Push-up Steel Construction

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This paper was presented at the AISC National Engineering Conference, Houston, Texas, in May, 1969.

FOR THE PAST few years a team of researchers, architects and engineers* at the Massachusetts Institute of Technology have directed their efforts at finding methods for reducing the cost of multistory steel-frame construction. This research, which has been sponsored by the United States Steel Corporation, was initially directed to examine the structural frame of high-rise apartment houses. Our choice of this restricted area of investigation was based on: social need for housing; the possible market for apartment houses; and the competitive position of steel-framed construction vis-á-vis other possible materials of construction.

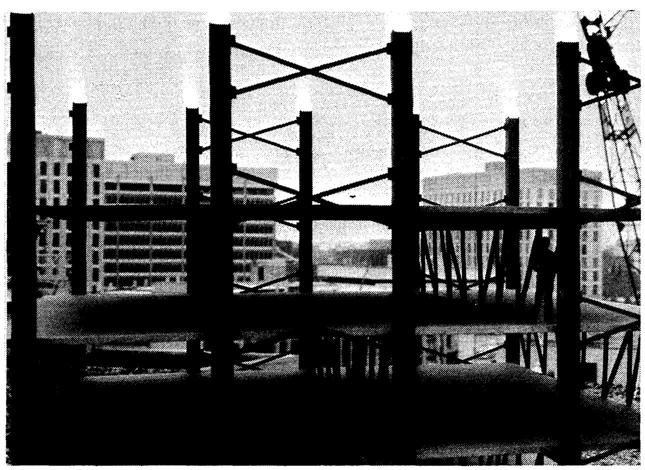

Fig. 1. The staggered truss concept

* *Marvin Goody, Robert Pelletier, Calvin Opitz, Architects; William J. LeMessurier, Peter Pahl, engineers; and others.*

** *First reported by William J. LeMessurier in Boston at the 1966 AISC National Convention.*

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The results of this initial research effort was "the staggered truss," a unique structural framing system** (Fig. 1) which reduces the tonnage of steel required for high-rise apartment houses by substantial amounts, as much as 40 percent in comparison to more conventional framing systems for buildings of 20 or more stories. This system was first applied in practice in a housing project for the elderly in St. Paul, Minnesota, shown in Fig. 2 under construction, designed by Bergstedt, Wahlberg & Wold, Inc., architects, and Bakke & Kopp, structural engineers. A second building, the 22-story Raddison South Motel, has also been constructed in South Minneapolis. Cerny Associates are the architect and engineers.

Following this, the MIT team turned its attention to the whole building problem: that is, the total process including the statement of desires or needs of an owner (or developer) for a building, through its design, construction, and finally delivery to the owner. Inherent in this objective is the direct recognition of the fact that minimum cost or maximum benefit does not come

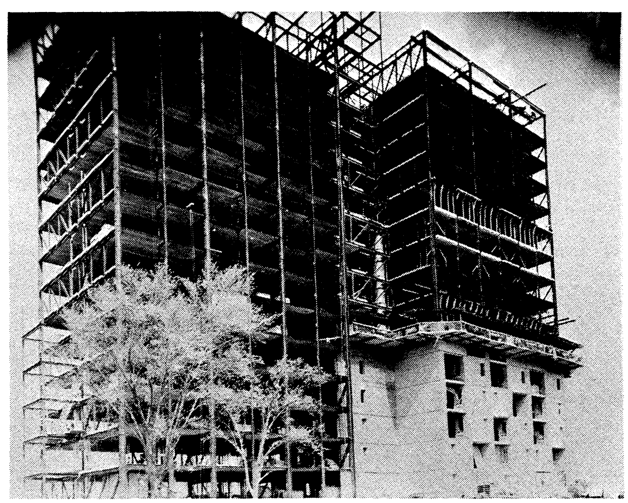

Fig. 2. Home for the Elderly, St. Paul, Minn.

necessarily from the optimization (for least cost) of a portion of the total process.

In this case, however, in contrast to the earlier study, the group concentrated on high-rise office buildings, in order to introduce the added complexities of more elaborate environmental control systems characteristic of modern office buildings. In addition we considered buildings of 20 stories or more, since for these heights certain characteristics and problems tend to dominate. These are: repetitive floor plans; large lateral forces due to wind loads; centralized circulation and elevator transportation; vertical transport of men and materials required for construction.

The process of investigation included a study of what high-rise office buildings are like; i.e., geometry, framing systems, floor systems, central core areas, mechanical-electrical systems, etc. We also undertook a study of the many methods of construction, including steel erection techniques.

From this complex study, many possible innovations in design concept and construction techniques seemed worthy of investigation. One basic strategy, the "push-up" or reverse construction technique, appeared to be particularly interesting to us as having potential for significant savings in total project cost.*

It is admitted that this choice of a concept to investigate was based on judgment, and not on the exercise of an analytic cost model of the total process, although such a technique could be highly effective. Of course, our failure to use optimization techniques was based on the fact that no reliable cost models yet exist.

The "push-up" concept was first applied (to our knowledge) in England** in the construction of a 17-story reinforced concrete building.

THE PUSH-UP CONCEPT

The push-up concept involves a radical revision of the erection technique for multistory buildings. In essence the procedure involves the following:

1. Foundations and other substructure are built as in normal construction.
2. The remainder of the building is constructed in a reverse sequence; that is, the roof is built first, the ground floor last in a time sequence.
3. To accomplish the above sequence: All steel placement, and bolting and/or welding occurs at or near ground level. As soon as one level of the building is assembled at grade, it is jacked up and the next lower level of framework is assembled in place below the previous lift.
4. Finishing operations for the building are distributed throughout the ever rising superstructure with floor installation occurring at the second or third level above grade, with final painting occurring at a much higher level, on the order of the 10th to 20th, dependent on overall scheduling. All other operations occur in between. Thus, each time a structural level is completed and is lifted one story, every floor above is also lifted and is advanced along a quasi-assembly line.

A number of characteristics for this sequence of construction can be identified.

1. All primary heavy construction is accomplished at or near grade.
2. Wall panels, windows, and all other closure components are assembled and installed near grade. These operations can be accomplished from staging which surrounds the building, which also can be weather-enclosed. Thus, the entire work operation (after foundations have been completed) can be in closed areas permitting all-weather construction.
3. All materials and equipment to be used in the building may be loaded onto the appropriate floors when they are near grade. All of these are thus lifted with the building and are in proper location when they are to be used.
4. Installation of roof-top equipment should be started near the beginning of the project at the time the roof is actually constructed near grade. Included in this equipment are the following: cooling tower, HVAC equipment, high-rise elevator machinery and controls. Obviously the actual roofing should also be installed.
5. For this method of construction to be economic, a certain minimum number of floors must be built. This minimum is in all probability some function of the number of working levels necessary for effective finishing of the building. To date we have not made a sufficient number of studies to determine the probable relative economy achieved with variation in numbers of floors.

EVALUATION OF ECONOMY

The first experience in England using this technique involved costs in excess of the contract price. One must recognize that this initial project, daring in concept, included costs due to development and the learning process; however, there are many reasons to believe that the basic concept is worthy of further development.

* *Project cost includes land costs, design fees, construction costs, inspection costs, and interest on construction loans.*

** *Adler, Felix* Jig for the Construction of a 17-Storey Block of Flats at Barras Heath, Coventry, *Proc. Instn. Civ. Engineers, Vol. 27, pp. 433–464, March, 1964.*
Also, Discussion on the above Paper, Proc. Instn. Civ. Engrs., Vol. 32, pp. 76–96, September, 1965.

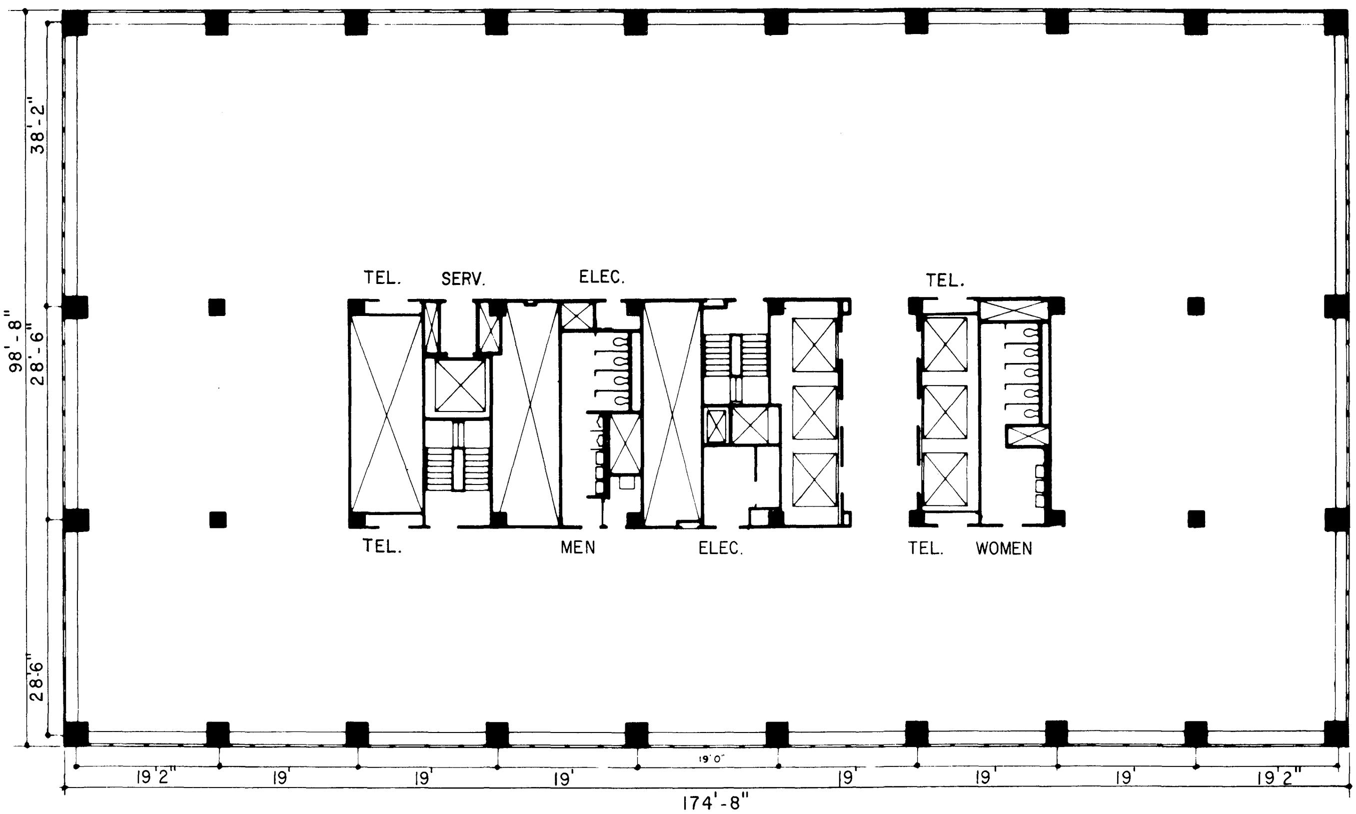

Fig. 3. Plan view and Section, New England Merchants' National Bank Building, Boston, Mass.

With these general judgments, our research team turned to:

(a) The development of a jacking system suitable for high-rise steel-frame buildings
(b) An examination of the strength, stability, and deflection characteristics of the structural system under all conditions
(c) An examination of all construction procedures and necessary revisions to subsystem components
(d) A careful study of the scheduling of all work operations
(e) An evaluation of the economy derived from application of the technique to a typical 40-story-high office building

We selected for intensive study the 40-story New England Merchants' National Bank Building, Boston, Mass., under construction (1966–1968) during the period of research. Our intent in the study undertaken was to prepare cost estimates for the construction and total project cost of the same building using the push-up concept, and to make direct comparison to the actual construction and project costs available from the builder and the developer of the building. Our choice of the particular building was motivated by several factors: general suitability of the building's characteristics, the fact that good and close relations could be achieved with the developer and the general contractor of the building, its proximity to MIT, and the fact that it was under construction (hence available for close study of work operations during the period of research).

The study building is nearly ideal for several reasons. For example, the plan shown in Fig. 3 is typical of many of the office buildings currently constructed, having a central core including elevators, ducts, toilets, stairs, etc., surrounded by space which can be subdivided to suit tenant requirements. Second, the structural frame is reasonably representative of many current office buildings. A section of the building is shown in Fig. 4. The exterior walls of the building consists of cut-face granite veneer with precast concrete backing. The interior walls are of block masonry with plaster finish for walls in the core area; demountable solid gypsum dry wall partitions are used in tenant areas.

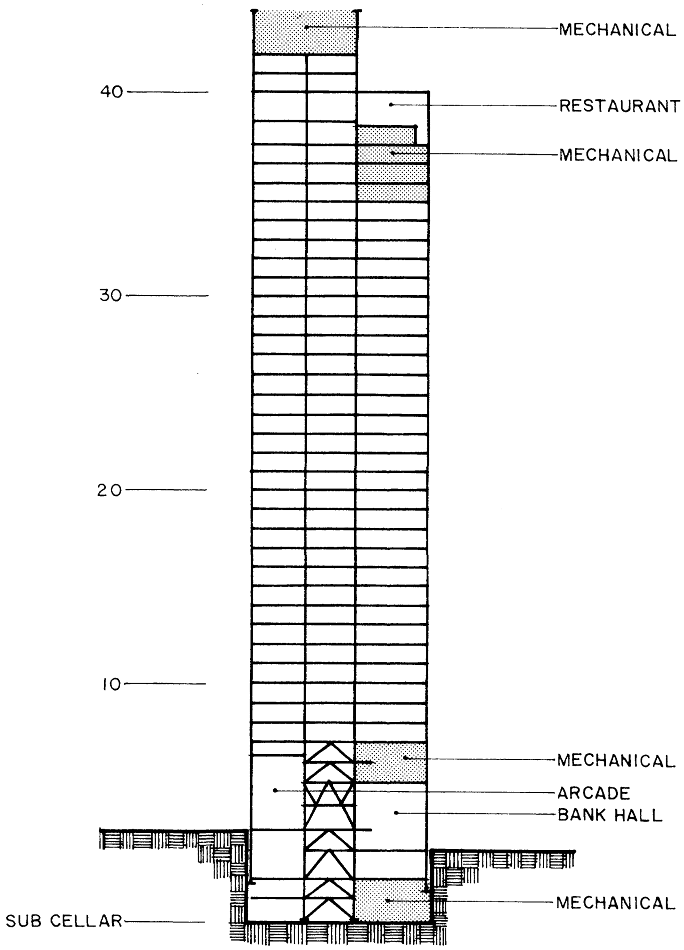

Fig. 4. Section, New England Merchants' National Bank Building, Boston, Mass.

JACKING SYSTEM

The jacking of a 40-story-high building, involving column loads of the order of 5,000,000 lbs under combined dead, live and wind loadings, is not simple. Of critical importance is the maintenance of stability of the entire building weight under all conditions of position in the lift and under all conditions of wind loading.

In the course of a number of months we conceived of and examined many potential jacking systems. All but two of these systems were rejected, either for failure to provide adequate stability to the building, overcomplexity, or excessive cost.

The system finally selected for more intensive development is shown in Figs. 5 and 6.

The basic concept of the system is to lift the column by a lifting shoe, as shown in Fig. 5, which is connected by large threaded lifting rods to a lifting beam. The lifting beam in turn is raised, by incremental amounts, by wedges which are actuated by a hydraulic ram as shown in Fig. 6. The ram-wedge-lifting beam system is supported by the structural lifting floor. This lifting floor in turn is a permanent part of the foundation system, and may be supported by doubled columns which surround the columns being jacked.

Figure 7 gives a schematic section of the push-up process, illustrating the working floor which serves to structurally support the building, which is gradually being "extruded" from the foundation. The operation of the lifting sequence is as follows:

1. The threaded lifting rods are fully extended and the lifting shoes are inserted under the column bases.
2. The hydraulic ram strokes forward, actuating the wedges and raising the lifting beam by ½-in.*
3. The lifting beam bears against the lifting nuts, raising the rods by ½-in., and in turn the column by ½-in.
4. As the holding nuts which bear on the structural lifting floor become unloaded, they are rotated and advanced by a constant torque hydraulic motor until friction precludes their further rotation.
5. The hydraulic ram is retracted, the wedges withdrawn, and the lifting beam is dropped by ½-in., the column being held at elevation by the lifting shoe-rod-holding nut combination.
6. The lifting nuts are rotated by the constant torque hydraulic motors in the direction that the lifting beam has moved until friction stops rotation.
7. The cycle is repeated.

A number of observations are in order. Since an entire building is being lifted, lateral restraint must be provided to all of the columns as they are lifted.

The doubled columns below the lifting floor serve not only to support the jacks, but also serve as lateral guides to the column as it is raised. Several schemes have been devised for mechanisms to supply the necessary constraints, including fixed guides which bear on the lifted column, and rolling guides attached to the lifted column, to mention two.

Another point of significance is the alignment and plumbing of the lifted column. This alignment must be accomplished before the column splices are completed and the load transferred to the next column section. Erection tolerances are accommodated in the girders and connections which are attached at a location just above the lifting floor.

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* *Characteristic of our design. Other magnitudes could be used.*

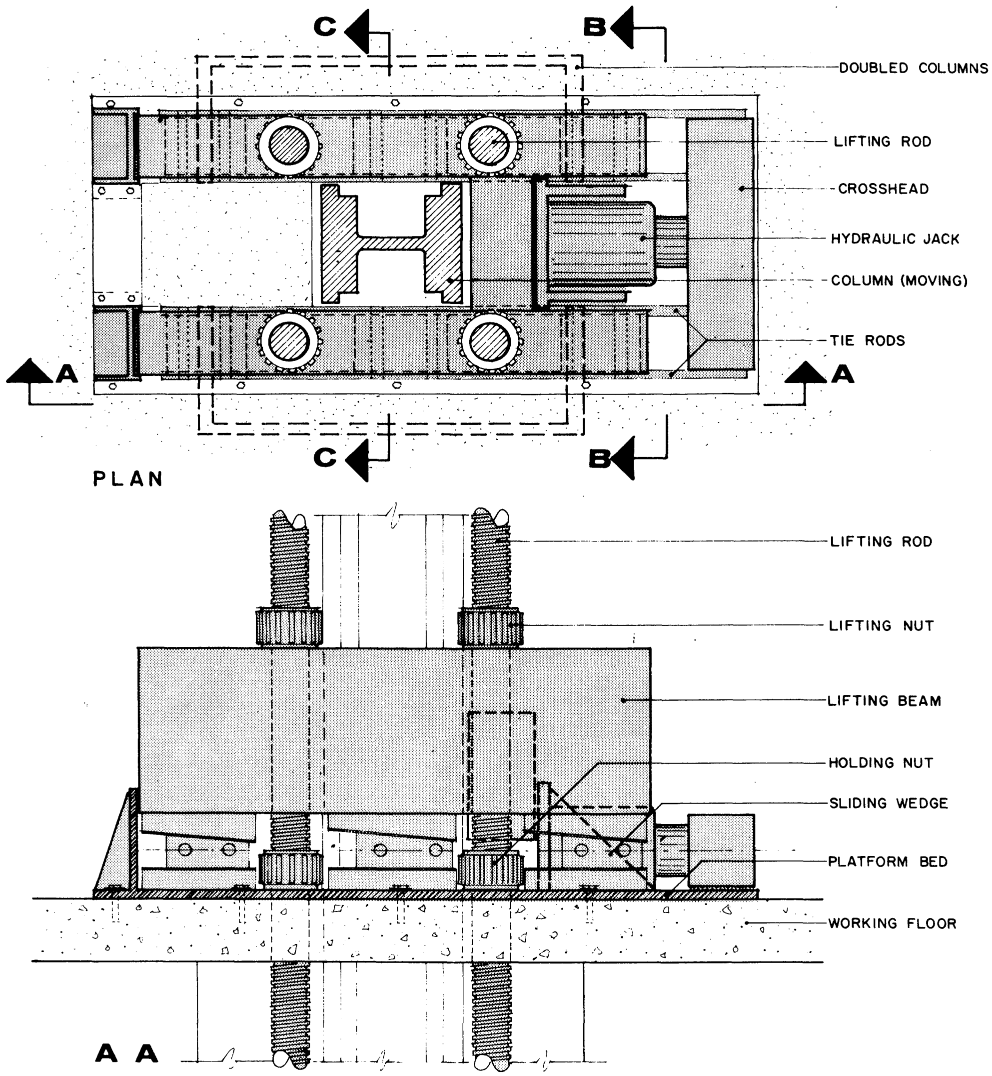

Fig. 5. Lifting device—plan view

CONSTRUCTION SEQUENCE

The first portion of construction for a push-up building is the same as in conventional construction. That is, all of the foundation work, viz. sheet piling, excavation, caissons, piles, spread footings, or mat foundations, are functions of particular site characteristics as well as building parameters.

For the push-up system that we have devised, at least two levels of sub-structure are required below the lifting floor. This region is used for the column placement and lifting operation. Figure 7 illustrates the space arrangement required for the lifting operation for the building studied (New England Merchants' National Bank Building).

After the foundations and basement walls are completed, the following sequence of construction is followed:

1. The steel columns and girders for the cellar(s) and first (or grade) floor are erected by conventional means.
2. All large equipment items to be located in the subcellar are placed by conventional cranes.
3. The floors in the cellar and at the first or lifting floor are placed.
4. The lifting devices are placed on the lifting floor, assembled and prepared for operation.
5. The column sections for the topmost floors of the building are placed on the foundations, and after

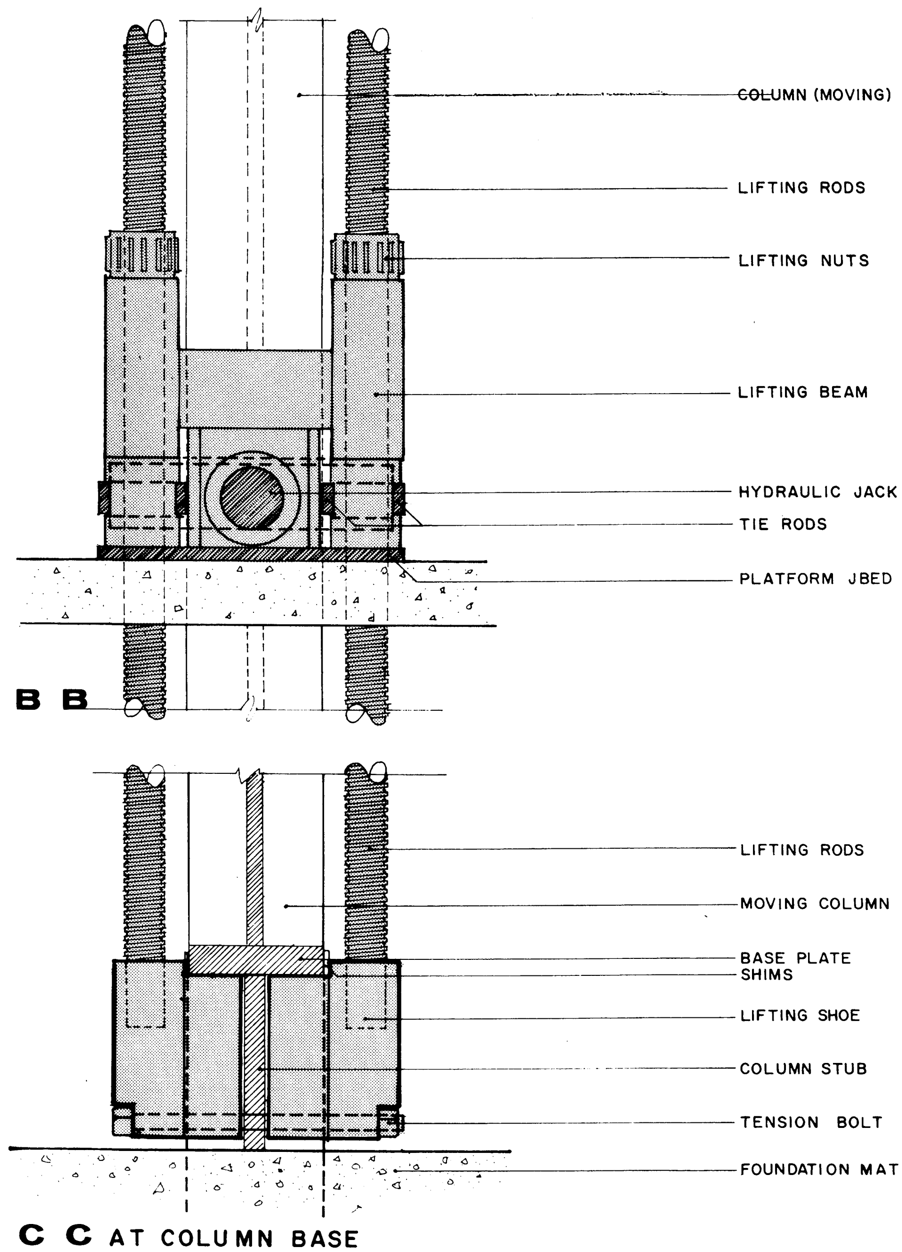

Fig. 6. Lifting device—sections

appropriate lifting by the jacking devices, the girder and beams for the roofs or penthouses are placed from the lifting floor by small mobile cranes which operate on the lifting floor.

6. The roof deck is placed.
7. Elevator machinery and all other penthouse or rooftop equipment is placed by crane.
8. The lifting shoes are engaged at the bottom of the topmost columns.
9. The next lower columns are worked into place in the basement and upper ends are shackled to the appropriate lifting shoes.
10. The first lift is made.
11. The girder and beams for the next lowest level are erected from the working floor.
12. The second lift is made, and the columns below are aligned and spliced to the top columns.
13. Cyclic operation starts.

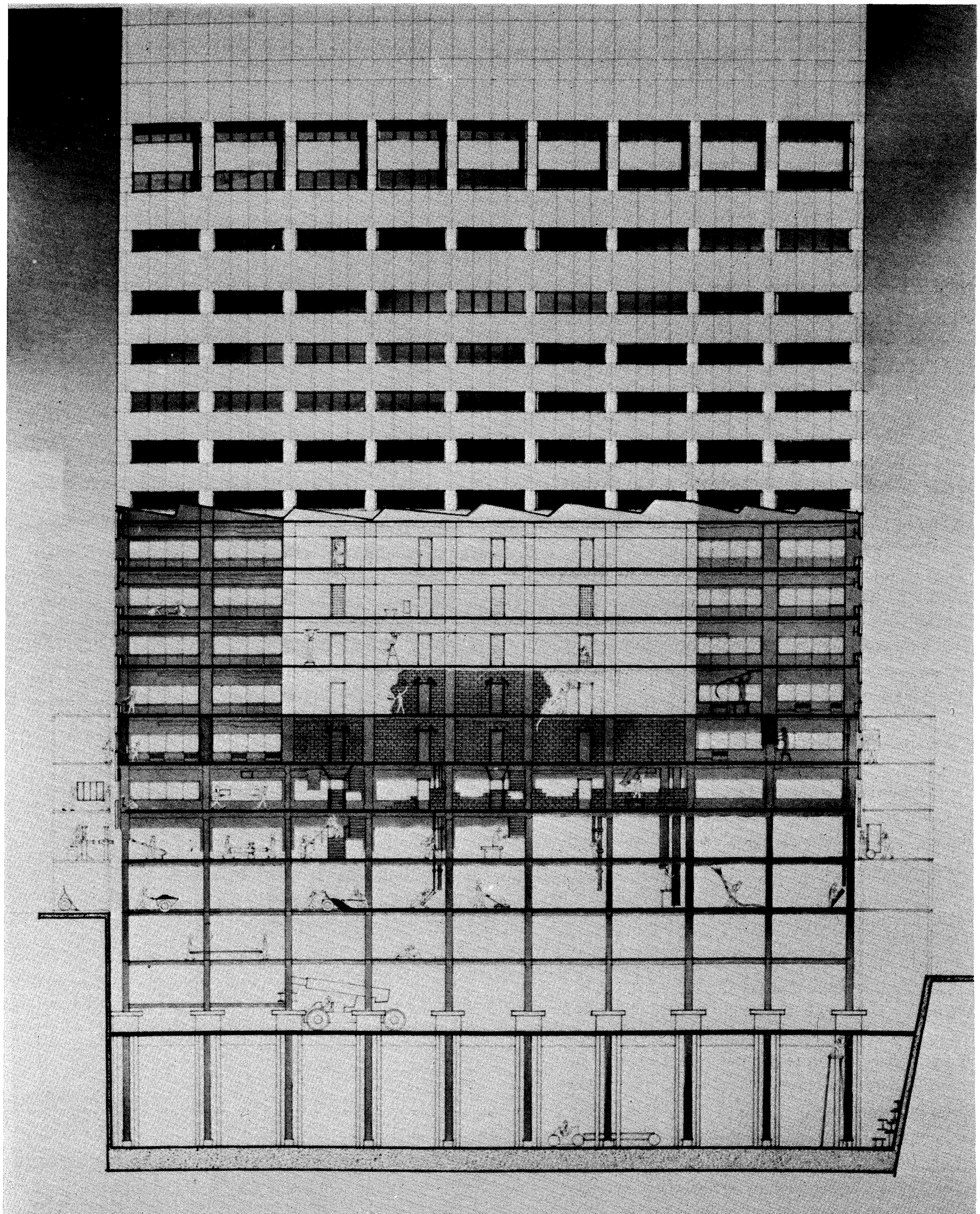

Fig. 1. Schematic section — Push-up process

A number of observations may clarify some of the more obscure points:

1. The lower movable columns of the building rest at one stage on the column stubs which protrude from the foundation. Normally we would use two-story column segments.*
2. All horizontal framing is placed from the lifting floor; thus columns must be lifted off of the column stubs for this operation to occur.
3. New column sections are attached to the lifting shoes by means of a shackle linkage and lifted into place by the jacking operation.
4. Lifts occur in one-story heights.

The above description has related to the structural erection procedure. Integral with this operation, and the reason for all of this, are the other construction operations. Repetitive operations occur at particular levels above the working floor. The particular levels chosen depend on a careful scheduling of materials flow, crew sizes, etc. For the New England Merchants' National Bank Building, the following work locations were selected.

1st working level:** Horizontal framing installed and connected.
2nd: Steel floor deck installed—HVAC and rough plumbing started.
3rd: Rough plumbing continued. Steel stairs installed. Concrete deck and core fireproofing placed. Spray-on fireproofing commenced on underside of steel deck.
4th: Curtain panels installed. Spray fireproofing and rough plumbing completed. Duct work begun.
5th: Window frames installed. Duct work and insulation continued. Interior masonry commenced.
6th: Glazing and caulking installed. Scaffolding and enclosure are terminated just above this level. Furring and lathing commenced.
7th: Lathing completed. Venetian blind pockets, induction unit enclosures installed.
8th: Plastering.
9th: Ceramic tile installed in lavatories. Hung ceiling and lighting fixtures installed.
10th: Plumbing fixtures and resilient flooring installed. Hardware and metal doors started, as is painting.
11th: Toilet partitions and accessories are installed. From this point on, tenant partitions and finishes may be installed.

Inherent to this construction sequence are alterations to the normal construction modes. For example, elevators, plumbing, electrical work are installed from the top down. Our investigations reveal that these alterations pose no insurmountable problems; in fact elevator installation appears to be aided by this process.

* *Although other column lengths could be used.*
** *Above column erection level.*

CONSTRUCTION DURATION

From our careful studies of crew sizes, work scheduling, etc., it appears that total project duration can be significantly shorter for the push-up mode of construction, as compared to conventional techniques. For the study building, actual construction time was about 580 working days. Our projected construction time for the push-up mode was 400 days.

PROJECT ECONOMY

Based on a careful analysis of our 40-story study building, we project a substantial savings to the owner for the push-up mode of construction compared to conventional techniques.

Portions of the construction sequence cost more for push-up than for conventional. Major savings to the owner accrue from:

1. Shorter construction time, hence less construction loan interest
2. Earlier return of rental income

Of great significance to note here is the time interest value of capital.

Table 1.
Cost Summary for Push-up Construction

Item	% of Building Const. Cost	Cost Change for Push-Up Const. (%) Increase	Decrease
Equipment—Push-up:			
Lifters, pumps, etc.	1.60	1.60	
Yard cranes, fork lift	0.10	0.10	
Equipment—Conventional:			
Derricks and hoists	1.02		1.02
Structure:			
Foundation	5.50	0.55	
Steel frame	17.94	1.79	
Building Service Systems:			
Plumbing	2.39	0.13	
HVAC	11.95	0.56	
Electrical	7.91	0.60	
Elevators	7.92	0.19	
Labor:	30.00		6.00
Finance:			
Construction loan int.	9.70		5.32
Rental income	9.60		5.40
Totals:		5.52	17.74
Net change in cost for push-up construction:			12.22

Other savings to the owner accrue from greater labor efficiency. For example, work crews are collected in restricted areas, hence subject to easier and closer supervision. Second, workers are not required to go up many stories to their work locations. Further, building elevators may be used for worker transport.

Of great significance is (after foundation and substructure work is completed) the all-weather construction capability of this system.

Another major savings may be attributed to simplified materials handling. All structural steel is delivered at grade; walls are installed at the third or fourth level above grade; all finish materials are loaded on the floors and jacked up with the building, etc.

We do not propose to say that steel erection will be less expensive by the push-up concept. We do say that project cost will be less—and this is what counts in the market place.

Our analysis of the study building indicated a project savings of 12 percent. Details of the cost summary are indicated in Table 1.

CONCLUSIONS

The push-up concept offers significant potential for reducing project cost for multistory steel-frame buildings. No alteration in building quality is necessary to achieve these savings. Inherent to this concept are, however:

1. New jacking devices, as yet untried in practice.
2. Revised construction procedures which must be developed in practice.
3. A construction technique which should have significant advantage to labor by virtue of all-weather construction capability, centralized work locations, no long stair walk or long hoist ride up to work, to cite a few.
4. A construction technique for which very careful scheduling and trade coordination are mandatory. Almost all operations are on the critical path.

In conclusion, we have great confidence in the concept. We believe it will soon be applied in a building project and we are directing our efforts to that end.