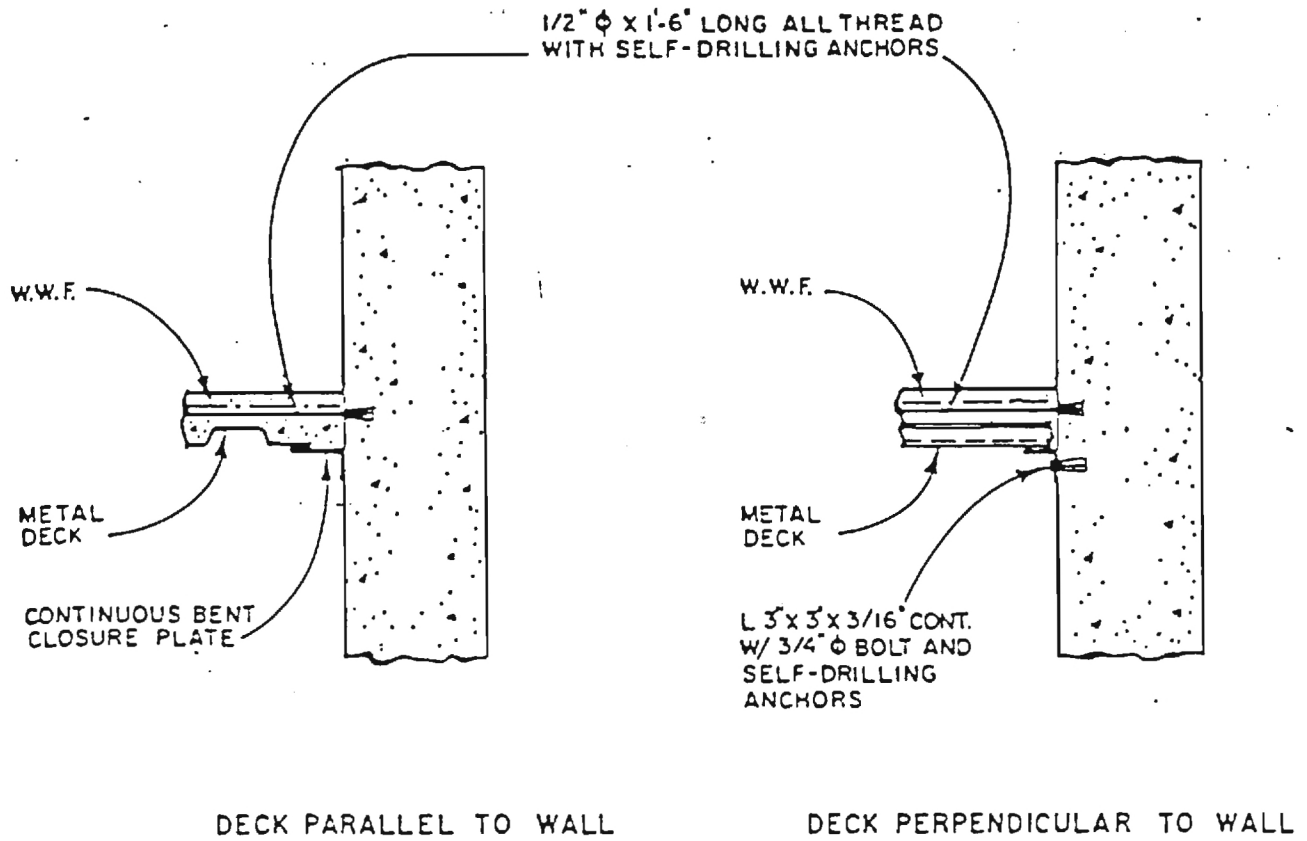


Fig. 6.3.- Typical Slab to Core - Wall Connection, Courtesy Sundt Corporation

- c) Larger hydraulic jacks (22 Ton), instead of the three ton jacks located at each joke.
- d) Rigid slipform jokes with the necessary clearance to place, tie and inspect the horizontal rebar before it is covered with concrete.

6.1.3 Construction Sequence

There are two widely used alternates to coordinate the construction of the core and the erection of the structural steel. Sundt's experience has been based on using a heavy tower crane for hoisting for the core and, frequently, for erection of structural steel.

The first alternate is to run the core construction and the erection of the structural steel simultaneously according to the following sequence:

- a) The structural steel must be available for erection before the core gets about 10 floors.
- b) The core provides lateral bracing to the tower crane as construction proceeds, which is mast mounted near to the core.
- c) Portable boom cranes, ground mounted, are used to erect the heavy structural steel elements for the lower levels, minimizing the required size of the tower crane.
- d) The structural steel erection has exclusive use of the tower crane during the day shift. The core has the tower in the evening shift.
- e) When the structure reaches typical floors and the tower crane can lift all structural steel members, the core and steel erection can proceed with the one-floor-per-day schedule.
- f) Normally the core construction is two or three floors ahead of the steel erection. Concrete is placed and formed during the day shift; it is raised by pumping or by winch powered skips.
- g) The tower crane is used on the evening shift to restock rebar, location of opening forms and cleanup [33].

The second alternate takes place when the core construction is subcontracted. In this case the core and the structural steel erection are independent processes according to the following sequence:

- a) Core construction advances independently and has full time operation of the tower crane.
- b) The tower crane is mast mounted and will use the core for lateral bracing as construction advances.
- c) The erection of the structural steel in lower levels, is carried by ground mounted, portable boom cranes while the core construction advances.
- d) Concrete for the core is hoisted by the tower crane. Cleanup, rebar restocking and relocation of opening forms are performed on an evening shift for a one-floor-per day cycle.
- e) Once the core is completed and the slipform removed, the remaining structural steel is erected by the tower crane [33].

6.1.4 Slipforming System.

As it was mentioned before, Sundt's experience has shown that typical slipforms like those employed in grain silos, powered by 3 to 6 ton jacks, are not suitable for large core work. It is difficult to maintain dimensions in a multi-celled structure, and also is very difficult to place long vertical rebar or shop fabricated rebar assemblies with a conventional slipform. Sundt has been developing a system that produces the quality and precision required by large concrete core work.

The system utilizes a jacking grid made of steel beams in which are mounted 22 ton jacks that push up on inverted 'U' shaped structural supports called "lifting yokes" that are connected to the steel grid. The grid is x-braced and acts as a horizontal diaphragm. It is also diagonally braced, which gives as a result a very rigid structure that helps to maintain in position the different components of the slipform system.

The slipforming is suspended from the grid ten feet below by three-inch-diameter (7.62 cm) jack rods, connected to standard yokes. These rods extend down into the concrete walls and act as support columns for the slipforming operation. The jacks, which have a maximum jacking speed of one inch every two minutes, use two sets of teeth to clamp on the jack rods. This system increases the safety of the system, since one set of teeth is clamped at all times during the operation.

Sometimes, larger than usual yokes are used, called "nuclear yokes" since they were developed for the construction of nuclear power plants. These yokes are spaced 20 feet (6.1 m) instead of the normal ones which are 6 feet apart (1.83 m). These yokes provide more space to locate long and massive amounts of reinforcing steel required in certain projects. The slipforming structure is made up of three working levels: "the upper deck", "the working deck", and "the finish scaffold". The following paragraphs describe the activities performed on each one of them.

Upper deck is directly supported by the structural steel jacking grid; is here where the operation and control of the jacks take place, and the installation of the jacking rods is made here also. In addition the following activities are performed at this deck:

- a) Landing, sorting and placement of vertical rebar.
- b) Landing and distribution of horizontal rebar.
- c) The concrete is delivered to this level, where it is placed into hoppers or directly into the forms below.
- d) Storage of utility items.
- e) Toilet facilities.

Working deck is in the middle level of the slipforming structure, connected to the lifting yokes. Is made up of a plywood/structural steel floor system and the four feet (1.22 m) tall form. Operations performed at this level are:

- a) Distribution, pouring and consolidation of the concrete.
- b) Placement of horizontal rebar.
- c) Placement of anchor for slab to core connections.
- d) Vertical rebar splices.
- e) Installation of embeds and blockouts.
- f) Installation of anchorage assemblies for the structural steel beams.

Finish scaffold is suspended below the working deck. According to Carlson [6]: "The craftsmen on the lower deck provide the function of finishing off the emerging concrete. Depending on the ultimate use of the structure and whether the quality of appearance is important will determine the

level of activity needed on this deck". Other activities in this level are:

- a) Strip off forms for openings.
- b) Strip off forms for keyways and dowels.
- c) Installation and welding of brackets and tees to bear the beams.
- d) Installation of the elevator lobby floor beams.
- e) Application of curing compounds to preserve the final strength of the emerging concrete. Also insulation is provided during cold weather.

6.1.5 Work Shifts

Generally the slipforming of concrete core is not a continuous task, in contrast with the non-stop operation required by building silos or other structures where cold joints are not allowed. In the case of the concrete core, there are two eight-hour shifts that perform the necessary activities to keep the operation at the usual progress of 12 to 13 feet (one floor) per day. These shifts are called day and night shifts. During the day the concrete pouring starts at 7:00 a.m., the horizontal rebar and concrete are placed. The day floor pouring is finished by 2:00 or 3:00 p.m. The emerging concrete is also finished in the areas where it is needed. The crews usually begin slipforming at the top of the longest doorway on a floor and stop at the top of the lowest doorway in the next floor.

The night shift prepares for the next day concrete placement. They clean forms and decks, hoist rebar and miscellaneous items, distribute and place vertical rebar, distribute horizontal rebar for placement on the next slip. Also install structural steel elevator lobby floor beams and install rebar assemblies for link beams between elevator lobby doors.

According to Sundt's experience, mentioned by Mr. Pruitt and Mr. Henry [33, and 34] on their paper: "the production of 13 feet (4 m) of core per day is a routine two-shift operation, even on a 152 x 38 foot (46.3 x 11.6 m) core containing 38 c.y. (95 m³) of concrete per foot (meter) of height. We have achieved routine production of 13 foot (4 m) lifts in one 8 to 9 hour shift on cores in the 80 x 35 foot (24.4 x 10.7 m) range with 20 c.y. (50 m³) per foot (meter) of height".

6.1.6. Form Removal and Safety

The removal of a slipform from a core can be a hazardous task, especially when the second alternate construction sequence is used. The removal sequence and details must be established when designing the slipforming for fabrication. The safety record for slipforming system applications is very good. One the most important safety features of the slipforming system is that it can be designed and built as a semi-permanent structure during the form assembly. It is not necessary assemble and then disassemble scaffolds, handrails, ladders, etc. for every lift of concrete. It is also possible to install fire control sprinklers and water supply risers for use by a fire pump unit in case of a fire in the slipforming system. Such systems may be required in congested, downtown areas [33, 34, and 35].

6.1.7 Cost Considerations

The cost to fabricate and erect a slipforming system is competitive with self-rising, conventional tied form systems. The cost to operate and clean a slipform system is a small part of the cost to set, strip, clean and raise any other form system. The use of slipform can reduce in-place costs and skilled manpower requirements, but the major economic reason to use the slipform system for core construction is speed without incurring in significant overtime labor costs.

Core construction operation must be coordinated and keep pace with the foundation work, material hoisting system erection and structural steel erection in order to start the installation of the elevator, mechanical and electrical systems at the earliest possible date. The system also assures that the concrete construction operation will meet the schedule at any weather condition.

Sundt's customer have experienced time savings for the total construction period of 3 to 6 months when compared with alternate building designs. The cost of the construction facilities, overheads of all parties involved in the construction, insurance, and, most importantly, interest of the construction financing, are directly related to the construction time. Reducing this time results in earlier income from the tenants and reduced risk due to unpredictable market developments.

At today's rates, the savings of reducing the construction time in one month in a \$50,000,000 construction building will approach savings of \$1,000,000.

6.2 SELF-CLIMBING WALL SYSTEM

6.2.1 General

The following paragraphs contain the description of another rapid forming system for concrete cores. The system is called Self-Climbing Wall form, and has been specially designed for core construction in high rise buildings and has been introduced by Patent Scaffolding Company, a Fort Lee, N.J. based company.

The system does not have a limit in the core dimensions; it also could be a single cell or numerous elevator shafts. The shape has no restriction either; it could be rectangular, triangular, curved or cores with wing walls. Different systems that can be utilized in combination with the concrete core: a) contains a poured in place concrete frame, b) shows a combination of concrete core and steel frame, c) is a composite steel frame and concrete deck, and d) shows a precast concrete frame.

Self-climbing construction can be approached in different ways:

Pour core separately: if the core is specially large the self-climber can be split into two independently operated assemblies to reduce both crew and pour size.

At floor levels: if preferred, the core can be formed at the same pace as the floor slab's construction, filling the wall form with concrete right after the floor slab has been poured.

A Single Unit for Two Cores: one self-climber unit can form two or more individual cores when they are close. This eliminates the need for a second control booth or two separate work crews.

6.2.2 Components

6.2.2.1 Superstructure

The backbone of the self-climber is comprised of lateral and transverse beams. It locates and supports both the gang forms and a heavy work platform. Hydraulic jacks push the superstructure to the next level, raising all forming and platform areas [28].

6.2.2.2 Forms

The forms are designed to suit any common floor height. They are hanging from the superstructure on a trolley system in

order to have an easy opening and closing. The forms are faced with plywood sheets for a smooth finish; but also may be overlaid with form liners or rustic scripts to create special finishes.

6.2.2.3 Platforms

There are two platforms in the system: the level scaffolding platforms hang below the forms to create comfortable and efficient working spaces. The platform at the top of the superstructure provides a work deck from which to pour concrete, and also gives a storage area for reinforcing steel and other equipment, simplifying the material handling. All platforms travel with the forms when the lift is performed. Nothing is dismantled between raises, which is an important safety consideration. At the same time, because of this safe working environment, the productivity does not suffer as the core's height increases.

6.2.2.4 Jacks

The jacks are mounted behind the forms, all of them are readily accessible. Each jack is self contained and has its own pump and reservoir system to allow for individual control during a raise. Since they are powerful, few of them are needed for the operation.

6.2.3 Typical Cycle

A new cycle starts the day after pouring. Workers remove the ties, roll back the outside forms and release the inside forms. They also remove any attachments to the form faces.

The operator activates the hydraulic jacks from a central control point on the platform, and the entire self-climber begins raising to the next level. The system is kept level during the raise by adjusting individual jack speeds and monitoring the water levels. The raise concludes when the bottom of the forms overlap the new cast wall. Overlapping and attention to levelling will guarantee alignment for the next pour.

Once the forms get to the new position, the next pouring preparation starts. Crew members clean and oil the form face and also insert any necessary box-outs. Once the forms are cleaned, the work starts on placing and tying the reinforcing steel. As workers finish each section, they roll the forms in. Other crew workers check vertical alignment and reposition the adjustable screw jacks at the form support bracket.

The forms are generally designed to take a full liquid head, which means that concrete can be poured as fast as it is available [28].

6.2.4 Work Environment

Contractors are able to assemble and operate the self-climbing system with their own concrete forming crews. Many forming tasks related to self-climbing system are already familiar to an experienced crew. That is why the learning curve is really short, no more than three lifts, according to Patten's experience.

The weather is not an obstacle for the system, since the top platform acts as a roof in case of rain. During cold weather, the system can be enclosed and equipped with heaters assuring the normal construction process.

CHAPTER 7

DESIGN CONSIDERATIONS

This chapter will cover some of the facts that must be considered when the slipforming structure is being designed, design loads for the decks, jack capacities. Also includes some of the considerations for the form construction. Since the concrete mix is a very important element in the slipforming operation, this chapter will also describe some information about the concrete set control. Finally, it will contain the tolerances required by the system.

7.1 DESIGN OF THE SYSTEM

7.1.1 Lateral Pressures on the Formwork

The essential feature is to design a system that is strong enough to cope with the pressures created. The lateral pressures exerted by freshly poured concrete on the formwork are enormously and unpredictable variable. The pressures are a result of concrete consistency, weather conditions, type of formwork face, wall thickness, rate of concreting, type of compaction, initial set and amount of reinforcement.

Assuming the slide is slow, the lateral pressures will try to separate the formwork from the concrete at a distance h_1 as it is shown in Fig. 7.1. In the contrary if the speed of slide is high the separation will take place at h_2 . Then h_1 or h_2 provides the contact height at which the effective pressure head of the concrete acts on the formwork. It is this factor which determines the pressures and frictions, regardless of any effect due to increase wall thickness.

The nature of the formwork face, specially its permeability and surface condition, has a great deal to see with the pressures that are developed over them. With the earlier used timber forms, certain amount of grout passes through the forms, thus reducing the lateral pressure and increasing the friction. In the contrary the actual plywood faces are less permeable, which results in a higher lateral pressure and less friction.

There are several methods to calculate these pressures:

a) Bohm's Method

It is based on the fact that pressures on the formwork are grater at low speeds. Calculations are based on a sliding speed of 4 inches per hour and a separation point 23.6 inches (60 cm) below the uppermost level of new concrete. Bohm

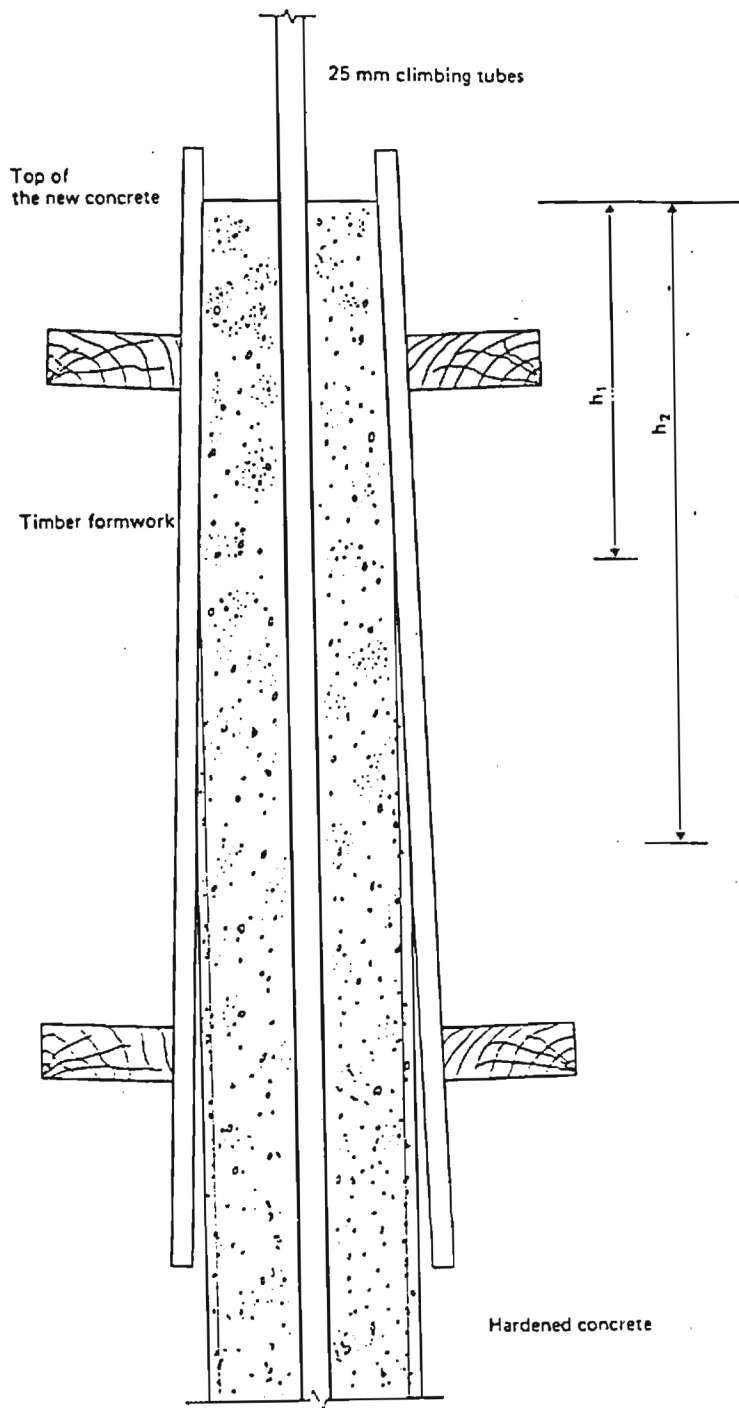


Fig. 7.1.- Section Indicating Formwork Batter,
 Courtesy of Batterham

suggests a setting time of one hour, producing a resulting force of 280 Kg/m for D acting 14 inches (35.5 cm) down from the top; as can be seen in Fig. 7.2.

b) Nanning's Method

Nanning assumes a parabolic pressure distribution over the depth of the effective concrete cross section, giving a resultant force of 375 Kg/m for a head of 3.28 feet (1 m). This applies to slow sliding speeds only. Fig. 7.3 illustrates the distribution of forces according to Nanning. The effective depth h can be calculated by using the equation:

$$h = 2a = 2 V_b t_v$$

Where: t_v = Setting time of concrete; V_b = Rising speed of formwork; and $a = 0.5 h$. The resultant horizontal force per meter is determined by the equation:

$$P_h = \frac{2}{3} (V_b t_v)^2$$

c) American Regulation

This formula gives a way to calculate the pressure exerted on sliding formwork at speed of 15.74 inches/hr (40 cm/hr) with a concrete temperature of 40°C and a formwork height of 4 feet (1.2 m). The resultant force of 1,100 Kg/m was obtained by using the following formula:

$$P = C_1 + 6000 R/T$$

Where: $C_1 = 100$ (coefficient of vibration); R = speed of formwork in ft/hr; T = temperature of concrete in °F; and P = lateral pressure in lb/ft².

The lateral pressure can be calculated by any of these methods; also the position of the resultant horizontal force can be obtained. With this information the formwork is designed in such a way that meets these forces [3].

Batterham [3] states that a series of tests were carried to investigate the general effects of lateral pressure and friction on the formwork. The conclusion of these experiments was that none of the above methods to calculate lateral pressure was accurate enough. In general they stated values for lateral pressure and friction that were too low

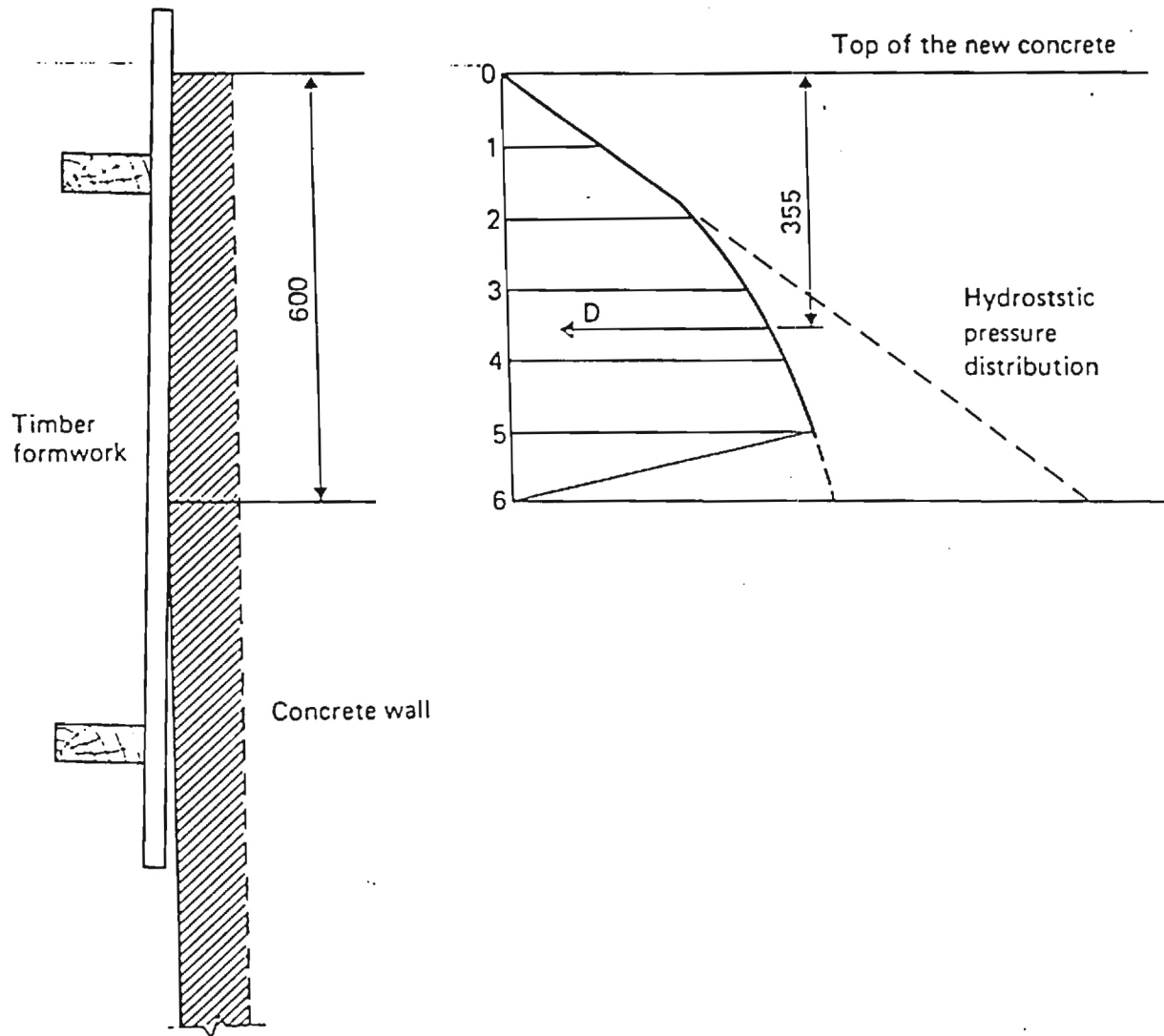


Fig. 7.2.- Formwork Pressure Distribution according to Bohm
 Courtesy of Batterham

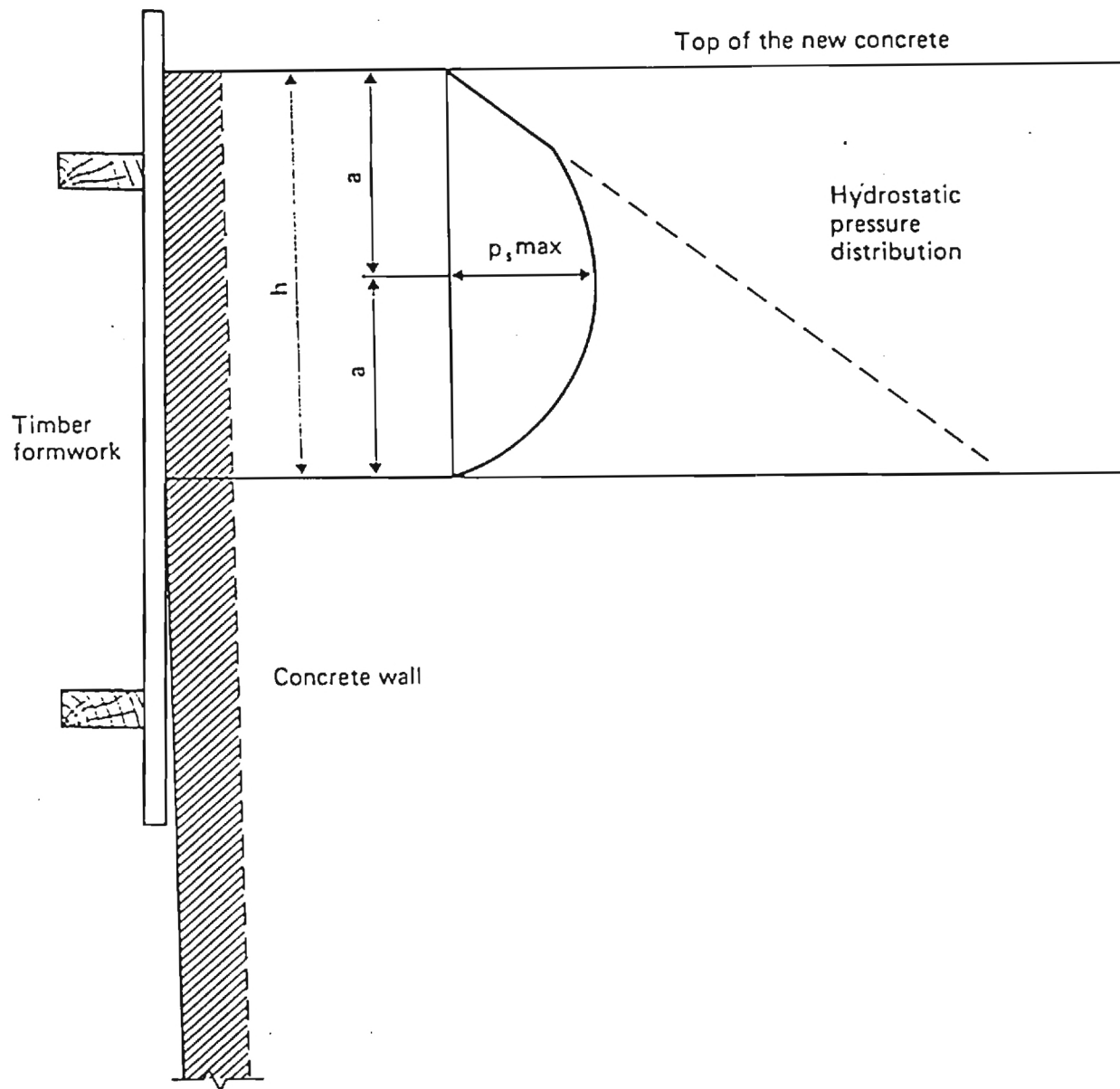


Fig. 7.3.- Formwork Pressure Distribution according to Nanning, Courtesy of Batterham

compared with the ones obtained in the laboratory; with high sliding speeds they become more acceptable.

As it was said earlier the effective head of concrete, which determines the lateral pressure exerted over the formwork, is affected by the depth of vibrator action, concrete setting time and sliding speeds. Concrete compaction is not predetermined by design, it ranks high in the list of key considerations for good quality concrete and has to be carried out by an experienced operator. When concrete is lightly vibrated it will detach itself from the formwork when it is strong enough to carry its own weight; then the effective head is determined by initial set. On the other hand, with excessive vibration the energy produced will seriously affect the already setting concrete. This will produce unnecessary new pressures and may result in a weaker, less durable concrete [3].

7.1.2 Design Loads

Sundt Corporation has come out with some standard design loads for the different components of the slipform structure. They are as follows:

Dead Load	10 lb/sf	All Decks
Live Load	50 lb/sf	Top Deck
Live Load	50 lb/sf	Middle Deck
Live Load	30 lb/sf	Finishers Deck
Friction Load	200 lb/lf of wall	(100 lb/lf per side) includes both sides.
Equipment Load	40 lb/lf	Jacks, yokes, etc.
Steel Beam Load	50 lb/sf	Assume for design.

7.1.3 Jack Capacities and Considerations

The following factors should be considered:

Heede R-72 Jacks	(25 Ton Jacks)
Jack Capacity	48,400 lb @ 100% efficiency
Jack Capacity	36,300 lb @ 75% efficiency (Heede Recomm.)
Number of Jacks	Area of core/175 sf (Heede rule-of- thumb)

Some considerations about the layout of the jacks have been made:

- a) Locate jacks in such a way that do not pass through openings, column steel or similar items. The maximum unbraced length of a jack rod should be approximately 2 feet.
- b) Maintain a pressure of 1400 - 1500 psi under normal conditions.
- c) The load per jack should be uniform.
- d) Allow for versatility of rebar storage.
- e) It is recommended the use of type 6 yoke legs (36-inch clearance from deck) on the main core walls. Greatly facilitates placement of blockouts, weld plates, and rebar beams. Type 9 yoke legs (20-inch clearance from deck) resist deflection better though. The spacing of type 6 yokes should be limited to 6'-0" o.c. and type 9 yokes to a maximum of 7'-0" o.c. [44].

7.1.4 Concrete Placement Factors

The following factors should be considered:

- a) Determine the number of crane movements, hoisting capacity and speed.
- b) Check the number of crane tie-ins and location, for interference with weld plates, blockouts, etc.
- c) Check free standing height of crane and maximum height above tie-in for schedule purposes. The hook height should not exceed more than 100 feet above upper deck. Wind and decreasing perception of operator will slow pouring operation significantly above this height.
- d) It is important to evaluate the most economical concrete conveying system: Pump, concrete buckets with elephant trunks, hoppers with elephant trunks or hoppers and buggies. It is recommended the use of hoppers and buggies since crane time is more effective, concrete placement is quicker, clean-up at night is reduced considerably and interference with ironworkers is minimized [44].

7.1.5 Lifting Forms

The following factors should be considered for the lifting forms:

- a) Fabricate all blockouts $3/4$ "-1" narrower than wall dimension and all sleeves 1" narrower than wall dimension. It is also recommended the installation of guides for typical blockouts, and those blockouts that are to slip with the form must tapered.
- b) Remove alternate jack rods, if done during the construction process, as a precautionary measure.
- c) Minimum of two lasers should be maintained at all times. Form should also be checked daily with an instrument for plumb and alignment.

7.2 CONCRETE SET CONTROL

The set of the concrete is an important issue in the slipforming construction. The set is affected by ambient temperatures, placing operations and admixture selection. The rate of rise of a slipform can be controlled from a low speed of 3 inches/hr (8 cm) to a high speed of 18 inches/hr (46 cm). Once the desire rate of rise is given, which depends on the supply, handling and placing of every project, the technician can supply the correct concrete mix to meet that rate. Variations on this rate can be introduced at any time in the operation allowing slowdowns where inserts, special steel or special conditions require it and speedups where conditions are optimum for straight forward operations.

The concrete engineer or technician can introduce these different rates of rise considering the following conditions:

- a) Correlation between concrete setting time and concrete slipping time.
- b) Correlation of concrete setting time and form height.
- c) Mix design.

7.2.1 Correlation between Concrete Setting Time and Concrete Slipping Time

According to Mr. Fisher, there is a correlation between the concrete setting time as measured by the penetration resistance method (ASTM C 403-70) and the concrete slipping time and besides that there is an optimum concrete setting

time that produces the greatest benefits in the slipforming process [14].

Different mixes were studied by Fisher, as used in the slipforming, including plain concrete, set-retarder concrete and set-accelerated concrete. The studies indicated that concrete was slipped at any time after the concrete had reached a certain degree of set as determined by the penetration resistant test, even as low as 15 psi (1.05 Kgf/cm²). An optimum range was obtained by correlating the effects of various degrees of set on such as factors as ease of slipping and ease of finishing. This range is 25 and 100 psi (1.75 and 7.0 Kgf/cm²). Fig. 7.4 illustrates the setting time chart for plain concrete mix, the arrow indicates optimum time for slipping.

The concrete that was slipped below 15 psi (1.05 Kgf/cm²) fell out beneath the edges of the slipform. Concrete slipped in the setting time of 100 to 500 psi (7.0 to 35.0 Kgf/cm²) presented minor difficulties. Concrete that has been slipped above 500 psi (35 Kgf/cm²) which is defined as initial set under the penetration resistance method, showed scoring of the wall surfaces, difficulty in surface finishing, difficulty on slipping and was not generally favorable for methods of slipforming where dimensional changes in wall thickness are used.

7.2.2 Correlation of Concrete Setting Time and Form Height to Rate of Rise of Slipforming Operations

It is relatively simple to determine the time at which the slipform will be passing the concrete, by dividing the desire rate of rise by the total height of the slipform. Then concrete entering a form of height H moving at a rate R per hour comes out of the form in H/R hours. At this time, in order to get a good concrete quality, the degree of concrete set should be 25 to 100 psi (1.75 to 7.0 Kgf/cm²) by the penetration resistant test method.

Fig. 7.5 shows different setting times when varying the percentage of retarder on trial mixes at job site. When faster or slower setting mixes are required, the technician can make the necessary changes in the mix proportions. The technician should remember to supply the changes when the slipform is approaching the desire height. When several changes have to be made, they should be done in gradual steps to avoid drastic changes in the concrete setting time [14].

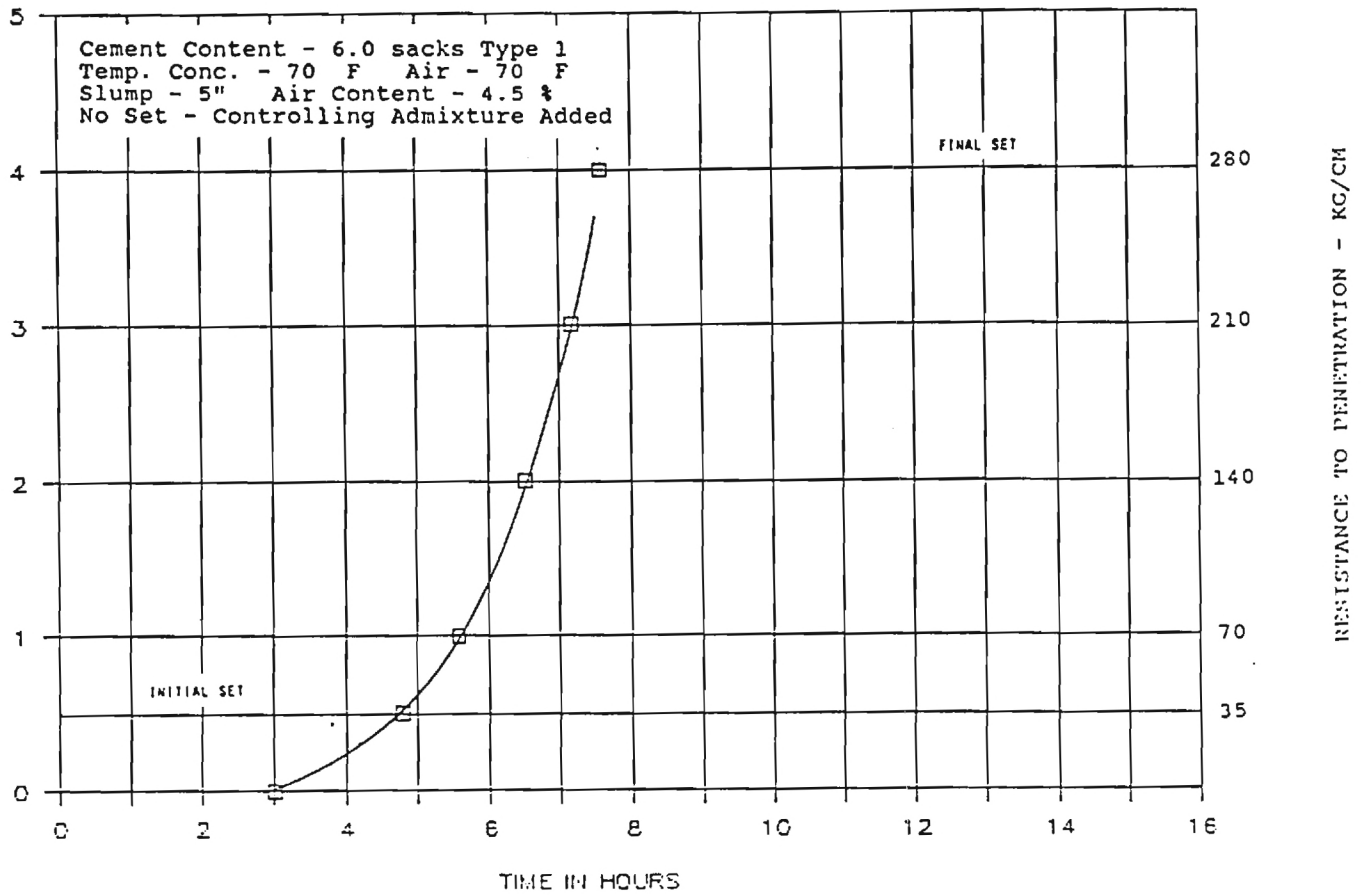


Fig. 7.4.- Setting Time Chart for Plain Concrete Mix,
 Courtesy of Fisher

RESISTANCE TO PENETRATION - P.S.I.
(Thousands)

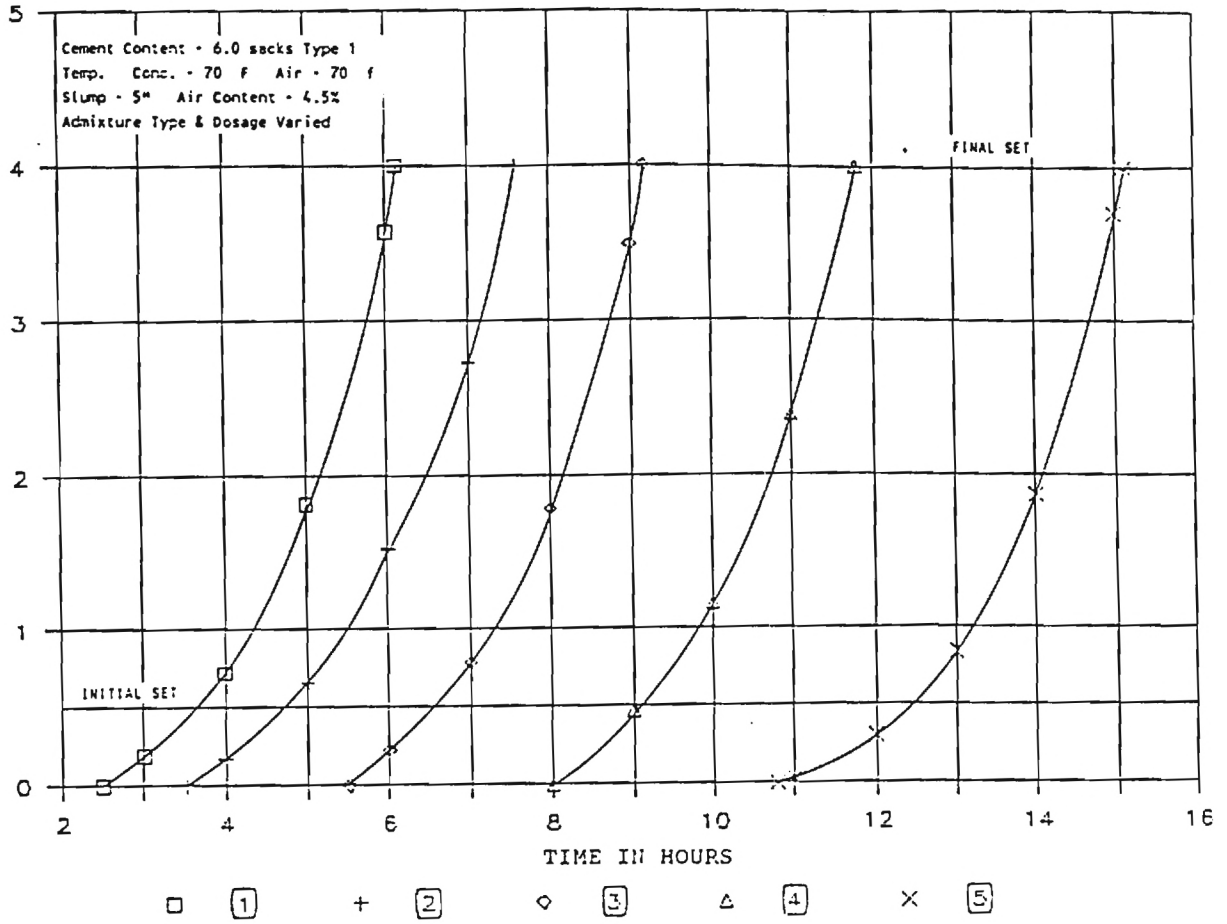


Fig. 7.5.- Preliminary Studies to Determine Effects of Admixtures on Setting Time of Concrete. Courtesy of Fisher

Empirically, Fisher [14] developed the following information that correlates setting times vs. the predicted rate of rise.

FINAL SET OF CONCRETE (hr)	PREDICTED RATE OF RISE OF SLIPFORM IN " (cm)
5	18 (46 cm)
6	14 - 17 (40 cm)
8	10 - 12 (28 cm)
10	7 - 9 (20 cm)
14	5 - 6 (14 cm)
18	3 - 4 (9 cm)

7.2.3 Mix Design

Sundt's experience has been to use very rich mixes for concrete strength to 7500 psi. Pruitt and Henry [33, 34, and 35] state on their paper that: "We recommend a lower cement content limit of 500 lb/cy (290 Kg/m³), attention to good aggregate size distribution, limit maximum aggregate size to 0.20 to 0.25 times the minimum space between rebars, use of retarders and accelerators to control set rate (no calcium), an upper temperature limit of 90oF (32oC) for concrete going into the form and enlightened slump control and avoiding superplasticizers".

Flyash must be used with extreme precaution on slipform concrete mixes. The mix designer must conduct an extended program to find compatible ratios between the cement, flyash and admixtures, in order to eliminate the possibility that concrete will attached to the form. Additionally, all materials incorporated into the concrete must be strictly monitored for continued compatibility.

7.3 TOLERANCES

Since absolutely accuracy is not possible, the structural designer must provide for flexibility on the dimensions and also in the connection points. The vertical alignment tolerances for a concrete core must be coordinated and compatible with the tolerances and specifications established for the fabrication and erection of the structural steel. The tolerances should anticipate that the structure may move horizontally in any direction at any time during the concrete construction operation.

The tolerances should limit the rate of horizontal movement and the maximum departure from plumb throughout the height of the structure.

The typical tolerances for Sundt's recent projects are:

- a. Variation from Plumb

Rate of departure from plumb in any direction.	one part in 300
Out of plumb in any direction up to at any point	1.5" (38mm) max 500 feet (152m)

- b. Wall Thickness

Maximum from specified	-1/4" to +1/2" (-6mm to +13mm)
------------------------	-----------------------------------

- c. Variation in Location of Embedded Plates

Horizontal and Vertical	+2" (51mm)
Maximum embedment from face of wall	1" (25mm)

- d. Sleeve Location and Size

Horizontal and Vertical	+2" (51mm)
Pipe or Duct Clearance	2" all round

- e. Openings

Heads	-0" + 3" (76mm)
Jambs	-0" + 1" (25mm)
Sills	+/- 1"

CHAPTER 8

CONSTRUCTION CONSIDERATIONS

Slipforming has many advantages, as it has been explained in earlier chapters, but to obtain a structure that meets the critical tolerances requires an extensive experience in the slipforming construction operation. During this operation, the constructor has to deal with different inconveniences that sometimes complicate the performance of the project and attempt the core not to meet the established tolerances.

This chapter will discuss some of these construction problems and the way they have been solved in order to achieve a structure of a good quality and that meets the specifications.

8.1 PLUMB

Keeping the plumb of the core is one of the greatest problems of the slipforming construction. First, this was accomplished with an interconnected water level system and specially made 45-pound plumb bobs suspended by piano wire. According to Sundt's practice, two engineers went down to the ground and double-checked the plumb bobs with a transit about every two hours. In recent projects, the plumb bobs and the transit have been replaced by vertical lasers which guide the core within strict tolerances. The lasers are set up at ground level in opposite corners of the core. In the other two corners of the core, the slipform pulls up long surveyor's tapes which are anchored at a set elevation near the bottom of the core. These tapes are used to double-check the slab elevation and the levelness of the slipform.

The lasers are aimed at clear plastic targets located in holes cut in the middle working deck. By checking where the lasers hit these targets, the jacking operator can find out if the core is out of plumb or rotated. Also every two hours the operator lays a piece of paper on the plastic target and records the spot where each laser is hitting its target. Once the operator realizes the position of the core he can make the necessary corrections to keep the core plumbed.

8.2 LEVEL

The vertical level is very important to determine the location of embeds, sleeves and blockouts. Instead of three workers with a transit and measuring tapes, laser is actually used for this purpose. With laser technique, one person can

make most of the measurements. It takes a couple of steps to mount the whole system and put it to work. First, a horizontal laser is mounted in one of the jack rods above the upper deck. It rotates and creates a level plane of light that hits the vertical rebar at some elevation. Then an Electronic Distance Meter (EDM) is mounted on another jack rod pointing to the ground and measuring its own elevation. With a tape, field engineers measure the vertical distance between the laser and the EDM. With this information they mark the elevation of the slab on the vertical rebar, simply measuring down from where the laser hits the rebar and marking the spot with a red tape. To record permanently the slab elevation at casting time, a field engineer marks it on a vertical steel channel embedded in the face of the core.

Once the upper deck has risen above the red tape, workers on the middle deck determine the vertical location of embedded items by measuring up or down from the red tape. In order to make it clearer and avoid mistakes, these locations can be marked on vertical rebar by different color tapes. According to Mr. Pruitt [8], Sundt's practice is: "Yellow for embeds, green for sleeves or door blockouts, blue for mechanical blockouts, orange for slab keyways, and white for the top of the day's placement".

The horizontal location of embeds is done by driving bolts or nails into the middle deck along the wall forms. If similar items are used at different elevations, workers install bolts and paint them with the appropriate color. If only one item has to be installed at that horizontal location, double-headed nails can be used.

8.3 REINFORCING STEEL

Since the core also takes lateral loads exerted over the structure (wind, earthquake, etc.) of the building, it generally has large amounts of reinforcing steel. The handling of this reinforcing steel sometimes complicates the process, and that is the reason why some considerations must be taken by the rebar detailer in order to avoid them:

- a) Long runs of horizontal rebar must be placed after the cross-beams of the slipform yokes have passed the bar position.
- b) The elements that held the vertical rebar in position, (sliding templates, hairpins and through-the-wall ties), must allow placement without bending the verticals out of position.

- c) The slipforming structure lends itself to the use of shop fabricated assemblies. These assemblies can be used in walls to minimize the amount of steel that has to be assembled on the slipforming; improving placement position, reducing amount of labor required on the slipforming and saving labor time lost due to vertical transportation of personnel to and from the slipform.

8.4 CRANE OPERATION

The crane is a basic element in the slipforming operation; without it the whole process has to be stopped. According to Chris Gray, Project Manager of the IBM Tower in Atlanta [18], the slipform of the tower was stopped by three days due to the failure of the tower crane.

A single crane can provide the necessary materials to keep the process going; sometimes two small cranes are used instead of a big one. On large structures more than one device is better. It can consist of a crane, either mobile or fixed, a powered independent man cage lift and on occasion a powered hoist set on the platform that pulls up a concrete bucket into a hopper. Due to safety reasons, normally a duplicate system is required.

As an example, during the construction of the IBM Tower in Atlanta, initially two "Favco Kangaroo" cranes were used. During the construction, soon one of the cranes was blocking the entrance to the site and the other crane were inside the building and interfering with the construction. Then the cranes were changed by a mammoth "Lieberr 200 HC" erected in the center of the building. This decision not only simplified the handling of materials but also made the work go much more quickly.

8.5 CONCRETE HANDLING

Concrete brought up by whatever means is usually stored in hoppers and distributed by chutes or occasionally by direct discharge from a crane bucket. It is important that the placement be continuous and in small lifts to guarantee that fresh concrete will be available to bond with the new concrete lift, in order to insure structural integrity. The form should be kept filled close to the top to insure uniform setting as it passes below the form.

Decks must be kept clean not only for safety reasons but to guarantee that old concrete mixes in with the new that is being poured. The vibration is done manually and sometimes is complicated because of the big amount of rebar that the core has, specially in the lower levels.

8.6 BLOCKOUTS

Provision for concrete horizontal slab or platforms can be made by blocking with wood or styrofoam void forms an area containing bent dowels to allow the passage of the slipform. Later it can be bent out to provide the proper length of lap for the slab or beam. Well spaced steel is required in these areas in order to take advantage of slipforming, otherwise the rate of pouring will be slowed to accommodate the placing of these elements.

Four feet height blockouts have been regularly used which are the same height of the forms. They are lighter and smaller than conventional ones, which allow them to be installed and removed by hand from the work deck.

Careful placement and vibrating procedures on the concrete deck is important so that the repair and patching of the concrete will be minimized, especially at corners of the blockouts. Also, attention to good form surfaces is important, specially when fiberglass is used [6].

According to Chris Gray, one of the biggest problems they had in the IBM Tower was trying to maintain the position of the non-typical blockouts. He also stated that if he were to build another building with this system, he would require a person to be in charge of inspecting them daily. Also the embeds were a problem because it was difficult to control the face of them [16].

8.7 WEATHER

Control of the concrete temperature and/or the use of retarders is recommended for hot weather operations.

Slipforming lends itself to cold weather operations. The entire form can be enclosed with a fixed-in-place perimeter wall which goes from some point above the upper deck to the bottom of the finish scaffold as shown in Fig. 8.1. The heat from the water-cement reaction can be utilized to heat the enclosed area and external heat can be added if necessary. Generally propane and/or electric heaters are installed to provide the additional required heat.

Insulating blankets or shields can be suspended below the finish scaffold, for a distance of 25 feet, to protect the exposed concrete. A recent innovation has been the application of a sprayed-on curing and insulation compound for protection after the concrete is exposed below the finish scaffold level.

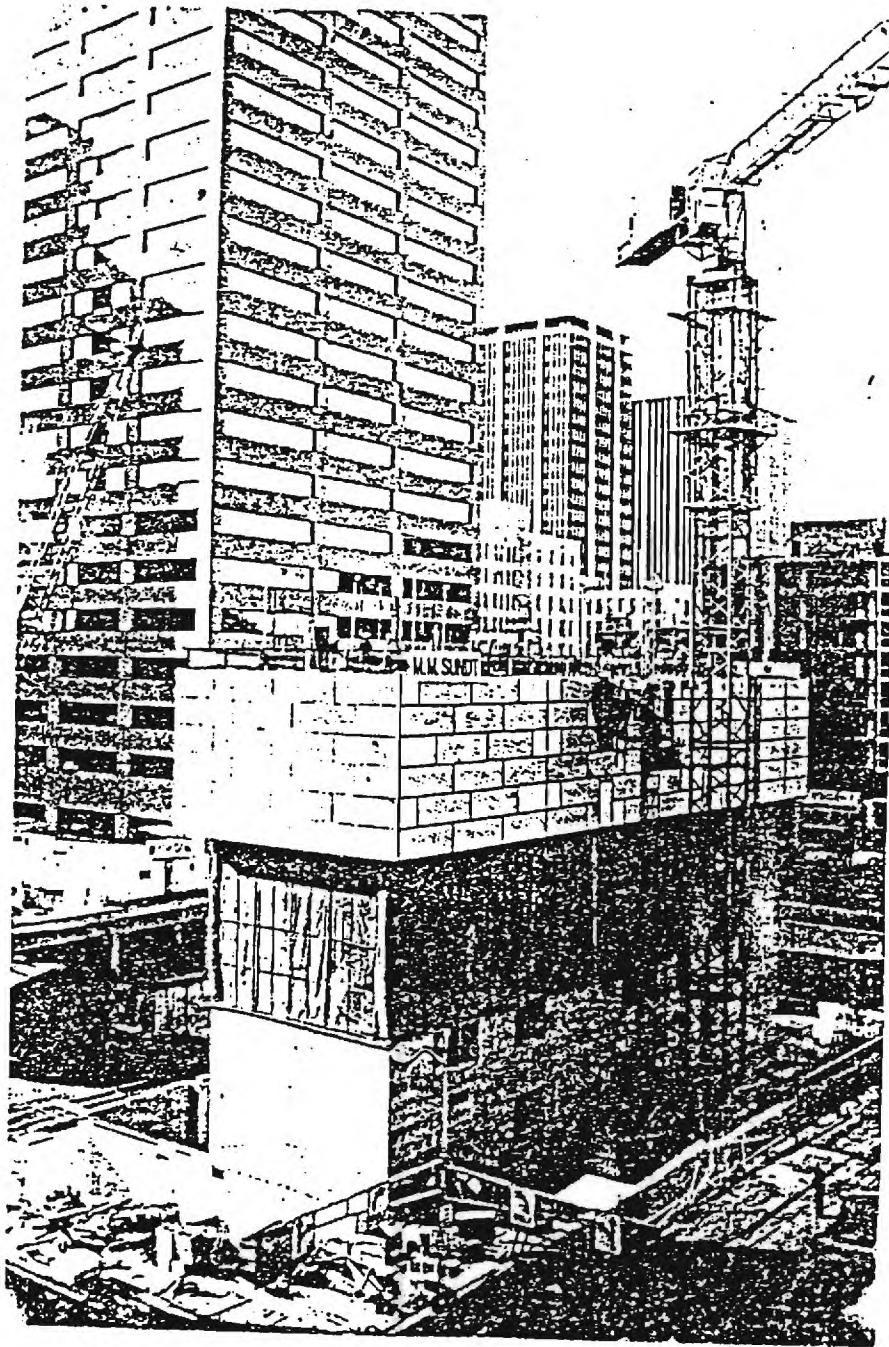


Fig. 8.1.- Cold Weather Operation, Courtesy
of Rocky Mountain Construction

According to Sundt's experience this allowed them to maintain its one-floor-per-day pace on all working days. When the outside temperatures drop below 10oF all work has to be ceased because curing temperatures inside the slipform can not be maintained.

8.8 JACK RODS

As it was stated in an earlier section, the jacking rods are steel channels embedded in the concrete that give support to the whole slipform structure. These rods are installed with steel sleeves in order to reuse them once they have been recovered. As the top of the rod is reached it is pulled out, the void is grouted, and a small metal plate positioned over the grouted hole. Another sleeve is placed on the top of it and the same section of jacking rod is used.

In the IBM Tower these rods were recovered, since they cost \$2.00 per linear foot. The tower crane was not used to recover them. A far less expensive reverse hydraulic pump was used. Work crews pulled each jack rod out of its sleeve in staggered order, to insure that only one or two jack rods were being reset at any one time.

CHAPTER 9

MICROCOMPUTER SIMULATION

Simulation of the IBM Tower construction was performed using MicroCyclone simulation program [17]. Simulation provided a clearer understanding of the slipforming process. The IBM Tower was constructed at an average rate of 0.9 floors per day, and the simulation results indicated 0.96 floors per day.

The elements of the network diagram shown in Fig. 9.1 are described in the following section:

- Node 1: QUE node, concrete is available for utilization, necessary to complete the cycle counting each cycle as one floor.
- Node 2: QUE node, Top crew is available.
- Node 3: QUE 3, Tower crane is available.
- Node 4: COMBI, Crane takes the concrete and steel reinforcement to the top of the form and is unloaded by the top crew.
- Node 5: NORMAL, The top crew installs the vertical reinforcing steel for core walls.
- Node 6: NORMAL, The top crew empties the concrete into the hopper.
- Node 7: QUE, Concrete is ready to be poured and spread.
- Node 8: QUE, Middle crew is ready.
- Node 9: COMBI, Middle crew installs horizontal reinforcing steel and inserts sleeves, blockouts, and weld plates.
- Node 10: NORMAL, Concrete is dropped into tremmies.
- Node 11: NORMAL, Concrete is distributed to the walls with buggies.
- Node 12: QUE, Concrete curing time.
- Node 13: QUE, Jack crew ready.
- Node 14: COMBI, Jack the form.

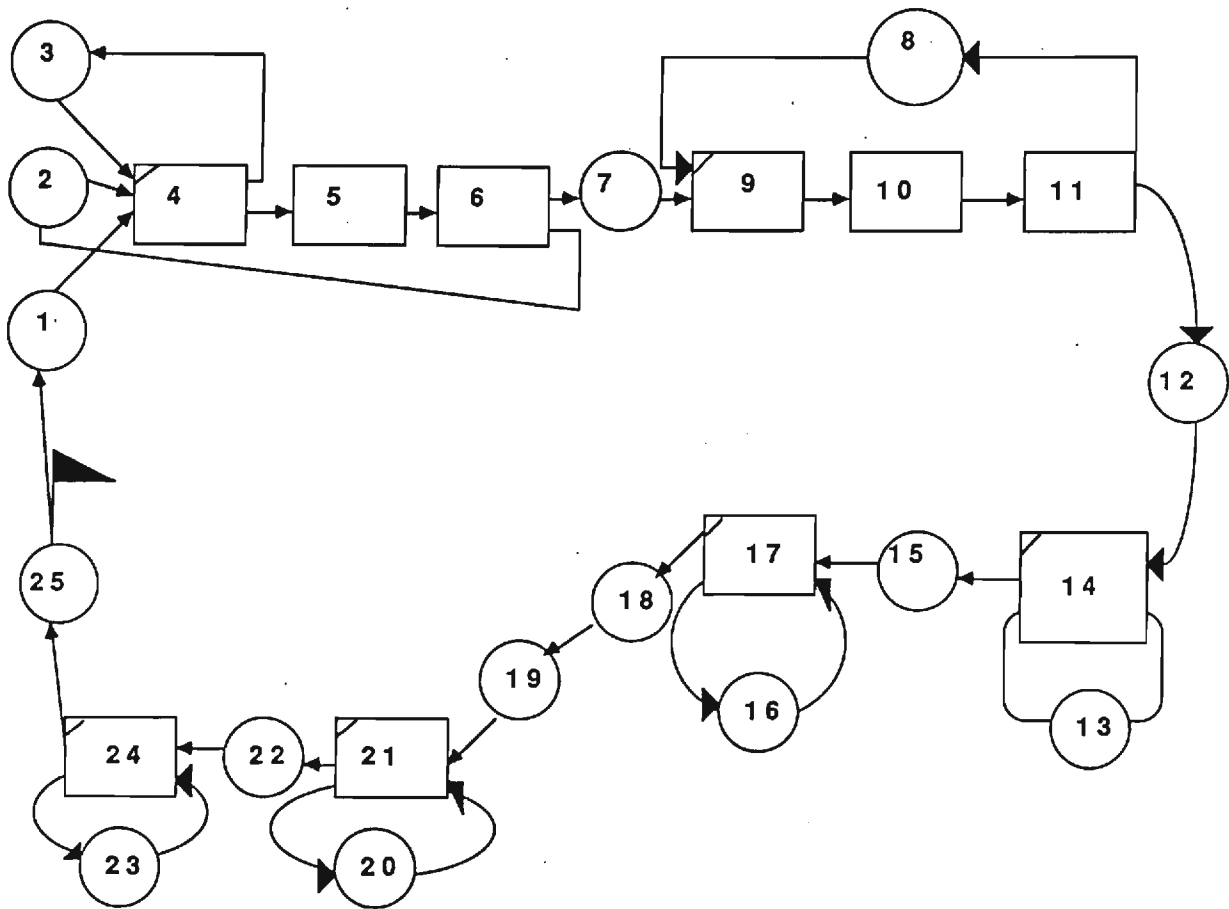


Fig. 9.1.- Elements of the Simulation Network Diagram

- Node 15: QUE, Finish work needed.
- Node 16: QUE, Finish crew.
- Node 17: COMBI, Finish work done.
- Node 18: QUE, This is a consolidate node. It collects the three sweeps of shift one and consolidated them into one blip so that the second shift can begin.
- Node 19: QUE, Second shift needed.
- Node 20: QUE, Second shift crew.
- Node 21: COMBI, The second shift stockpiles rebar, places vertical steel and link beams, and installs weld plates.
- Node 22: QUE, Third shift needed.
- Node 23: QUE, Third shift crew.
- Node 24: COMBI, The night crew installs vertical reinforcing steel, sets imbeds, cleans up, and does maintenance work. They also install complicated reinforcing and shear plates.
- Node 25: This is simply a counter.

CHAPTER 10

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

10.1 SUMMARY

Concrete slipforming was described as a concrete construction technique whereby the whole wall is cast as a monolithic and jointless structure. The different component parts from formwork or sheathing to the lifting jacks were described, pinpointing their respective functions. The historical development of the slipform system was dealt with, emphasizing the initial problems (such as rotation) and how they were solved given the level of technology prevailing by then.

With the emergence of high rise buildings along side construction technology development coupled with scarcity of resources (finance), slipforming assumed a central role in the construction of "cores", speeding up earlier completion of projects.

The major factors taken into consideration for slipforming were thoroughly discussed in the realms of satisfactory slipforming operation being a function of thorough planning.

The major problems in slipforming were stated. Such as out-of plumb, different wall thickness, and form sticking. The use of laser beams along side the water-level system to achieve correct alignments was detailed out. It was also shown how projects with heavy reinforced steel required bigger yokes of special types at greater distant - spacing, allowing enough room to place steel, and concrete at the needed rates of speed.

The use of crane to achieve optimum coordination was emphasized and all aspects of weather conditions were also diagnosed. All noted problems, solutions and limitations were discussed in respect to different projects.

Concrete handling including placing and compacting, and concrete set control was fully analyzed, emphasizing on the works of G.H. Fisher [14] in that area. Additionally some important factors to be carefully noted were recommended.

The design considerations for the slipform were also approach. Lateral pressures on the formwork and different methods to calculate them were studied. Design loads for decks were established according to Sundt's specifications; also, jack capacities and some considerations about them were

also stated. Important factors about the design of the construction operation, like the concrete placement were analyzed and some recommendations were given. Another important element of the slipform like the concrete were studied, especially the concrete set control. The factors that play important role were identified. Recommendations about the mix design were made and finally tolerances of the system were given according to those ones stated in Sundt's recent projects.

Slipforming of the IBM Tower in Atlanta, Georgia was presented as a case study. The project was described and the main issues were stated.

10.2 CONCLUSIONS

The following factors of monumental observation emerged out of this research:

- a) It was concluded that the tower crane is an essential element of a core slipforming construction operation. A careful design of location, capacity and quantity should be made to construct a successful projects without delays. Its efficient role also is a function of the character of the project in question.
- b) The major advantage of slipforming the core of a building is SPEED, leading to earlier return on invested capital to the owner and lower overhead casts to the contractor. But if the advantages of speed and economy are to be fully realized, then the designer must minimize changes in the horizontal cross section of the concrete core.
- c) There is a controversy over the limit of stories for slipforming. According to C.K. Austin [2], the height of a structure must be at least 20 meters to offset the elaborate pre-planning preparation and expensive form for very fast rate of casting advantage. Contrawise, Rocky Mountain Construction [39] opines: "Slipforming can be used for cores of virtually any height, although there are those who feel that above 30 stories the economy of concrete cores themselves decreases rapidly". So at present the yielding optimum stories for slipforming is not yet known or established.
- d) The control of the concrete setting time is one of the major factors in the success of a vertical slipform project. And it also influences the concrete mix and the speed of rise.

- e) The research reveals that in a bad weather with an outside temperature below 10 F, it will be uneconomical to maintain curing temperatures inside the slipform and all work must cease. And also in a continuous heavy rain pour, equipment will malfunction and therefore all work must stop.
- f) The study also shows that papers written on slipforming by field constructors are dominated by M.M.Sundt Co. and Heede-Uddemann Inc., although there are other big ones like The Rocky Mountain Construction in Denver, Colorado, and Pattent Scaffolding Company of New Jersey. There are other unrecognized ones like G.E.Johnson Construction Co. of Colorado Springs that do slipforming works but do not bring out their experience to the outside world. For example, G.E.Johnson Construction Co. slipformed 12-story office in Denver, the smallest concrete core yet slipformed. There were many problems and the slipform paced at a rate of 8 ft per day, far below the normal rate of the advantages of slipforming. It was not mentioned until Rocky Mountain Construction wrote about it just a piece at the corner of an article. So one does not know much the actual failures of slipforming in the field besides only the successful ones.
- g) The research shows that the non-typical blockouts must be monitored very close in order to avoid inconveniences and added costs to the project. The embedments also are, sometimes, difficult to control so it is important to attach them securely to prevent them from moving.
- h) Not all jobs are suitable for slipforming and each should be evaluated to see if a slipform is feasible. If the design is in an early stage, it is sometimes possible to make the basic design in such a way that it can be slipformed with a thorough exploration of all alternatives involving the owner, the architect, the structural engineer and the potential slipform sub or general contractor.

10.3 RECOMMENDATIONS

In the conclusion, it was stated that there is a controversy over the limit of height for an optimum realization of the advantages and economy of slipforming building cores. C.K. Austin [2] states that at least the height of the structure should be 20 meters. Others also feel that above 30 stories, the slipform economy diminishes rapidly. A 12-story office (in Denver) slipformed showed many problems and achieved only 8 ft per day, wiping away all the advantages of the

slipforming. This shows that there should be some further research studies to establish the upper and lower limits of height for slipforming.

This research focused on the techniques developed by the US firms. There is a need to study the Japanese approach in utilization of automation in slipforming construction. Some Japanese companies such as: Ohbayashi, has developed a Climbing Robot Jack System, that is a slipforming system which is controlled by a central robot unit operating the jacks and moving the whole structure at level. Shimizu has developed a similar system for automating the slipforming. A further study of these systems and their application in the US construction industry are necessary.

It was discussed in placing and compacting that with a lift greater than 2 ft (0.5 m), immersion vibrators are not fully effective in expelling air pockets from the lower part of the layer and also from the form boundary. Ohbayashi has recently introduced an automatic concrete vibrator into the construction industry. With several attached sensors, the system can detect the degree of consolidation of the concrete at a certain vibration point. And in case the consolidation is not enough, the vibration time automatically increases. The company effectively used the system in the construction of the 52-story massive core (consisting of a 39 in.- thick wall) of The Treasury Building in Singapore. With much more adaptability studies, the system will be of an immense help for solid consolidation of concrete in terms of better quality, greater speed, less manpower, and may be more room on the working deck for the crew.

APPENDIX I.- A CASE STUDY: WESTBURY CONDOMINIUM

APPENDIX I.- A CASE STUDY: WESTBURY CONDOMINIUM

The Westbury Project, located in the Waikiki area of Honolulu, Hawaii, U.S.A., is a forty-story residential reinforced concrete tower apartment condominium with a five-story parking garage surrounding on a difficult site in a heavily developed area. The apartments commence on the sixth floor.

Design Challenges

The project offered unique challenges to the architect, the structural engineer and the contractor.

a) The Architect

The project, surrounded by existing mid to high-rise buildings and almost two blocks from the beach, presented the challenge of meeting the market need for ocean view apartments to the architect besides the fact the project was prone to the parking, set-back and height restrictions of the Honolulu Building code. All these resulted into a forty-story tower with a horizontal dimensions of only 41' - 0" by 41 - 0" (12. m) as illustrated in Fig. A.1.

To design a workable layout for four apartments per floor was a further challenge, in addition to providing a stairway, an elevator, lobby, two elevators, a trash chute and an extended apartment storage volume - all within 1600 sq.ft (156 sq.m) as shown in Fig. A.1. The architect devised an ingenious way to increase the apartment storage volume (see Fig. A.2 of the cross-section view) and avoided violation of the "Glass Line" dictated by the building code [45].

b) The Structural Engineer

The challenge here was how to accommodate the huge height over width ratio while maintaining realistically the usable space in the apartment and garage areas. The result was shear walls functioning as apartment walls as shown in Fig. A.1. Prestressed concrete piles driven to end bearing and reinforced pile caps over pile clusters comprised the building foundation. The tower shear walls or cast-in-place columns carried the garage vertical loads, while the garage slabs were cast-in-place and post-tensioned.

All the vertical and shear loads of the tower were designed to be carried by reinforced concrete shear walls to the pile caps. The reinforced concrete slabs have 4" (144 mm) thickness in the interior and 6" (152 mm) beyond the glass line as illustrated in Fig. A.3.

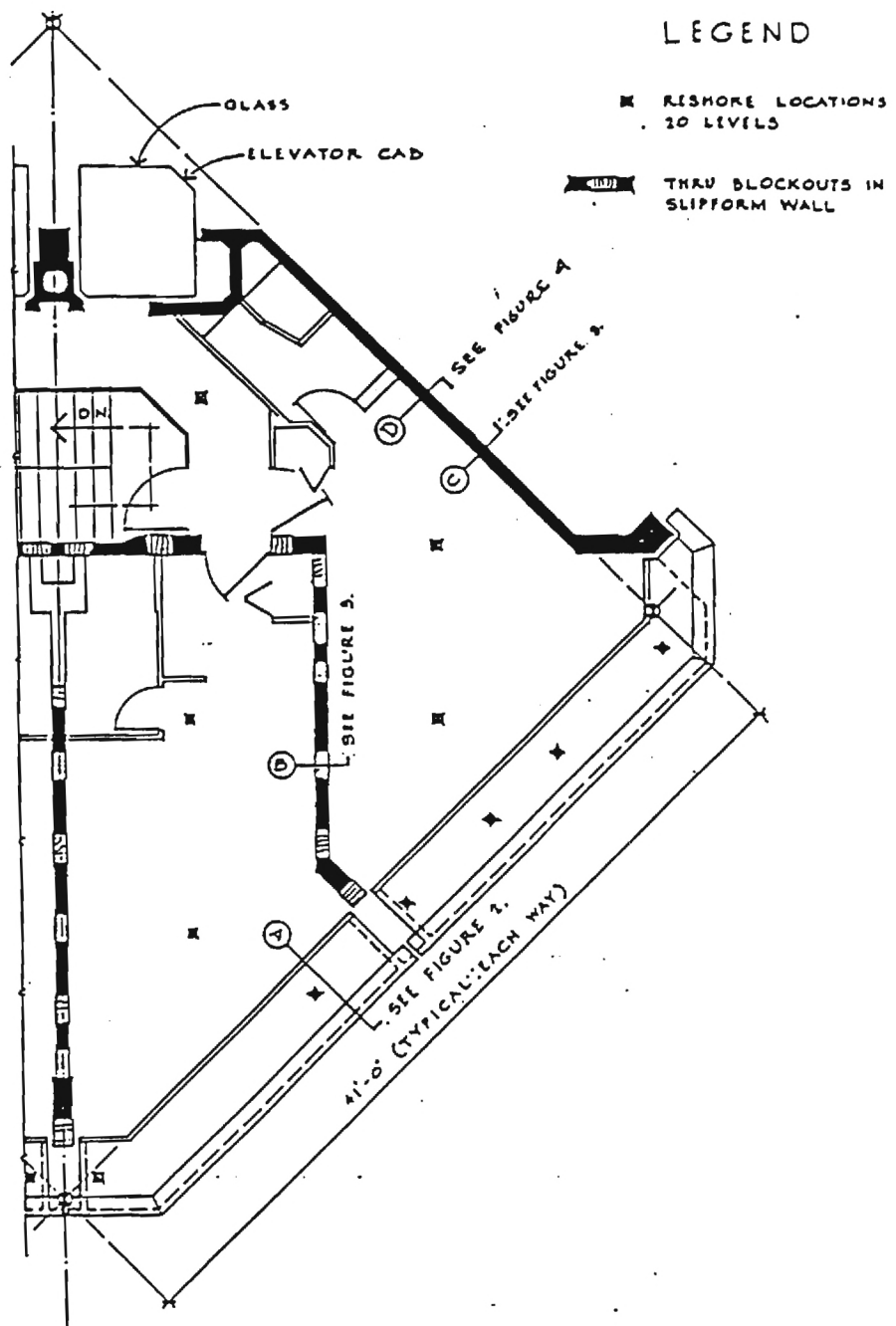


Fig. A.1.- Typical Tower Floor Plan,
 Courtesy of Heede-Uddemann, Inc.

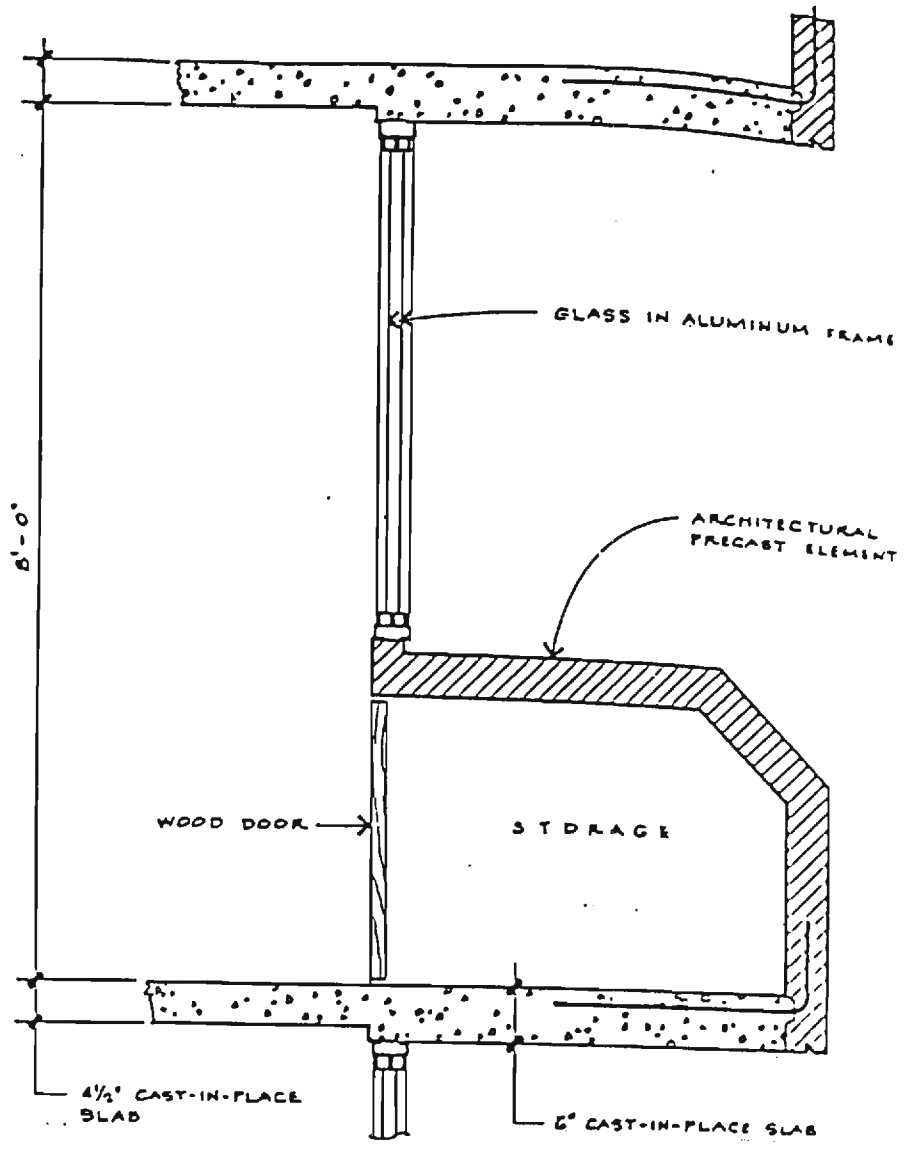
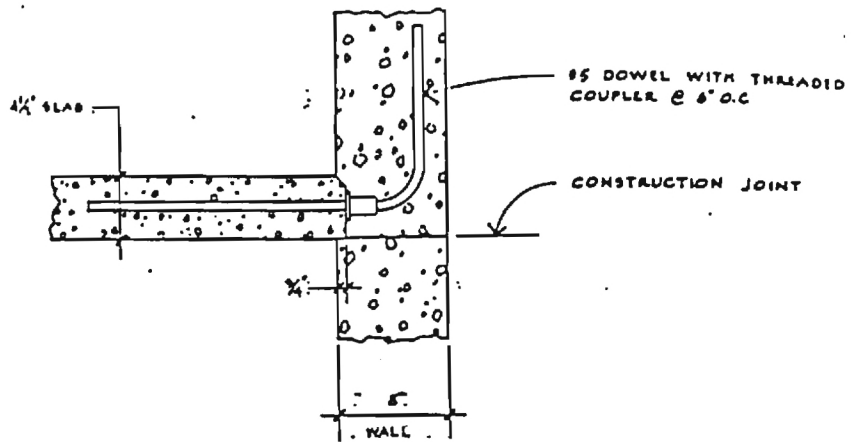
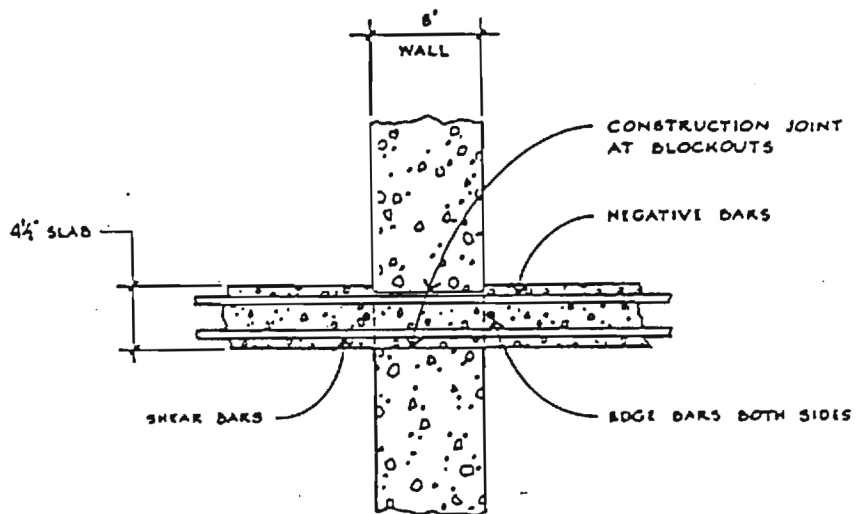


Fig. A. 2.- Slab Edge and Precast



SECTION C
 SLAB TO EXTERIOR WALL CONNECTION
 (INTERMITTENT HORIZONTAL SHEAR KEY NOT SHOWN)



SECTION B
 SLAB TO INTERIOR WALL CONNECTION

Fig. A.3.- Slab to Wall Connections

c) The Contractor

The contractor faced a challenge of providing a construction program that could produce and deliver the unusual building at a marketable cost to the developer.

The contractor did a preconstruction analysis based on the following factors:

- 1) The contract time would depend on a three working day per floor construction cycle for the tower structure.
- 2) The daily costs of the project must be fixed and constant.
- 3) The fixed costs would be unusually high percentage of the total cost except that a short floor to floor construction cycle could be achieved.
- 4) Overtime charges should be offset by decreased time-to-build.
- 5) Storage space at the level of the tower concrete floor construction would not be available.
- 6) Slab form stripping and restoring would present major problems.
- 7) Vertical access at slab construction level was a necessary measure against waiting for the hoist.
- 8) The application of video observation and time-lapse photography could help achieve a one day cycle.
- 9) All persons working on the project should be exposed to a training and motivation program [45].

Based upon these preceding factors, the contractor made the following choices of equipment and construction techniques:

- 1) A top-climbing, free standing, tower crane was chosen for hoisting of all form flying, precast erection, rebar, cast-in-place concrete, etc. materials.
- 2) A temporary passenger elevator was installed in one of the hoistways for workmen, tools and some small material hoisting.
- 3) The stairway was constructed simultaneously with the walls and the slabs to offer local vertical access and emergency escape.

- 4) All walls in the tower were constructed with THE SLIPFORM TECHNIQUE. Fig. A.4 shows a section through the slipform system.
- 5) The flying slab forms were designed to be supported on reusable, adjustable, brackets bolted to the concrete walls.

This was to avoid concrete construction loads on the slabs and thus minimizing reshoring. Fig. A.5 shows the details.

It must be noted that the choices of equipment and construction techniques were made early in the design phase, and all the structural details necessary to accommodate the selected construction techniques were also designed and incorporated into the contract structural drawings [45].

Slipform

The slipform was prefabricated (offsite) from structural grade lumber and 0.75" (19 mm) plywood. The vertical dimension was 4'-0" (12/20 cm). 3 ton hydraulic jacks climbing on 27 mm tubes were used and a new steel yoke was designed to minimize deflection under hydrostatic (concrete) loads.

The slipform workdeck was made from plywood on wood joists bearing on steel beams and the slipform wales. The workdeck had "trap doors", suitably located, to allow pouring crane hoisted concrete through "elephant trunk" chutes to the floor slabs two floors below the slipform at the time of slab pouring.

Scaffolds, secured to the slipform yokes and supported on cables suspended from the slipform wales and brackets, were constructed for finishing the concrete walls just below the slipform and removing wall block-out and keyway forms for reuse (see Fig. A.4).

Construction

Imported cement used on the project offered a significant price advantage [45]. Nevertheless, the project faced low seven day concrete compressive strength test results at the initial construction period. The test results and major concerns about deflection permitted a two working day per floor cycle for the tower from the 7th to the 14th floors.

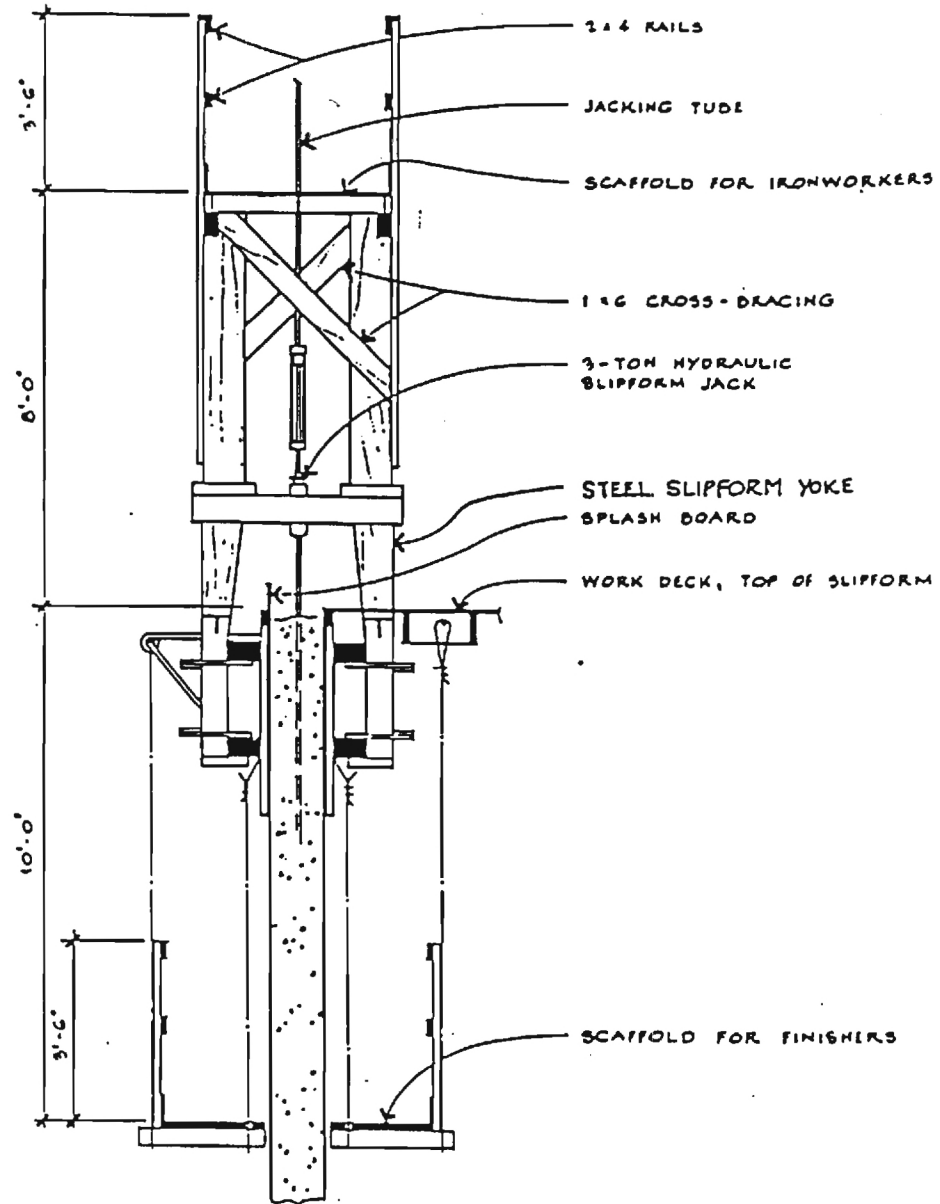


Fig. A.4.- Typical Section Through Slipform

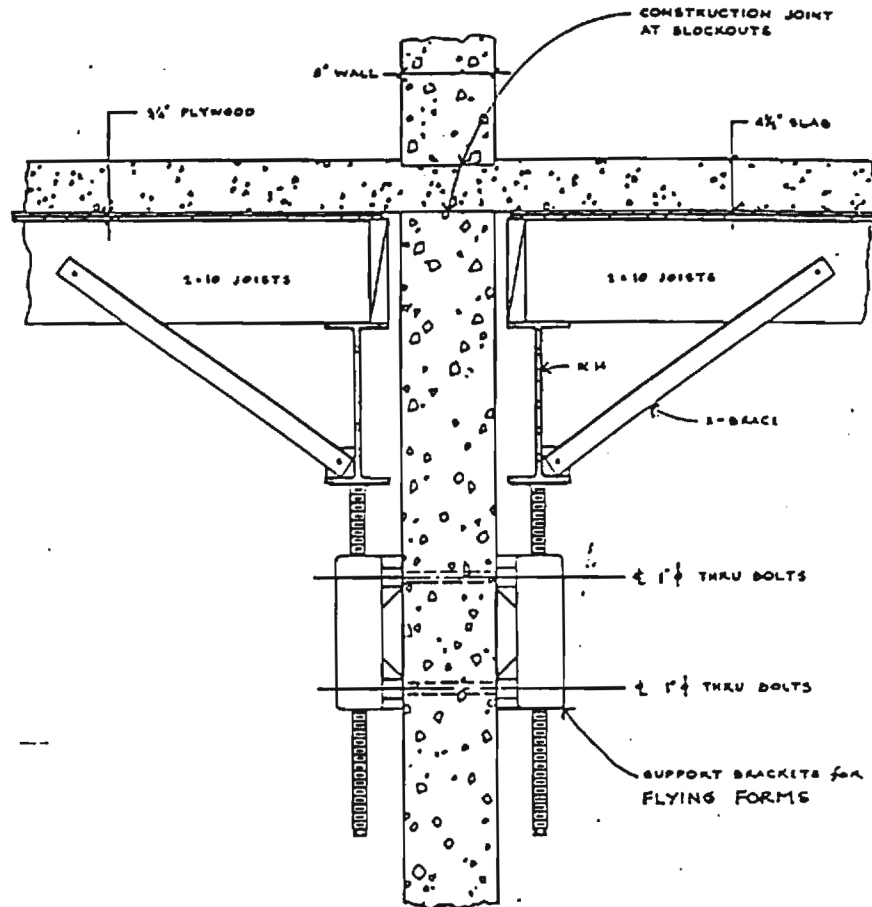


Fig. A.5.- Typical Section Through Flying Slab Form

The slipform construction of the tower shear walls started on the pile caps. The concrete strength specifications were as follows:

Pile caps	6,000 psi
Walls, to 12th floor	5,500 psi
Walls, 12th and 13th floors	5,000 psi
Walls, 14th and above	4,000 psi
Slabs	4,000 psi

All pile caps and tower shear walls were constructed with the 6,000 psi mix [45]. After solving the concrete strength problems at the reach of the 14th floor, the contractor changed to a one working day per floor cycle for the rest of the tower construction. At a one day per floor rate, the contractor added crane mast on each fifth day for an overall production rate of five working days for each four floors, that is, $5/4$ or 1.25 working days per floor for the one day cycle. Labor cost reduction peaked 35% [45]. Fig. A.6 shows the critical crane hoisting tasks plotted for a one floor per day cycle.

There were dramatic overall time savings, too. It was estimated that the two day cycle would require 80 calendar days for 26 floors, and the one day cycle needed 44 calendar days for 26 floors. In actuality, a total of 26 floors were constructed on the one day cycle for an overall time savings of 36 calendar days [45].

Time - Lapse Photography

The contractor used time-lapse film analysis and on-the-spot observation to streamline the tower construction operation and optimize the number of people in the various crews. 23 full days of time-lapse film were recorded. The camera was a super 8 type movie one, although modified to take individual frames at adjustable intervals. The camera photographed usually the subject at either 5 or 10 second intervals. A special projector was used to vary the film advance rate from "stop-action" to 18 frames per second. Therefore only abstracts of actions which allowed fast review and easy identification of problems such as congestion, idleness, etc. could be seen [45].

The time-lapse films were used to:

- i) Examine critical path tasks for means to reduce task duration.
- ii) Check manpower levels and look for idleness of workers.

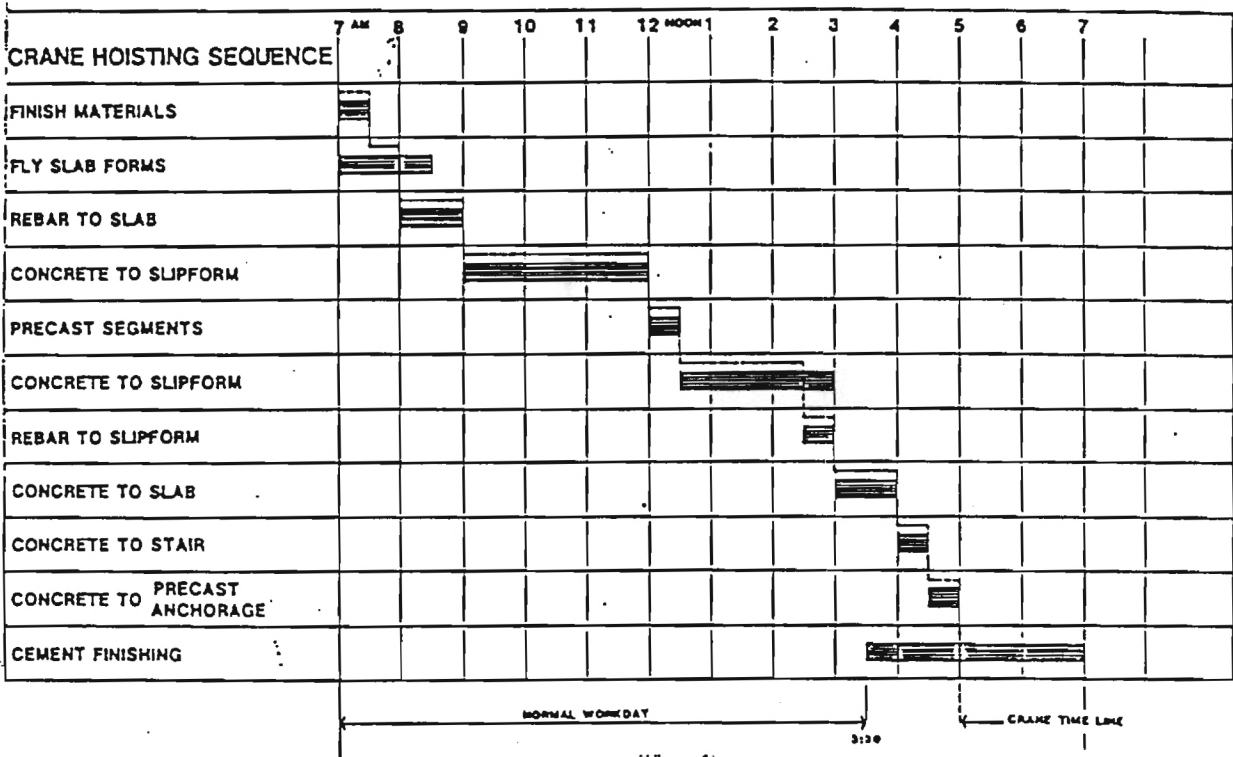


Fig. A.6.- Schedule of Priority Crane Time

- iii) Exam tool use, tool improvement, etc.
- iv) Monitor crane lifting sequences, analyzing loading and unloading points for reduced cycle time.
- v) Coordinate operations with subcontractors and suppliers. For instance, the standby costs due to late deliveries of concrete.
- vi) Look for potential safety problems.
- vii) Train the workers and arouse their interest and seek suggestions for improving the operation.

Training and Motivation

All the foremen and leadmen had access to the time-lapse film when available, and were encouraged to show it to the individual workers how their performance affected the overall operation.

"Pull-together" (a Hawaiian term), meaning team meetings after working hours was introduced by the management. Every person on the project took part, asked questions, expressed opinions and made suggestions. This resulted into an almost perfect safety record, high quality, labor costs far below the contract estimate and the crew being in anticipation of a new challenge after the project ended [45].

Cost Savings

The project was completed almost three months ahead of the contractor's preconstruction operating schedule, great savings for the developer and the contractor.

a) Savings to the Developer

- (i) Reduction in interest costs on the construction loan approached \$ 250,000.
- (ii) The land's carrying cost reduced.
- (iii) Early completion meant overhead costs reduction.

b) Savings to the Contractor

- (i) Reduction in rentals of project facilities such as cranes, hoist, trailers, tools, utilities, duration of insurance coverage.

- (ii) Three months early receipt of profits and retention money.
- (iii) Personnel available to man another project much earlier.
- (iv) Achievement of credibility in the development community since the site was considered to be impracticable for development by the local people.

APPENDIX II.- REFERENCES

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