PRECAST FLOOR SYSTEMS
Orthogonal, Open-web Concrete Structures

by

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Dean Pietro Belluschi
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Dear Dean Belluschi:

In partial fulfillment of the requirements for the degree of Master of Architecture, we hereby submit these three thesis projects entitled, "Precast Floor Systems".

Respectfully,

Robert P. Burns, Jr.

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ABSTRACT

"Precast Floor Systems"
"Orthogonal, Open-web Concrete Structures"

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Phillip A. Kupritz

John E. Rudquist

Submitted in partial fulfillment of the requirements for the degree of Master of Architecture in the Department of Architecture on July 25, 1962.

The development of structural floor systems within which are integrated mechanical services and other architectural features is one of the most challenging undertakings of current building technology. The rewards of successful realization - heightened architectural expression, structural efficiency, and unusual flexibility - have led a number of designers to devote great effort to this problem in recent years. With few exceptions, however, the solutions arrived at have been conceived as specific answers to specific problems, and a more general approach with wide application has been only suggested.

The following studies are directed towards the development of systems of floor construction whose geometry, techniques, and materials make possible the broadest applicability in buildings of many types. Three individual approaches, related in their general objectives and complementary in their realization, have been investigated and are herein presented. Recognizing that no universal solution exists, the proposals emphasize the general aspects of systematization while dimensions and details are considered alterable for specific applications.

It is hoped that the present study, developed on a cooperative basis and benefiting from the experience and toil of others, will serve as a guide for those who wish to extend and broaden its limitations.

While the general background work and research was maintained as a group effort, the detail investigation and design was carried out on an individual basis. The resulting three proposals are as follows:

Proposal 1 - Comparative study of two geometrical systems, intersecting Vierendeel trusses and an open pyramidal frame, using structural members precast in module-sized units (5'X5').

Robert P. Burns, Jr.

Proposal 2 - An open pyramidal system in which structural elements are precast in bay length trusses one module (5') wide.

Phillip A. Kupritz

Proposal 3 - A system of intersecting Vierendeel trusses utilizing structural members precast in bay length units one module (5') wide.

John E. Rudquist

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Professor Eduardo F. Catalano, thesis advisor

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Introduction

Building technology, at once a fearful master and willing servant to the architect, advances slowly and unevenly. While the vast bulk of construction feeds off the techniques of the past, practically every new achievement in the art of building has been brought about by a handful of dedicated pioneers. The examples of Labrouste, Eiffel, Jenney, Roebling, Freyssinet, Nervi, and Candela are pertinent. The average architect, pressed by the problems of specific client, program, and site, has neither the energy nor interest to extend the innovations of his more imaginative colleagues and is generally satisfied to adopt what is most obvious and readily understood in the field of building technology.

The Master's Thesis permits a focusing of attention on the pressing problems of building construction freed from the restrictions of the unique requirements of client, program, and site. While the discoveries and proposals made in a generalized investigation of this nature may never be realized in whole, they may have significance for the entire field of architecture by indicating solutions which are capable of adaptability on the broadest scale. In addition they may possess the potentiality for future development and refinement.

The increased need for unusual flexibility demands that buildings of many types be conceived in terms of long range adaptibility to new functional requirements. This is especially true in the case of buildings constructed of such permanent materials as masonry and reinforced concrete which can have a long life and are expensive to demolish.

The critical factor in a building's ability to adapt to new functions is frequently the possibility of furnishing the necessary mechanical services including heating and air conditioning, electrical and sanitary systems. The provision of a system of floor construction which permits great flexibility in the accommodation and alteration of mechanical services would essentially increase the long range usefulness of buildings.

The development of a prototype structure with the potentiality of widespread application depends on emphasizing aspects of systematization while minimizing specific dimensions, spans, and clearances which could be adapted to specific problems. In addition systematization of such a structure is essential to take advantage of the most advanced methods of present day technology.

The assumption of concrete as the principal building material is based upon its growing utilization for buildings of all kinds and the special need for great flexibility in concrete structures.

Concrete lends itself readily to many facets of systematization. As it is a plastic material which is given shape by its forms, real economy can be achieved through the use of repetitive modular units molded by forms which are re-used many times.

Such an operation can be executed most efficiently under factory control. Through precasting a high degree of precision can be effected and costly site labor and poor workmanship reduced. The erection procedure itself can be highly systematized with lifting machinery, cranes, post-tensioning, and other technological innovations.

The resultant quality of a structure so conceived will be one of geometric order based not on whim but on the logical processes of construction.

The investigations proceeded under the following outline (the first three stages developed in common, the last four on an individual basis).

Outline of Study

1. Formulation of general objectives
2. Assumption of material to be investigated
3. Research of background material
   a. Related structural systems
   b. Mechanical systems
   c. Construction methods
4. Determination of geometrical character of system
5. Erection procedures
6. Approximate structural analysis
7. Refinement and final proposal

Design Criteria

A. Application to Various Building Types

In order to maintain a certain logical design framework and at the same time preserve the possibility of maximum use, it is necessary to establish realistic limitations on the potential applicability of any proposals. The first step has been to eliminate from consideration extreme conditions. Those structures requiring little or no mechanical service can be treated in a number of conventional ways while structures whose requirements for mechanical service are unusually excessive possess many special conditions demanding unique solutions.

There is a wide range of building types including office buildings, educational structures, research laboratories, manufacturing plants, public buildings, light storage structures, and commercial buildings whose functional and mechanical demands on the system are sufficiently similar that it is reasonable to seek a solution for their general requirements.

Such building types generally require structures of generous overall dimensions and increasingly large bay sizes which are desirable for greater flexibility. For these reasons, systems capable of spans of 40' - 70' utilized within buildings having no less than 3 bays in the minor dimension will be considered.

A structure acting in two directions has been adopted for its inherent structural qualities as well as for the advantages gained in space division and visual uniformity. This results in square structural bays supported on columns, and for purposes of illustration and analysis, typical bays of 50' - 55' have been studied.

Finally it is considered reasonable to limit application of the proposed systems to structures of no more than 7 or 8 floors. In taller buildings the floor to floor dimension is a critical economic factor and efficient structural depth and mechanical services must be sacrificed to the overall reduction of height.

B. Quality of Space

The space created by the proposed floor systems should be sufficiently neutral to permit activities of many types.

The frank revelation of the structural elements with certain necessary ceiling accessories will present a richly articulated but rugged surface of a highly uniform quality.

C. Geometry and Dimensions

Systems of geometry proposed for the floor systems should be as simple as possible for ease of fabrication and for visual clarity. They should be a logical expression of the qualities of concrete and should accomodate the mechanical services without strain.

An orthogonal ceiling grid of exposed ribs spaced on a practical module is desirable to allow a high degree of partitioning flexibility. The module selected for the ceiling grid provides room sizes on multiples of five feet - 10', 15', 20', etc.

On the basis of stated limitations, the most direct geometrical solutions are the systems involving intersecting Vierendeel trusses or perforated boxes and combinations of open pyramids and tetrahedrons on a square grid. These two geometries have been the basis of most related systems previously designed and have been adopted for purposes of the present investigation.

The depth of floor slabs has been established on the basis of assumed requirements for mechanical services. Within an overall four-foot depth is contained the floor structure, voids to receive mechanical installations and finished floor and ceiling surfaces.

D. Structure

A primary motivation of the present thesis is to determine systems which take structural advantage of the full ceiling-to-floor depth by integrating rather than segregating structural and mechanical elements. This objective can be achieved by standardized elements, properly designed to accept the various services, which can be made to form a uniform flat slab acting in two directions. The result will be a structure of great efficiency with remarkable span potentialities. (see sec.IX)

E. Mechanical Services

Proposed floor systems should accommodate general mechanical requirements including heating and air conditioning ducts, water and sanitary systems, and electrical service. With the aim of broad application and flexibility, generous perforations should be provided in the structural depth for mechanical installations. Hollowed structural columns and service cores have been considered as alternate sources for the vertical transfer of mechanical services. The latter system allows the use of solid columns which contain only storm water drains from the roof.

In every case access for altering and adding to the various systems without undue difficulty after the completion of the construction should be a prime requisite. (see sec.X)

F. Techniques of Construction

The utilization of precasting on a wide scale and the minimization of site pouring and hand labor is the principal point of departure in terms of construction. The possibilities of complex forms, high quality finish, precision and control which this technique offers recommends it for this problem. The unification of the precast members can be effected by the combination of post-tensioning and simple reinforcing.

Attention should be paid to the repetitive use of casting forms and the economic necessity of placing the precasting operation of a twenty-four hour cycle.

Form work and scaffolding which are the chief expenses of standard poured-in-place concrete construction can be significantly reduced through precasting, and in those proposals involving bay-length precast elements, can be virtually eliminated.

Indeed, the entire sequence of construction must be analyzed to determine the most efficient possible building operation.

G. <u>Architectural Services</u>

1. <u>Acoustical Treatment</u>

A variety of acoustical problems will be presented in the many building types which could conceivably make use of the proposed floor systems. In the absence of specific requirements, many situations must be anticipated. The common problems of lowering the sound intensity level, reverberation, and the sound isolation of particular spaces can be accomplished by accessory panels fitted within the surface geometry of the floor system.

Reflective surfaces can be provided for sound reinforcement in class rooms or small auditoriums. Good distribution and flutter control can be achieved with the use of faceted surfaces which could be the structural unit itself or an insert panel.

2. Lighting Facilities

The system should be coordinated to standard sizes of lighting components and should provide a framework for the simple installation of different types of fixtures according to functional needs. The installation or removal of lighting fixtures should not interfere with mechanical equipment passing through the voids above, although it might be desirable to use the fixture for air return intakes.

3. Partitioning

An orderly and flexible system of partitioning can be achieved by integrating partition layout with the structural ceiling grid. Standard details developed for joining partitions to the grid should allow the use of a wide variety of materials for partitions - masonry, precast concrete, gypsum, glass, or prefabricated metal panels.

Structural Notes

A. Description

The floor structure is a truss system in two directions. The bottom members of the trusses lie in a uniform orthogonal grid. The top members of the trusses are formed by the slabs. Connecting the top and bottom of the truss are chord members vertically placed in a two-way Vierendeel type system or chord members pivoted to form pyramids.

Uniformity of the system is maintained throughout since girders are not used for collecting load to transfer to the supports.

B. Definition

The ability to distribute moments caused by loading into two directions is possible because of the uniformly massed grid of the structure. The American Concrete Institute (1957) defines this type of uniform hollow concrete floor, which is reinforced in many directions, as a flat slab.

C. Design Approximations

The entire group of projects does not go into an exacting detailed analysis, for the calculations in these reports are only intended to provide a reasonable basis for intelligent preliminary sizing of the component parts.

1. Bending

The flat slab structures are designed for bending by the empirical provisions given by the A.C.I. Building Code (1957). To use these provisions, the structures are subjected to the many limitations of continuity and dimension. Two of these limitations are as follows:

a. 'The construction shall consist of at least three continuous panels in each direction.

b. The ratio of length to width of panel shall not exceed 1.33.'

The building code approximated the action of the floor by considering the structure divided into column strips and middle strips. Moment coefficients, based on tests and theoretical consideration, are suggested for different support conditions. It is realized that because these floor structures attempted to solve the shear condition without capitol heads or solid concrete panels, the coefficients used are even more approximate.

2. Shear

Calculations for shear are computed through ultimate design because of the simultaneous occurrence of maximum shear and maximum moment at the support. As the floor is overloaded, diagonal tension cracks will develop. Cracking reduces the beneficial effect of reduced diagonal tension. Inelastic steel deformations at loads near the ultimate largely eliminate the prestress benefit. This further loading will cause crushing of the concrete due to maximum moment becoming a more critical condition.

D. Reinforcing

The schemes presented achieve the integrity of a continuous floor by using both prestressing and ordinary reinforcing in various parts of the structure.

Careful consideration is given to the zones of prestress and regular reinforcing. The zones are present because of positive and negative bending. They are separated by points of inflection which may vary widely. The handling of the reinforcing in two methods is necessary because of the incapability of the floor structure to accomodate the passing of a prestressing cable from the lower chord of the truss to the upper chord without undue frictional loss or problems of precasting. The cable is needed in the lower chord, not for its strength, but for its ability to tie the precast structure together. Ordinary reinforcing is used in the top slab because of its ease of placement. Reinforcing from the precast elements which are left protruding at the top will be used to tie the structure at the floor slab when the slab is poured.

"As far as the load moment is concerned, there is no major difference (in structural action) between reinforced and prestressed two-way slabs. Then, both behave according to the elastic theory with the prestressed slabs following the theory more closely." [1]

At ultimate load, the prestressed slab loses the advantages of its initial forces. Prestressed concrete can then again be analyzed with moment coefficients that are used for reinforced concrete.

It can be observed from the structural calculations that a very nominal prestress force is needed. The reason for such a small cable over the selected span of 50' - 55' is due to the very deep floor slab. In as much as the

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[1] T. Y. Lin, Design of Prestressed Concrete Structures, p. 329.

depth is primarily determined by mechanical requirements, any significant reduction in depth may be impractical. A greater use of the depth can easily be achieved if shear problems can be solved. The design of the panel for working loads finds that enough shear area for longer bays is difficult to provide, especially if the elimination of the column capitol, which contains an overwhelming mass of concrete, is desired.

One possibility of distributing punching forces into the floor is by passing added steel over the support. This is the solution adopted by the three proposals.

If shear becomes intolerably excessive, the replacing of the negative reinforcing by post tensioned cables will increase the allowable shear to 300 psi (5000f'c) even without web reinforcement. 240 psi is considered high for ordinary reinforcing because of the tremendous amount of web steel needed. If this same web reinforcement were utilized with prestressed concrete, there is no limit to the amount of shear allowable.[2] The reason

[2] Freyssinet, Freyssinet Methods, chapter II.

for this vast difference in allowable shear is due to the fact that initial compression from prestressing reduces greatly diagonal tension (shear). Concrete is extremely poor in tension.

E. Column

The condition that added area for shear is desirable makes the hollow column with its extended perimeter a strong contender for the support of these floor systems.

Both the solid and hollow column have enough mass due to axial load consideration which provides more than needed for the small moment and minimum inertia specified in the code.

TABLE 305(a)—ALLOWABLE UNIT STRESSES IN CONCRETE

Description		Allowable unit stresses: For any strength of concrete in accordance with Section 302 $n = \frac{30,000}{f_c'}$	Maximum value, psi	For strength of concrete shown below: f_c' = 2000 psi $n = 15$	f_c' = 2500 psi $n = 12$	f_c' = 3000 psi $n = 10$	f_c' = 3750 psi $n = 8$	f_c' = 5000 psi $n = 6$
Flexure: f_c								
Extreme fiber stress in compression	f_c	$0.45f_c'$		900	1125	1350	1688	2250
Extreme fiber stress in tension in plain concrete footings	f_c	$0.03f_c'$		60	75	90	113	150
Shear: v (as a measure of diagonal tension)								
Beams with no web reinforcement	v_c	$0.03f_c'$	90	60	75	90	90	90
Beams with longitudinal bars and with either stirrups or properly located bent bars	v	$0.08f_c'$	240	160	200	240	240	240
Beams with longitudinal bars and a combination of stirrups and bent bars (the latter bent up suitably to carry at least $0.04f_c'$............	v	$0.12f_c'$	360	240	300	360	360	360
Footings*	v_c	$0.03f_c'$	75	60	75	75	75	75
(For flat slabs, see Chapter 10)								
Bond: u								
Deformed bars (as defined in Section 104)								
Top bars†	u	$0.07f_c'$	245	140	175	210	245	245
In two-way footings (except top bars)	u	$0.08f_c'$	280	160	200	240	280	280
All others	u	$0.10f_c'$	350	200	250	300	350	350
Plain bars (as defined in Section 104) (must be hooked)								
Top bars	u	$0.03f_c'$	105	60	75	90	105	105
In two-way footings (except top bars)	u	$0.036f_c'$	126	72	90	108	126	126
All others	u	$0.045f_c'$	158	90	113	135	158	158
Bearing: f_c								
On full area	f_c	$0.25f_c'$		500	625	750	938	1250
On one-third area or less‡	f_c	$0.375f_c'$		750	938	1125	1405	1875

*See Sections 905 and 809.

†Top bars, in reference to bond, are horizontal bars so placed that more than 12 in. of concrete is cast in the member below the bar.

‡This increase shall be permitted only when the least distance between the edges of the loaded and unloaded areas is a minimum of one-fourth of the parallel side dimension of the loaded area. The allowable bearing stress on a reasonably concentric area greater than one-third but less than the full area shall be interpolated between the values given.

PANEL			INTERIOR		EXTERIOR							
MOMENT			SUPPORT	CENTER OF SPAN	1ST. INTERIOR SUPPORT	CENTER OF SPAN	EXTERIOR SUPPORT		1ST. INTERIOR SUPPORT	CENTER OF SPAN	EXTERIOR SUPPORT
END SUPPORT							B	A			C
MARGINAL HALF COLUMN STRIP	SIDE SUPPORT	3	-12	+6	-13	+7	-8	-10	-17	+10	-3
		2	-18	+9	-19	+11	-12	-15	-25	+15	-3
		1	-23	+11	-25	+14	-16	-20	-33	+20	-3
MIDDLE STRIP			-16*	+16	-18*	+20	-20	-10	-24*	+28	-6
COLUMN STRIP			-46	+22	-50	+28	-32	-40	-66	+40	-6

← DIRECTION OF ALL MOMENTS →

Fig. 1004(f)a—Moments in flat slab panels in percentages of M_o—Without drops

See Table 1004(f) for notes and classification of conditions of end supports and side supports

*Increase negative moments 30 percent when middle strip is continuous across a support of type B or C. No other values need be increased.

Mechanical Notes

A. Air Conditioning

1. Problem

In buildings of generous dimensions, a typical floor may easily have three different temperature zones.

a. The temperature within the area 12-18 feet from the exterior wall (exterior zone) is considerably effected when subjected to climatic conditions.

b. That part of the exterior zone in sunlight is further distinguished from that in shade.

c. The effect of climatic conditions beyond the 12-18 foot band is negligible. Hot or cold days contribute very little to temperature change. Occupancy, lighting, machines, and conditioned air effect this portion of the building.[3]

2. Solution

Air is the only conditioning element able to accomplish the complex task of heating, cooling, dehumidifying, and ventilation. Because air is less efficient than water for carrying heat, the bulk

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[3]'Architectural Record', September, 1961, p. 230.

needed is enormous. This has dictated to a major extent the depth of the floor structures considered.

3. Source

The air which will service the floor will arrive from either of two sources, or both simultaneously.

Air that arrives horizontally to the structural bay is assumed to come from a source not more than 150 feet away. This assumption is based upon the maximum distance a room may be placed from a fire exit because of code restrictions. As is normally done, the fire exit is considered grouped in a utility core with the mechanical equipment which supplies the conditioned air.

A hollow column will serve as vertical service duct for air as well as other utilities supplied to the structural bay.

To conserve space, the heating and cooling systems will be assumed to share the same ducts.

4. Ducts

Because the air from the mechanical core may require an extensive dimension for supply ducts, the air supply may need to be delivered by many supply ducts in order to pass through the limited size of the horizontal openings within the floor.

Placement of ducts in the floor will be from below after the structure is complete.

Duct materials depend on required insulation, acoustics, flexibility, order, and ease of installation.

5. Diffusers

Normal velocities of air will be introduced into a room near the base of a wall. The heat will rise to the room's top, not only because of primary circulation, but also because of the effects of gravity. If cool air comes from the same diffuser, it is better to place it near the ceiling.

Exterior walls in the northern climates will always have air delivered from the exterior wall in order to counteract the draft created by cool air from the outside.

High velocity air will be introduced into rooms at the ceiling. This utilizes the ceiling level as an intermediate level to avoid drafts.

Exhausting may be done either by vent or diffuser or by allowing the exhausting air to travel through cracks to central exhaust ducts.

B. Electrical

The coordination of room partitions and floor areas with the services to them will be through the ordered, modular floor structure which is in accord with the partition module. Being a relatively insignificant consideration in terms of space required, electrical service can easily be incorporated in the floor slab as well as the voids of the structure. The ability of the system to service both the floor above and the floor below when placed within the hollowed floor produces significant flexibility.

C. Sanitary

Unlike the electrical system which may provide channels for future use, sanitary provisions are designed for specific cases. The predictability of the components of this system is entirely dependent upon specific planning problems. Because a pipe from this system may vary in pitch from one sixteenth of an inch to one half inch per foot, the ordering of these components with those of the heating system is necessary.

Research

A. Related Systems Previously Designed

The information available regarding the integration of mechanical systems with structural systems is limited. Few attempts at this type of study or the application of this type of thinking have been made. As a result there is a very limited amount of published material toward which one can turn for background information. The systems herein described were the only ones on which published material was available at the time of this thesis study.

TEXAS INSTRUMENTS SEMI-CONDUCTOR BUILDING FIGURE 1

O'Neil Ford and Associates, Architects

Description

This is a precast space frame system spanning 63' - 0" with poured-in-place tension and compression slabs which was designed for a factory with very specialized needs. The requirements were such that the mechanical systems had to be readily available; hence, the 9' - 0" depth to allow maintenance personnel to move freely within the depth of the mechanical floor. The top and bottom slabs are prestressed. The reinforcing of the pyramids is tied directly to the reinforcing of the slabs to provide the continuity necessary for two-way action.

The precast elements were cast as V's which were joined perpendicularly at the apex to form open pyramids.

Comments

The specialized mechanical demands of this program require a depth of structure which is not necessary in the typical building. The method of precasting and placing of the precast elements is appropriate to the large scale but at a smaller size would be impractical. The geometry provides a structurally efficient framework which can be adapted to a reduced depth.

LABORATORY FACILITIES FOR RESEARCH IN EXPERIMENTAL GEOLOGY FIGURE 2

The Architects Collaborative, Architects

Description

This system is composed of double main beams and double secondary beams between which the mechanical services are placed. Removable access panels on the inside of the building shield the services from view. The main beams span 22' - 11" and the secondary beams span approximately 20' - 0". The total depth of this poured-in-place system is 3' - 4".

Comments

The one-way system shown here is limited in the possibility of partition moving and flexibility of mechanical service placement. Because of the short spans and lack of uniformity, it has little potentiality for widespread application.

ADDITION TO THE MOORE SCHOOL OF ELECTRICAL ENGINEERING

FIGURE 3

Geddes, Brecher and Cunningham, Architects

Description

This system is an orthogonal grid with a 30" module which spans a space 50' - 0" by 60' - 0". The floor is raised above the structure by means of small posts at the intersection of the grid. This raising of the floor allows space for the mechanical services to pass. The structure, having a total depth of 3' - 4", is poured-in-place. The space is used for classrooms and offices.

Comments:

The structure is a straightforward solution, but it is somewhat limited in application because of the necessary perimeter beam and many perimeter columns. The module of the grid is so small (30") that maintenance or changing of the mechanical services is very difficult.

RICHARDS MEMORIAL RESEARCH LABORATORIES FIGURE 4

Louis I. Kahn, Architect

Description

The structure is of intersecting precast Vierendeel trusses which are post-tensioned horizontally and tied to the columns by means of vertical post-tensioning. The span is 45' - 0" square with columns at the perimeter at the third points. The structure is approximately 38" deep. The major trusses are in line with the columns and the secondary members span between the major members. The space is used for laboratories.

Comments:

The precasting and post-tensioning techniques employed are of special interest. The structural scheme is eccentric and not easily adapted to buildings of more than one bay.

YALE ART GALLERY FIGURE 5

Louis I. Kahn, Architect

Description

The floor structure is poured-in-place tetrahedrons 2' - 8" deep spanning 40' - 0". The code of New Haven required the architect to misuse the geometry by making some of the sides of the tetrahedrons continuous to achieve beam action.

Comments

This triangulated grid is not applicable to the usual orthogonal partitioning methods. The triangulated voids restrict the mechanical services as does the relatively shallow overall depth. The continuous "beams" allow only linear mechanical services, although they provide a good "cover" for the mechanical equipment.

A PROTOTYPE FLOOR STRUCTURE FIGURE 6

Master of Architecture Thesis Bruce Erickson M.I.T. 1960

Description

This system is composed of truncated precast pyramids with solid sides. Precast covers span between the pyramids and provide the forms for the poured-in-place slab. The pyramids are on a 4' - 0" module. The span of the system is 48' - 0" square and the total depth is 3' - 1½". The voids provide areas for the mechanical services to pass. The area 12' - 0" square around the columns is filled solid with concrete to provide a column capital.

Comments

The enclosed feature of the pyramids provides a finished quality to the ceiling but it requires installation of the mechanical services before the structure is complete. Therefore it is difficult to service or alter the mechanical equipment after pouring the slab. The column capital, which provides a good shear condition, restricts access to the area around the column for mechanical services.

A PROJECT BY NORTH CAROLINA STATE COLLEGE STUDENTS

FIGURE 7

Description

This was a project very similar to this thesis study. The bay size was 48' - 0" square with 6' - 0" and 12' - 0" modules and a 5' - 0" depth. The units precast were open pyramids of one module square, open tetrahedrons to form one module square and intersecting Vierendeel trusses cast in a variety of ways. In each case the rough slab was a precast unit on top of which the topping slab was poured.

Comments

This was a project directed more toward construction details of and building of scale models. Many features and dimensions were assumed which needed greater clarification.

"INTER-GRID" SYSTEM FOR PRE-FABRICATED SCHOOLS IN ENGLAND

Messres. Gilbert-Ash FIGURE 8

Description

"A prestressed concrete frame with precast cladding and internal partitions of gypsum plaster. This system, in spite of its adaptability, contains only twenty-six components; they are all small factory-cast units which are assembled and post-tensioned on the site." [4]

The basic structural floor unit is 3' - 4" long with a depth of 2' - 0". This system is used with spans up to 40' - 0".

Comments

This system is structurally sound and works for its particular application but it is not applicable to a wider range of projects. The 2' - 0" depth is too restrictive for ducts as is the diagonal element within the basic unit.

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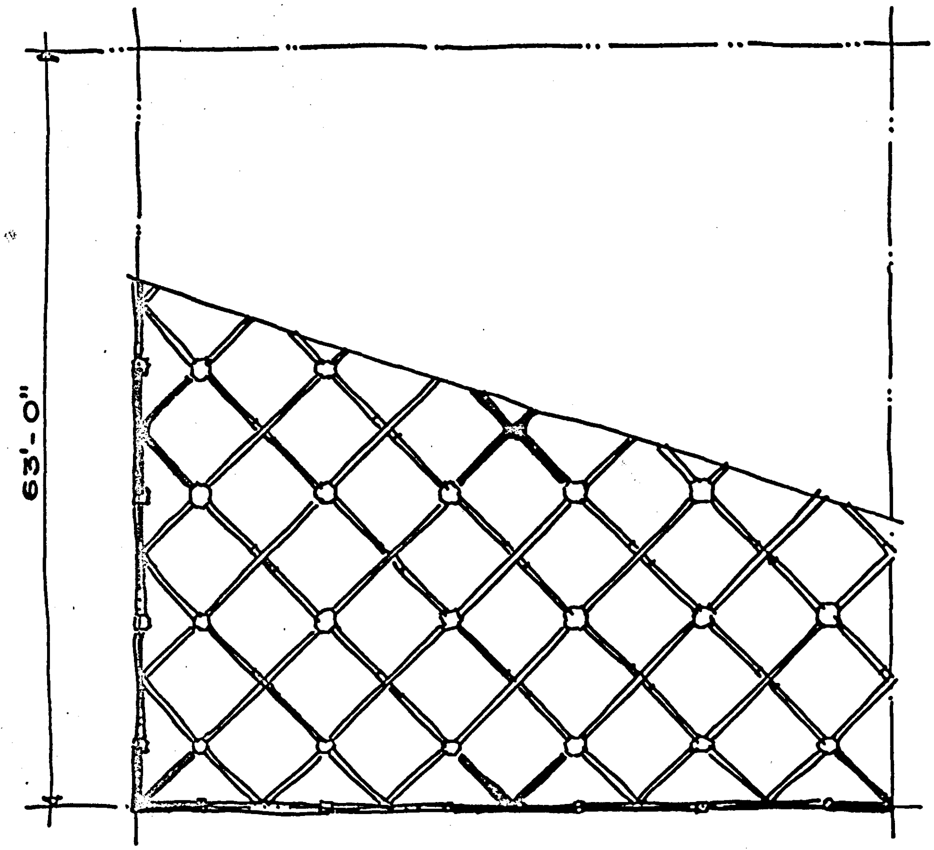
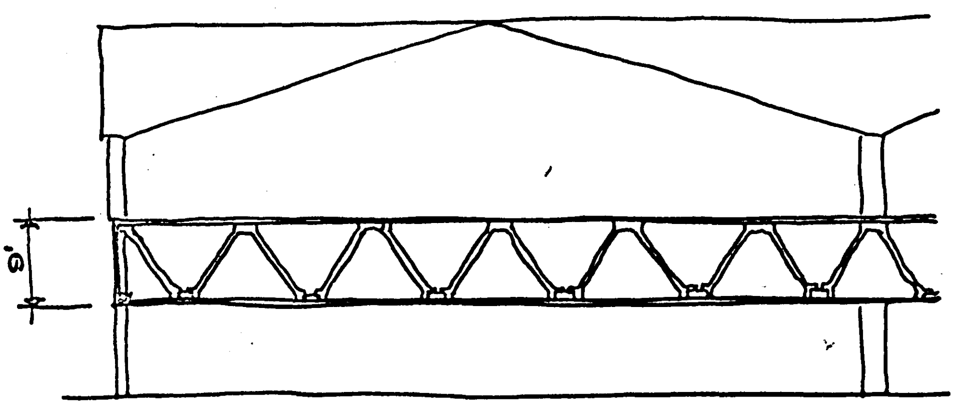
[4] Anthony Part, "Prefabricated Schools in Britain", Architectural Record, February, 1956, pp. 209-217.

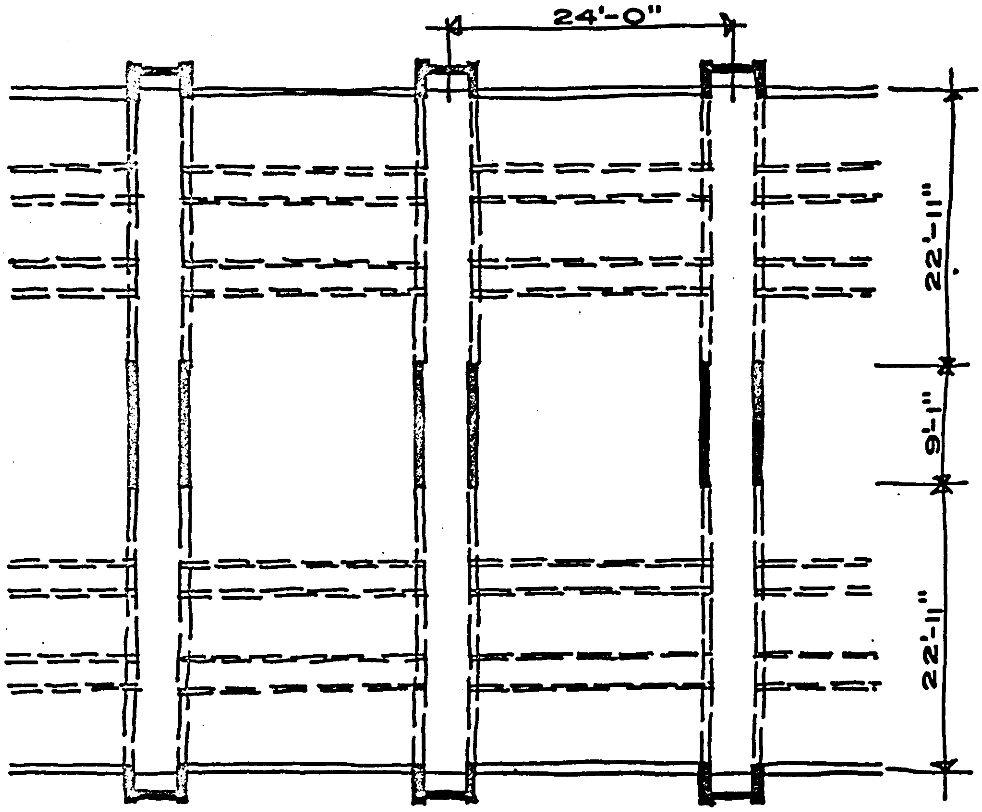


PLAN SCALE: 1/16" = 1'-0"

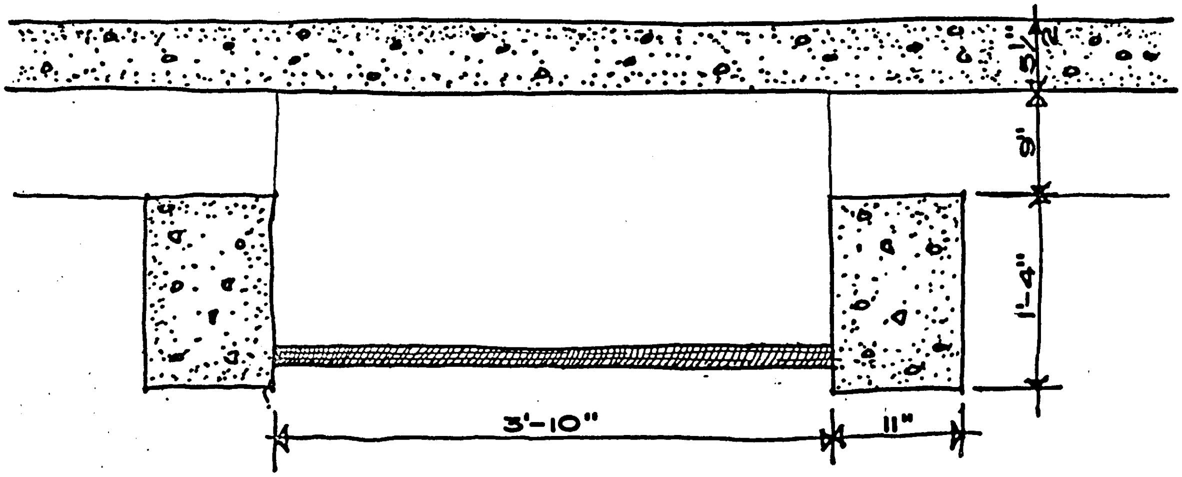


SECTION SCALE: 1/16" = 1'-0"

FIG. I TEXAS INSTRUMENTS BLDG. DALLAS, TEX.
O'NEIL FORD & ASSOC., ARCHITECTS

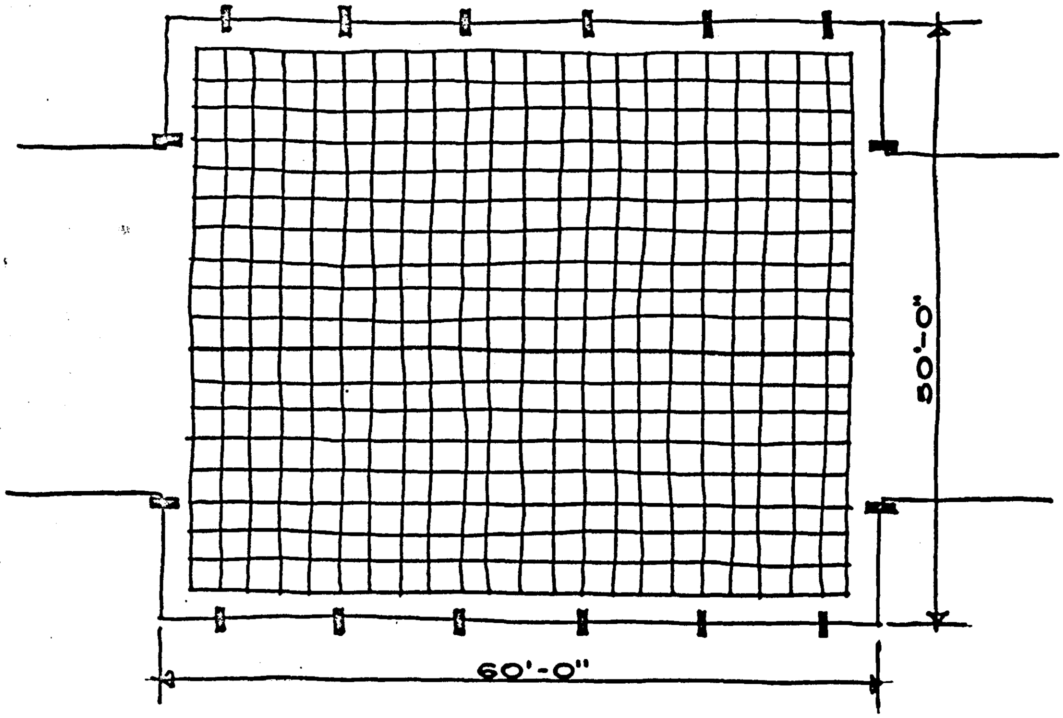


PLAN SCALE: 1/16" = 1'-0"

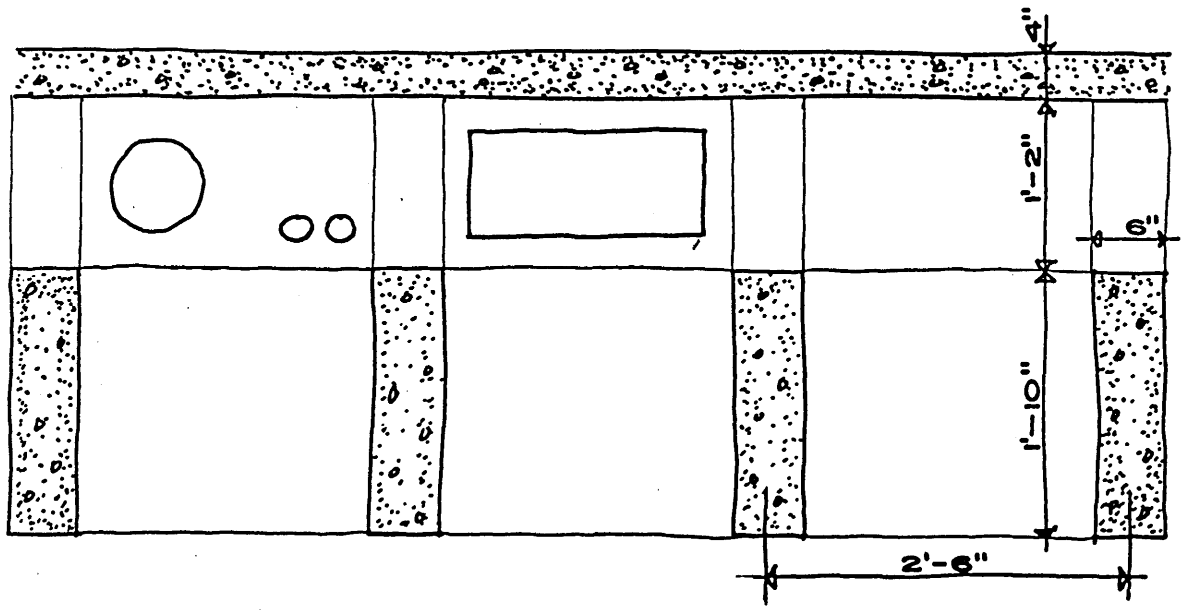


SECTION SCALE: 3/4" = 1'-0"

FIG. 2 LAB. FAC. FOR RESEARCH IN EXPER. GEOLOGY HARVARD
THE ARCHITECTS COLLABORATIVE, ARCHITECTS



PLAN SCALE: 1/16" = 1'-0"



SECTION SCALE: 3/4" = 1'-0"

FIG. 3 ADD'N. TO MOORE SCHOOL OF ELEC. ENG. U. OF PENN.
GEDDES, BRECHER & CUNNINGHAM, ARCHITECTS

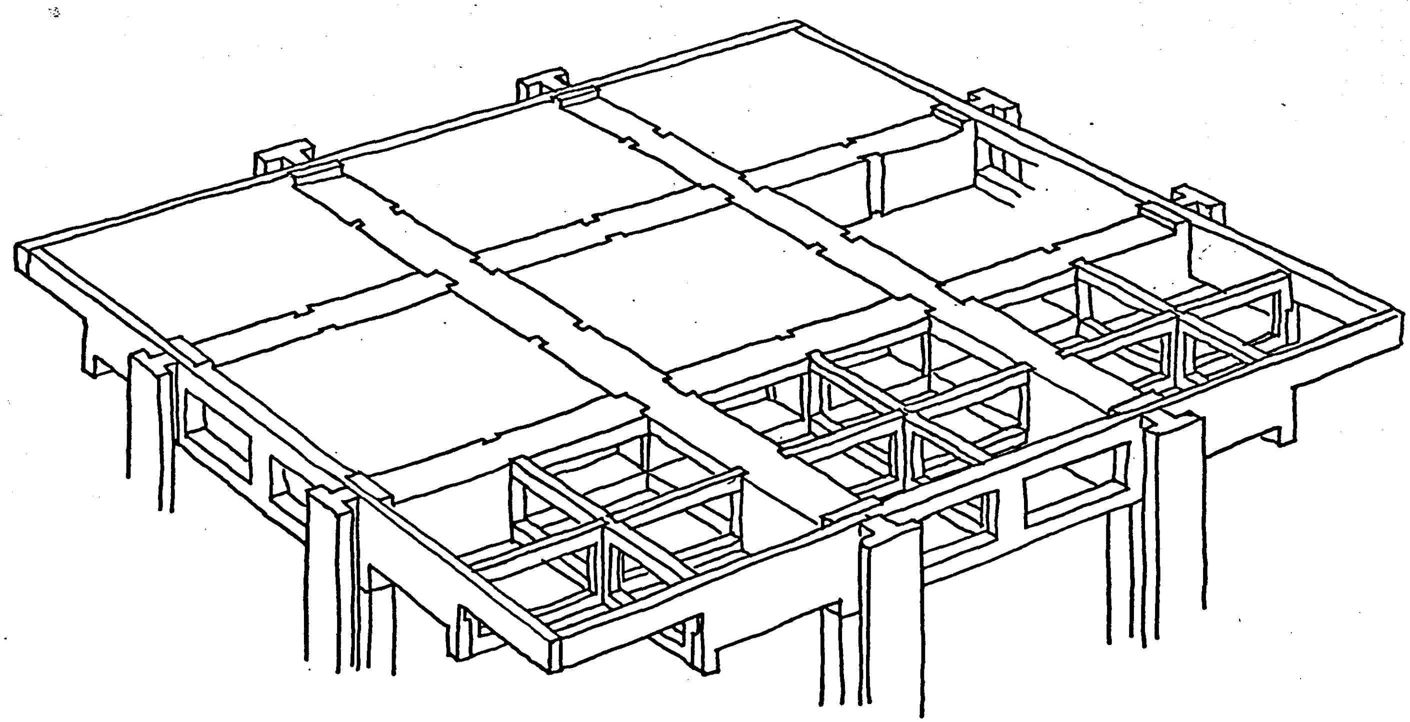
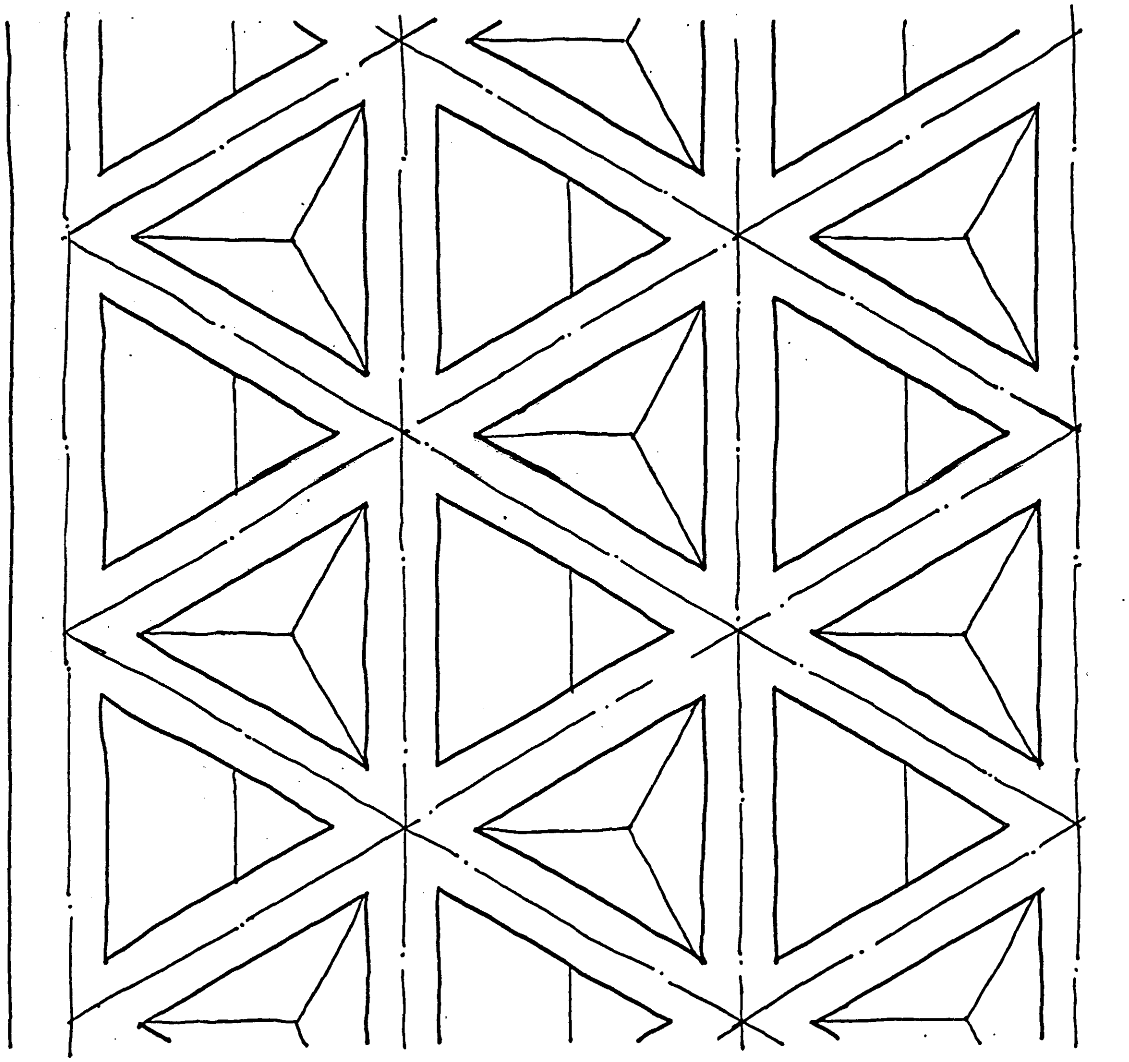
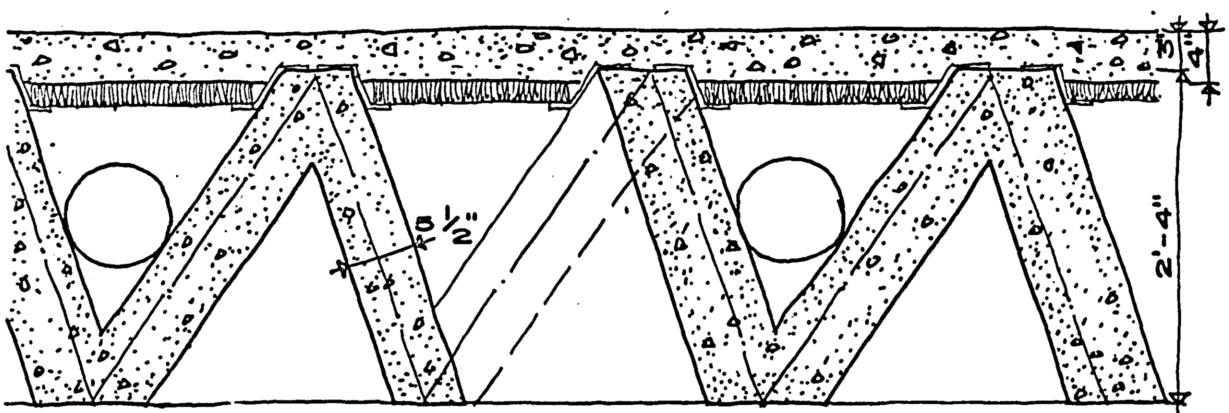


FIG. 4 RICHARDS MEMORIAL RESEARCH LAB. UNIV. OF PENN.
LOUIS I. KAHN, ARCHITECT



TYPICAL REFLECTED CEILING PLAN SCALE: 3/4" = 1'-0"



SECTION SCALE: 3/4" = 1'-0"

FIG. 5 YALE ART GALLERY YALE UNIVERSITY
LOUIS I. KAHN, ARCHITECT

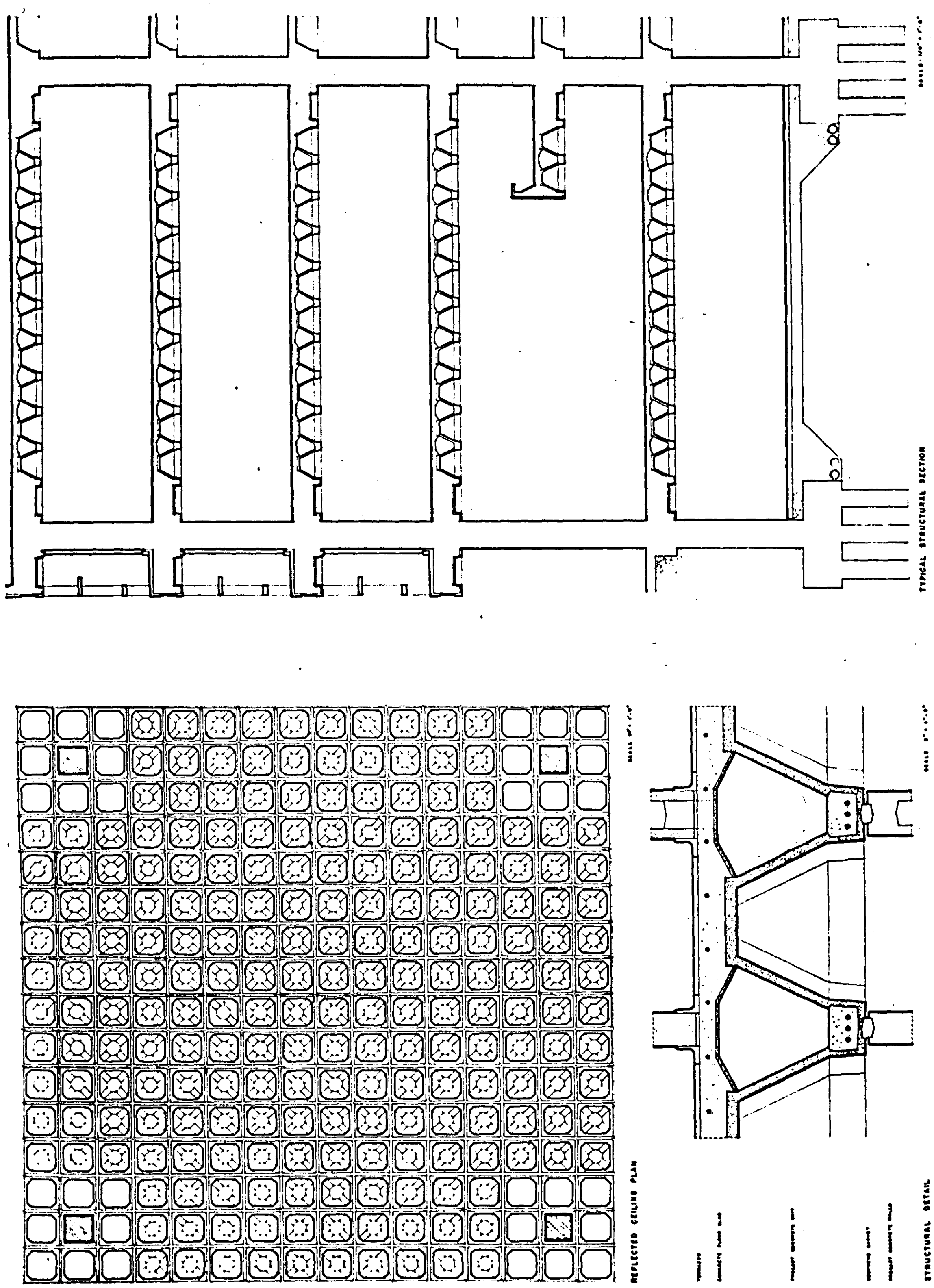


FIG. 6 A PROTOTYPE FLOOR STRUCTURE M.I.T.
BRUCE ERICKSON M. ARCH. THESIS 1960

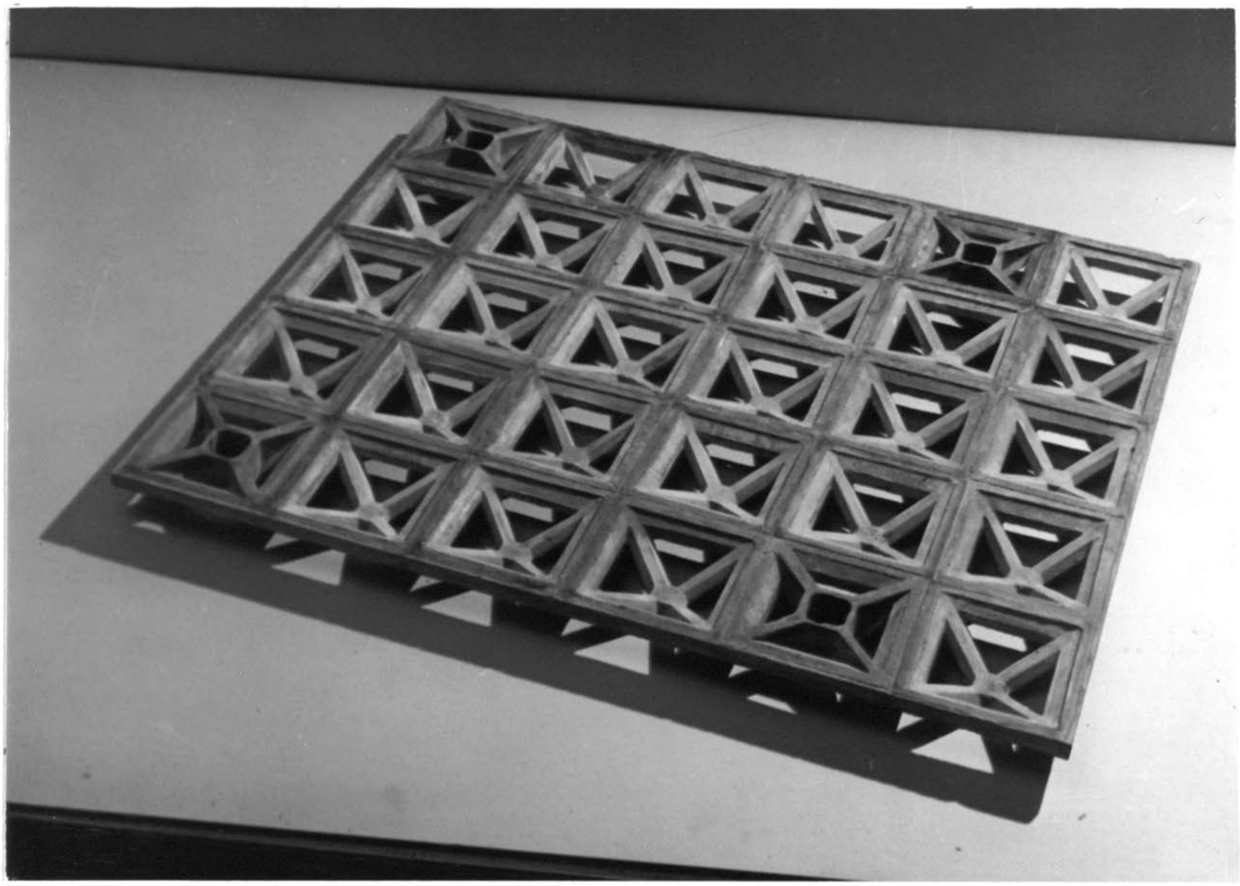


FIG. 7 STUDENT PROJECT NORTH CAROLINA STATE COLLEGE

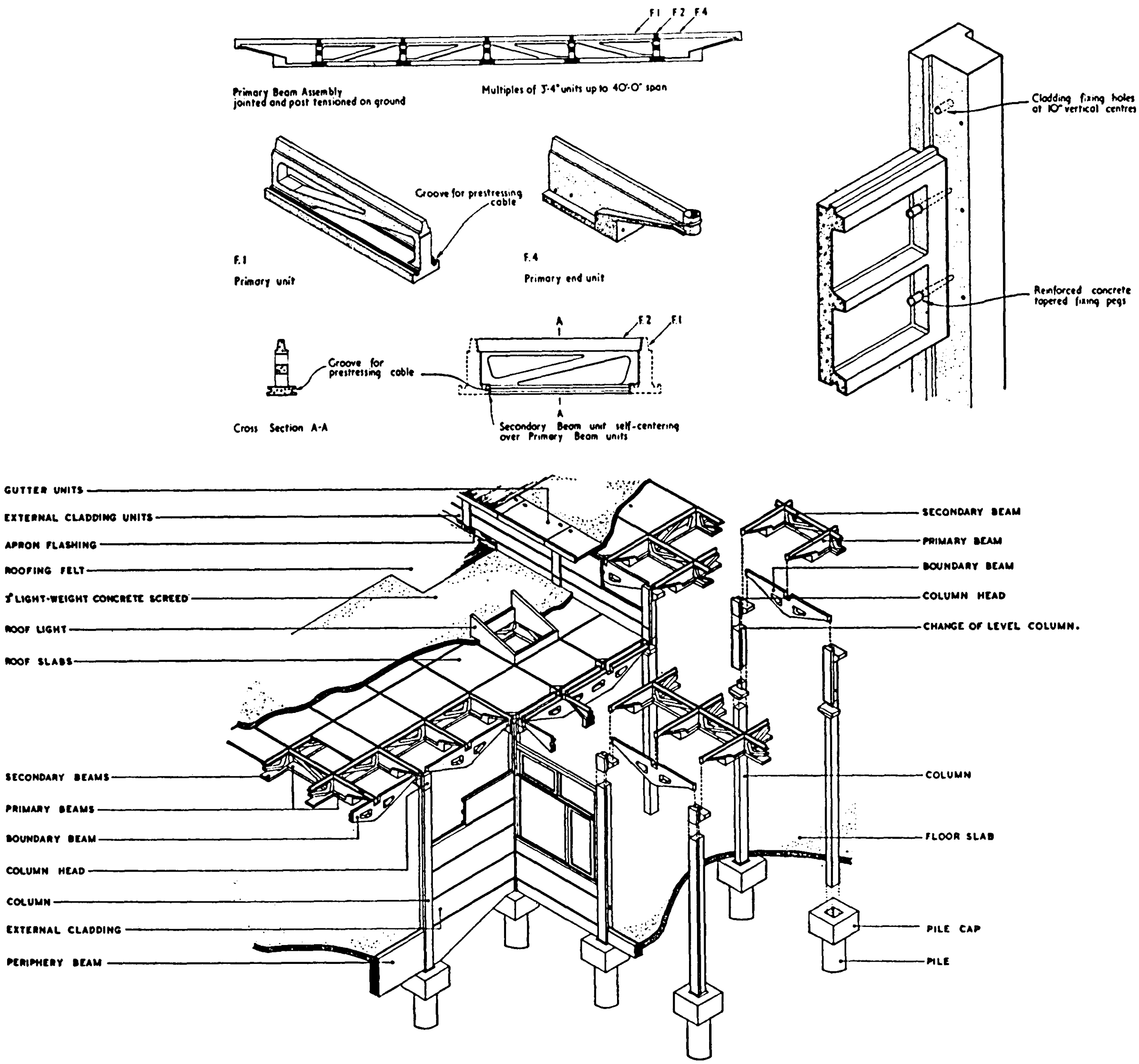


FIG. 8 "INTER-GRID" SYSTEM ENGLAND
MESSERS. GILBERT-ASH

B. Prestressing

Definition

"Prestressing means the creation of stresses in a structure before it is loaded. These stresses are artificially imparted so as to counteract those occurring in the structure under loading."[5]

Prestressing is done most commonly today by two means; pretensioning and post-tensioning. Pretensioning is the act of putting a stress on a wire or wires, pouring concrete around the wires, letting it set, and then releasing the wires which puts a force on the concrete section.

Post-tensioning is the act of putting a stress on a concrete section, after it has been cast, with a wire, cable or a high tensile rod.

Post-tensioning is an effective way of tying precast members together to act as one member. This

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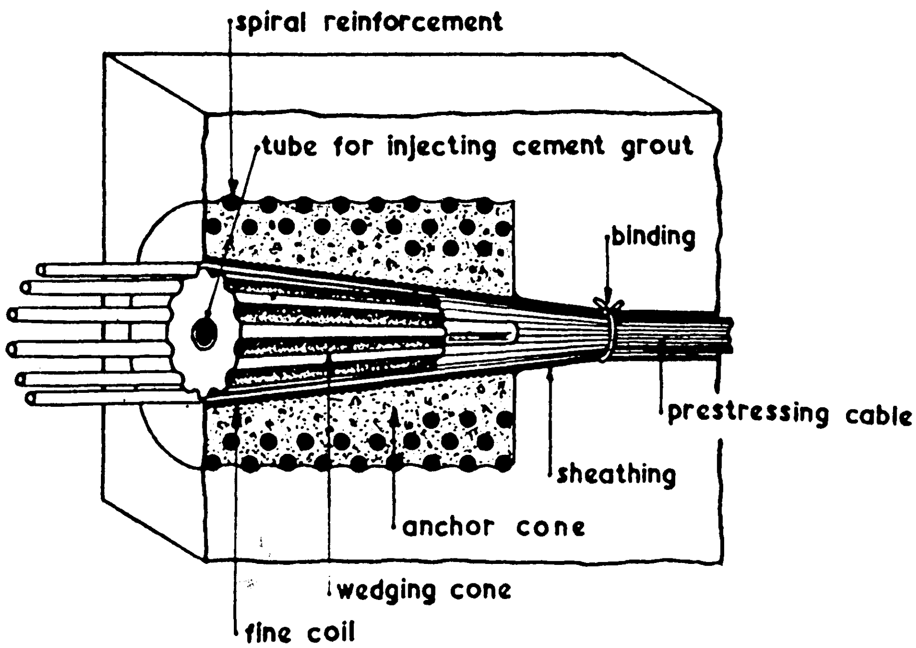
[5] P.W. Abeles, The Principles and Practice of Prestressed Concrete, p. 1.

is the method employed by the theses under consideration to help provide the continuity necessary for two-way action within the structure.

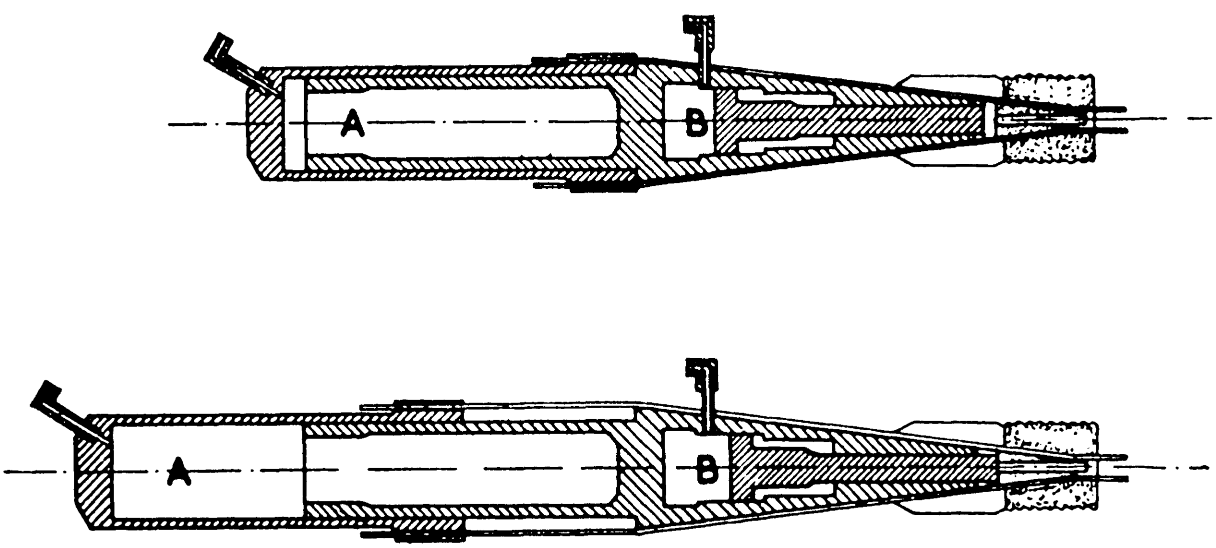
There are several patented systems for applying the stressing force and anchoring this force to the unit stressed. In selecting a system to use one must take into consideration the amount of prestress force needed. This will determine the size of jack used to apply the force to the cable. The force applied will also determine the size of the cable required. The size of jack will indicate the amount of clearance needed for its operation, and the size of the cable or cables will indicate the sizes of the anchorage and the hole needed to insert the cable. In considering the forces needed and the amount of clearance for jacks available, the authors decided to use the Freyssinet system (see fig. 9) of post-tensioning due to its apparent simplicity of operation, anchorage details, and the size of jacks available.

Oil is pumped into the piston A until the required extension is reached, after which piston B is pumped up to force the male cone



—Section through the Freyssinet anchorage

in. The wedges holding the wires are then knocked out and the jack removed. The wires are then trimmed and the cable grouted through the hole in the male cone.



—Freyssinet jack before and after stressing the cable

FIGURE 9

STRESSING SCHEDULE

Item	Description	Symbol	Value	Units
1	Type of Freyssinet Unit			
2	Area of steel per unit	A_s		sq. in.
3	Type of Freyssinet Jack			
4	Area of Jack Tensioning Piston	A_T		sq. in.
5	Jack Friction Coefficient	C		
6	Stress from (one) (two) ends			
7	Length of Cable (out-to-out of anchorages)	l		inches
8	Length from anchorage to marks	l'		inches
9	Total Stressing Length	$l+l'$	═══	inches
10	Cable Friction Coefficient	$e^{KX+\mu\alpha}$		
11	Required Final Stress	f_s		p.s.i.
12	Losses after Stressing:			
	a. Shrinkage of Concrete	L_s		p.s.i.
	b. Creep of Concrete	L_{cc}		p.s.i.
	c. Creep of Steel	L_{cs}	═══	p.s.i.
13	Required Average Initial Stress at Section investigated after stressing is completed	f_{si}		p.s.i.
14	Losses during stressing:			
	a. Elastic Shortening	L_e		p.s.i.
	b. Anchorage Set	L_d	═══	p.s.i.
15	Required Initial Jacking Stress at section investigated	f_1		p.s.i.
16	Anticipated Initial Stress at Jack	f_o		p.s.i.
17	Anticipated Gage Pressure	P_A		p.s.i.
18	Maximum Permissible Gage Pressure	P_M		p.s.i.
19	Elongation - 500 p.s.i. Pressure to Final Pressure	Δl_n		inches
20	Recommended Plugging Pressure			p.s.i.

NOTES

ITEM 1 and ITEM 2

Type Of Freyssinet Unit*	Area of Steel per Unit
8 - 0.196	0.241 sq. in.
10 - 0.196	0.302 sq. in.
12 - 0.196	0.362 sq. in.
18 - 0.196	0.543 sq. in.
12 - 0.276	0.718 sq. in.

* The first number indicates the number of wires per unit, and the second number indicates the diameter (in inches) of the individual wire.

ITEM 3, ITEM 4, and ITEM 5

Jack Type	Area of Jack Tensioning Piston	For Freyssinet Units	Jack (1) Friction Coeff.
A	10.35 sq. in.	10 - 0.196	1.10
B	12.70 sq. in.	8, 10, 12 - 0.196	1.10
C	12.60 sq. in.	12 - 0.196	1.07
D, F, (2)	24.90 sq. in.	18 - 0.196 (D) 12 - 0.276 (F)	1.07
E	16.70 sq. in.	18 - 0.196	1.10
H	24.50 sq. in.	12 - 0.276	1.10
J	12.13 sq. in.	12 - 0.196	1.10

(1) These factors have been determined by test.
(2) Interchangeable stressing heads.

CHAPTER 2 - DESIGN

201-ALLOWABLE UNIT STRESSES IN CONCRETE

Description		For any strength concrete	Allowable unit stress f'_c = 4000 psi	f'_c = 5000 psi	f'_c = 6000 psi
a) Stresses in completed structure					
Flexure: extreme fiber stress					
- compression	f_c	$0.40\ f'_c$	1600	2000	2400
- tension, no reinforcement	f_t	$-0.04\ f'_c$	-160	-200	-240
- tension, with properly designed reinforcement	f_t	$-0.08\ f'_c$	-320	-400	-480
Diagonal Tension: 1. at service load					
- without web reinforcement	S_t	$-0.02\ f'_c$	-80	-100	-120
- with properly designed web reinforcement	S_t	$-0.075\ f'_c$	-300	-375	-450
2. at ultimate load					
- without web reinforcement	S_t	$-0.06\ f'_c$	-240	-300	-360
- with properly designed web reinforcement		----- no limit -----			
b) Stresses during erection					
Flexure: extreme fiber stress					
- compression	f_{ci}	$0.55\ f'_{ci}$			
- tension, no reinforcement	f_{ti}	$0.06\ f'_{ci}$			
- tension, with properly designed reinforcement	f_{ti}	$0.09\ f'_{ci}$			

202-ALLOWABLE UNIT STRESSES IN PRESTRESSING STEEL

(a) Pretensioning:

1. Strand forces

Diameter	1/4"	5/16"	3/8"	7/16"	1/2"
Minimum Ultimate Load (lbs)	9,000	14,500	20,000	27,000	36,000
Recommended Design Load(lbs)	5,000	8,000	11,000	14,900	19,800

2. Evaluation of losses due to creep, shrinkage and elastic deformation:

$$8{,}000 + 15\ fcs + 0.06\ fsi$$

(b) Post-tensioning:

1. Initial stresses

Type cables	8,10,12,18x.196	12 x .276
Max. initial stress	$0.80\ f'_s$	$0.75\ f'_s$
Recommended initial stress	$0.75\ f'_s$	$0.70\ f'_s$

2. Evaluation of losses due to creep, shrinkage and elastic deformation:

$$3{,}000 + 11\ fcs + 0.04\ fsi$$

203-FRICTION IN POST-TENSIONING

(a) Values of coefficient of friction (f) and enclosure coefficient (K):

Type of enclosure	K	f
Preformed holes	0.001	0.50
Ungalvanized enclosure	0.002	0.30
Galvanized enclosure	0.001	0.20

(b) Determination of stress conditions at various points along the cable; see FRICTION LOSSES IN PRESTRESSING UNITS.

204-WEB REINFORCEMENT

(a) Diagonal tension at design load:

$$V' = V - P \sin\alpha \pm \frac{M}{d_r} \tan\beta$$

where: α = angle of prestress with neutral axis, including effect of haunch if used
β = angle of haunch

Using above shear, determine diagonal tension at c. g. c. by:

$$v = \frac{V'Q}{I\,b} \qquad S_t = \frac{P}{2A_g} - \sqrt{\left(\frac{P}{2A_g}\right)^2 + v^2}$$

(b) Diagonal tension at ultimate load:
Determine net shear as above when loads are multiplied by minimum specified safety factors, using the final prestress. Compute diagonal tension at c.g.c.

(c) Computation of amount of Web Reinforcement:
When the diagonal tension exceeds the allowable unit stress, web reinforcement shall be provided according to the following method which assumes a diagonal tension crack:

1. Compute slope of anticipated crack at ultimate based on values obtained under 205 (b).

   Horizontal projection of crack is:

$$\frac{jd}{tg\gamma} \text{ where } jd = \frac{I}{Q}, \text{ and } tg\gamma = \frac{S_t}{v}$$

2. Compute shear under external loads at ultimate on one side of the crack.

CHAPTER 3 - CONSTRUCTION

301-SPACING AND COVER OF PRESTRESSING STEEL

(a) Pretensioning:

	Cover (between surface & center of steel)		
	Members not exposed to weather (inches)	Members exposed to weather (inches)	Spacing c. to c. (inches)
Smooth wire (to .2")	1	2	1
5/16" strands	1-1/2	2	1-1/2
3/8" strands	1-1/2	2	1-3/4
7/16" strands	1-3/4	2	2
1/2" strands	2	2	2-1/4

(b) Post-tensioning cables:

Clear Cover (inches)		Clear Spacing (inches)	
Members not exposed to weather	Members exposed to weather	Hori-zontal	Verti-cal
1-1/2	2	1-1/2	1/2

Horizontal clear spacing between cables shall not be less than 1-1/2 times the maximum aggregate size.

(c) Post-tensioning Anchorages:

Type of Anchorage	8,10,12 x.196	18 x .196	12 x .276
Min. clear cover in beams (inches)	2	2-1/2	3
Min. clear cover in slabs (inches)	1	1-1/2	2
Min. spacing c. to c. (inches)	5-1/2	6-1/2	7

302-MIXING & PLACING CONCRETE

(a) All concrete shall be handled and placed in accordance with ACI 318-51, Chapter 4.

303-FORMS

(a) All forms shall be in accordance with ACI 318-51, Chapter 5.

304-STORAGE

(a) All members shall be lifted and supported at the same points as they will rest in the completed structure, unless otherwise approved by the Engineer.

305-POST-TENSIONING METHOD

(a) Post-tensioning cables shall be handled and stored in accordance with the Manufacturer's recommendations.

(b) All post-tensioning cables shall be secured at the ends by means of approved anchoring devices which shall be of such nature that they will not kink, neck down or otherwise damage the high tensile wire.

(c) No welding shall be done in the vicinity of cables unless special precautions are taken to prevent heating of wires and arc action from stray currents. Such special precautions shall be approved by the Engineer prior to commencing any welding.

(d) Stressing may commence when the concrete has reached a strength of 0.8 f'_c. Preliminary stressing to facilitate handling may be commenced at an earlier age, but stresses shall at all times be within the limits provided under Section 201.

(e) Stressing shall be carried out by means of jacks and calibrated gauges. The elongations shall be checked by means of measuring the gauge pressure on the jack, and any discrepancy shall be adjusted as directed by the Engineer.

(f) Stressing shall be carried out in a proper sequence so that excessive stresses are not induced in the member.

306-PRETENSIONING METHOD

(a) Welding in vicinity of high tensile steel shall be governed by Section 305 (c).

(b) Stressing may be achieved by stretching one strand at a time or in groups. The elongations shall be checked by measuring the force produced thereby and any discrepancy shall be adjusted as directed by the Engineer.

(c) Release of pretensioning shall not commence until the concrete has reached a strength sufficient to resist the stresses induced therein by the strands, but in no case shall the strength be less than 3,500 psi for strands up to 3/8" diameter, and 4,000 psi for 7/16" and 1/2" diameter strends, as measured on standard cylinders cured under the same conditions as the product. In order to prevent overstress of strands due to temperature reduction when reducing the curing temperature, partial release of prestress will be permitted; otherwise, maintain steam temperature until final release.

(d) Release of strands shall be in such a manner as to minimize any lateral eccentricities. Release shall be gradual and in general simultaneous.

A. PROPOSAL 1 Robert P. Burns, Jr.

1. <u>Individual Objectives</u>

In addition to the basic criteria common to all three of the individual projects, the following objectives and limitations have guided the development of Proposal 1 and distinguish it from the other two proposals:

a. To make a comparative study of the two common geometrical systems adopted for the problem - intersecting Vierendeel trusses and the pyramidal frame.

b. To utilize for each system precast elements which have the basic dimensions of one module, 5' X 5' X 4'.

c. To propose logical and economic techniques for unifying the precast elements into a monolithic structure.

d. To evaluate the two systems with respect to
   (1) Structural efficiency
   (2) Precasting

(3) Integration of mechanical and architectural services

(4) Weight of floor system

(5) Visual expressiveness

2. Preliminary Proposal

a. Assumption

In preliminary studies, the source of all mechanical services was assumed to be one or more utility cores in which would be incorporated air conditioning equipment, toilets, vertical chases for mechanical services as well as fire exits, elevators and other utility requirements. Air ducts and other mechanical services would be introduced into the slab from the side. No vertical service other than storm water drainage and ventilation pipes were required within the system.

b. Description

The preliminary designs are quite similar to the final proposal, differing in certain dimensions, details, and general completeness. To avoid repetition they will be discussed briefly and the final proposal described more exhaustively.

(1) Scheme "A"

The floor slab in its completed state is formed by an orthogonal grid of intersecting Vierendeel trusses supported on four columns 50' on centers.(fig. 10) The typical precast unit (fig. 11) is a four-sided box perforated on each face to permit the passage of mechanical services. Its dimensions from center to center of opposite faces is 5', although its overall dimensions are larger by the thickness of the side (8" at lower edge, slightly larger at top).

The units are assembled by joining them at the corners. Grout is poured into the recess, forming a key to insure against slippage. Grooves in the underside of each rib accommodate the post-tensioning cables which are necessary in areas of positive moment for unifying the precast members. Grouting could be done from below. The structure would then be completed by placing specially

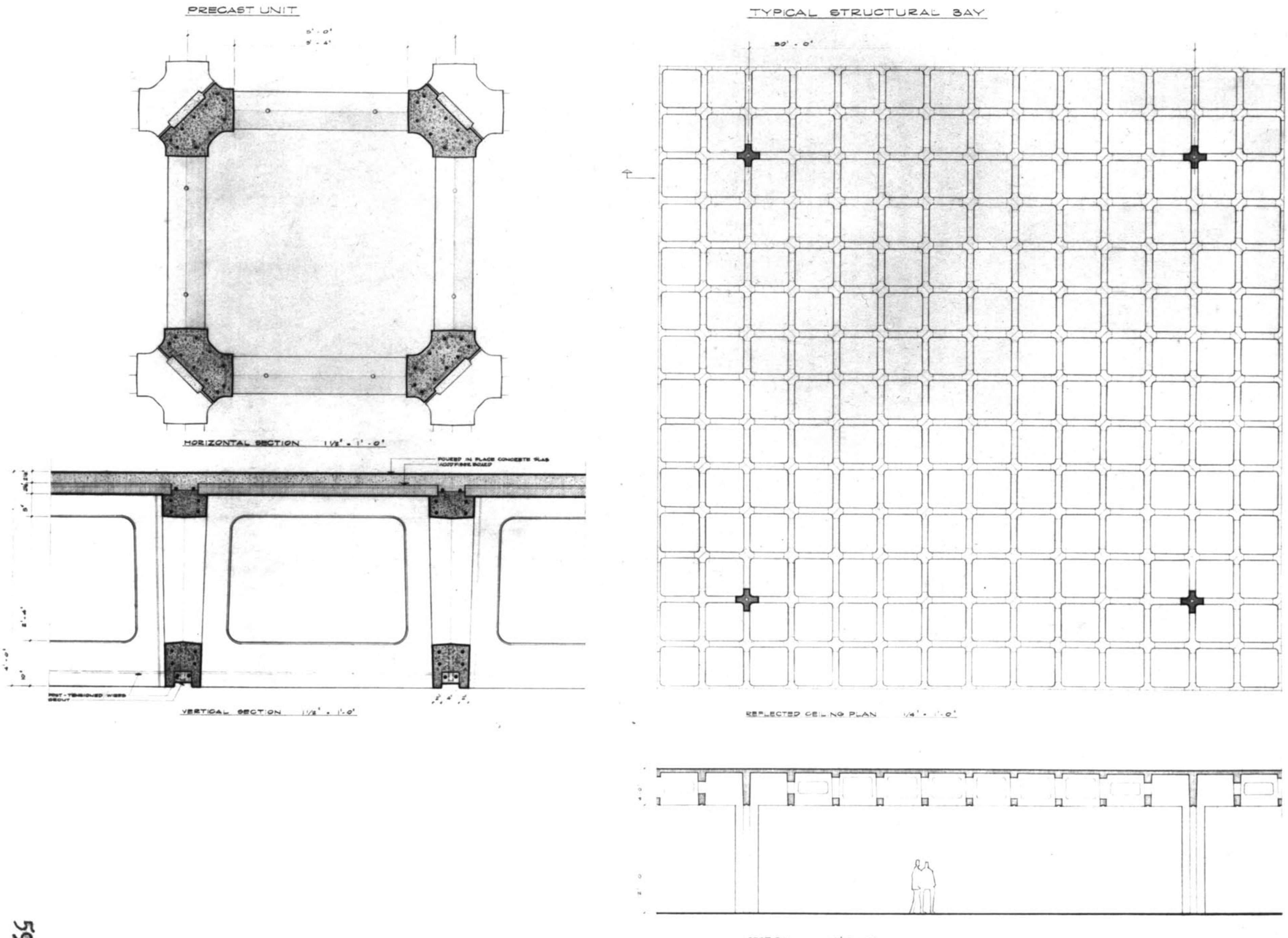


FIG. 10 PRELIMINARY PROPOSAL - SCHEME "A"

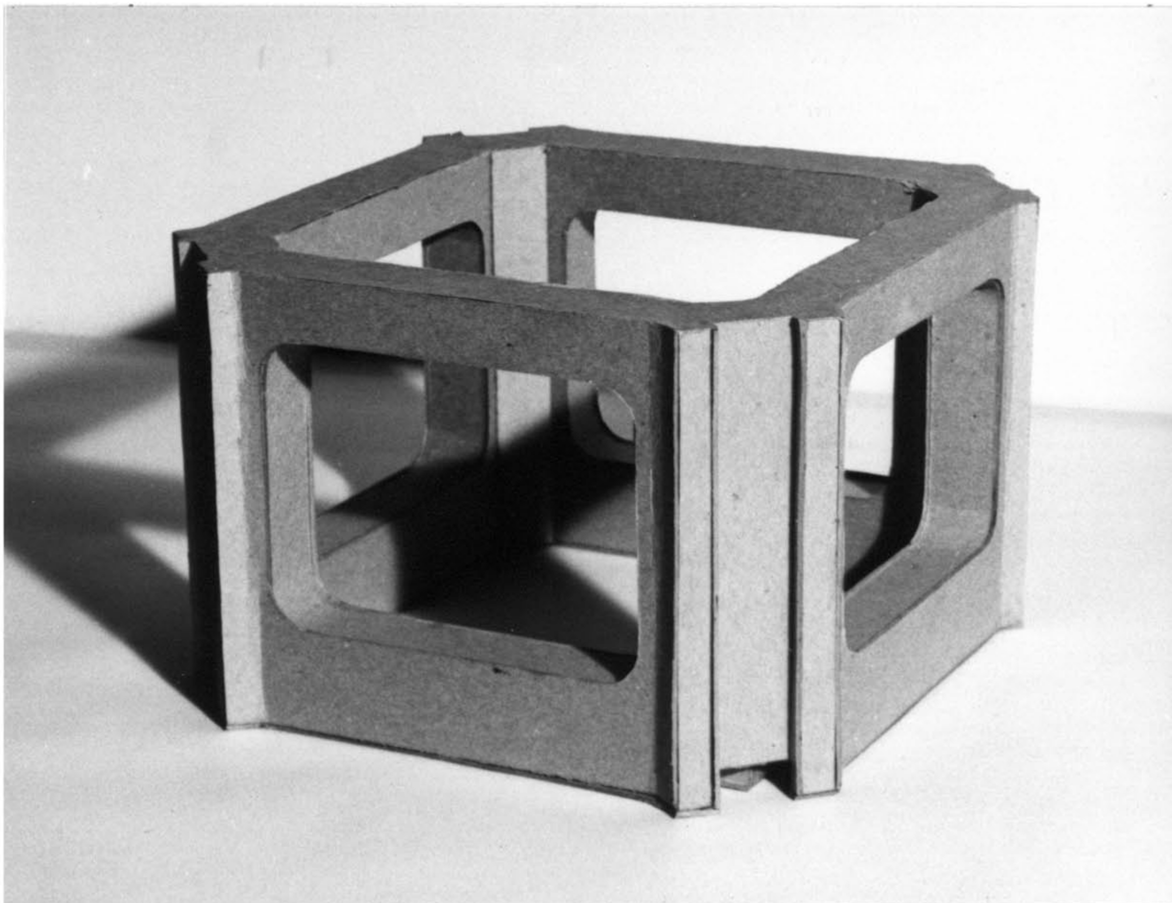


FIG. 11 MODEL PRECAST UNIT - SCHEME "A"

formed panels of a mixture of wood fibers and cement (similar to products manufactured under the trade names of 'Tectum' by the Tectum Corporation and 'Insulrock' by the Flintkote Company) to serve as the form for the cast-in-place reinforced floor slab. The acoustic advantage offered by their absorptive quality makes their use doubly beneficial.

The column is conceived basically as a cruciform shape, 30" face-to-face, to conform to the crossing of the ribs. It is poured-in-place and contains a drain pipe for storm water from the roof.

Although no detail calculations had been made at the time of the preliminary study, the problem of shear concentration is recognized by the elimination or reduction of openings in ribs in the column area.

(2) Scheme "B"

The floor structure (fig. 12) is loosely interpreted as a flat slab formed by precast pyramidal units and a cast-in-place floor slab. The precast unit (fig. 13) is approximately 5' X 5' X 4' and its four inclined faces are perforated to accommodate passage of mechanical services.

A slot for post-tensioning is provided between the lower edges of adjacent units. The floor is formed as in the previous scheme by supporting cement-wood fiber panels in the apex of the pyramids and pouring a reinforced concrete slab.

The structure is assumed to act similarly to Scheme "A", and the erection procedure is virtually the same.

However, there are two dissimilarities which should be acknowledged. One is the necessity of providing twice as many precast pyramidal units as box units (Scheme "A") for the same area.

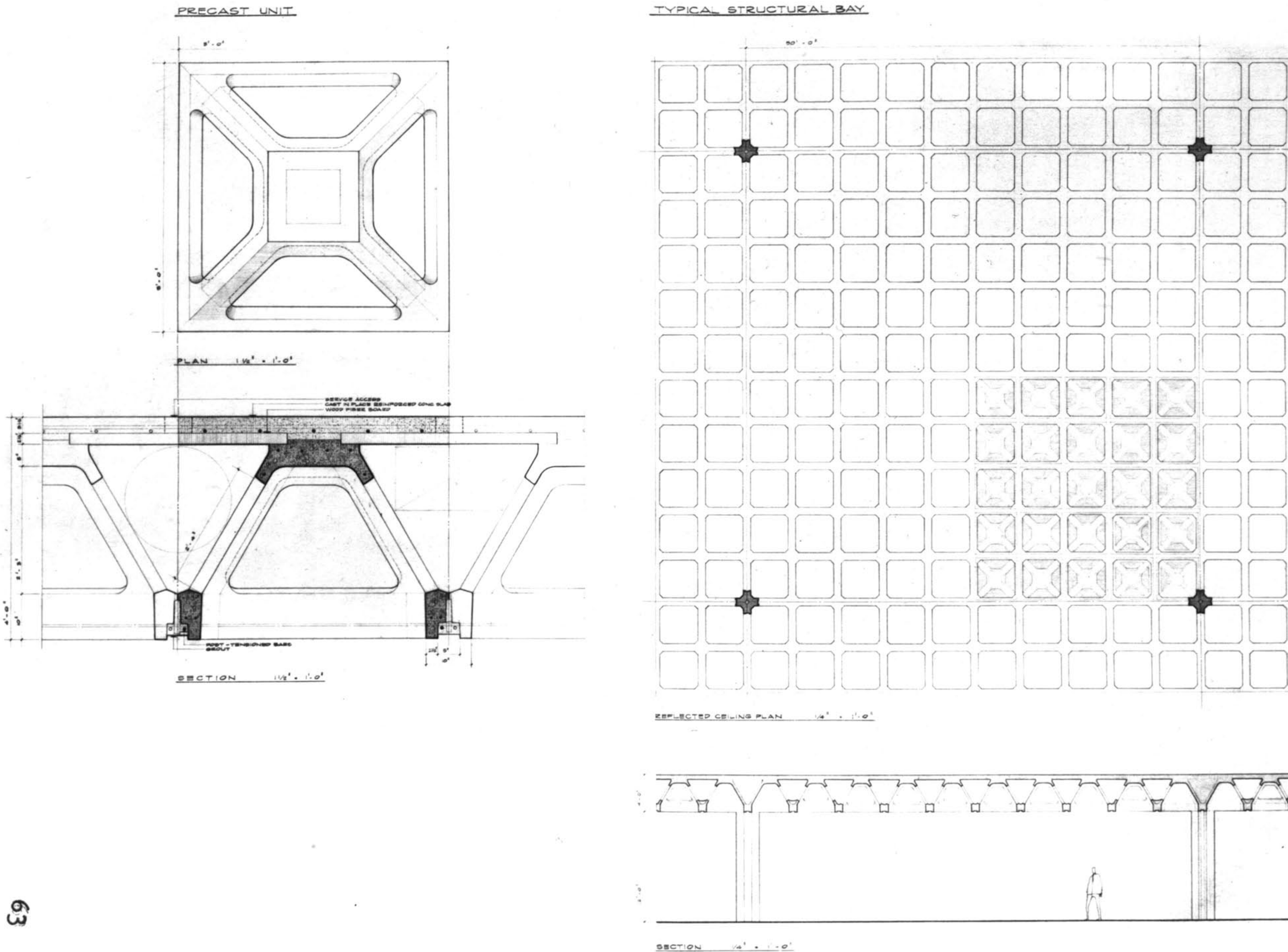


FIG. 12 PRELIMINARY PROPOSAL - SCHEME "B"

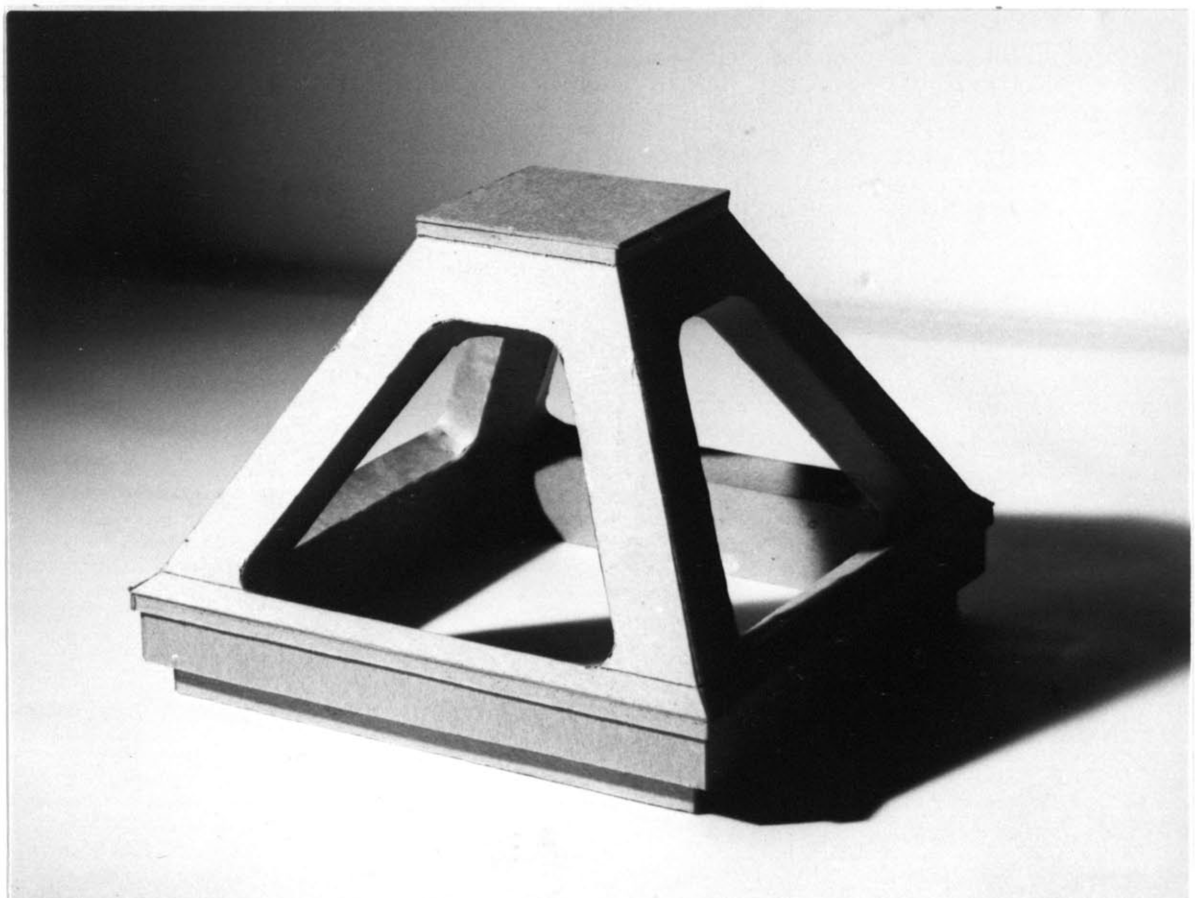


FIG. 13 MODEL PRECAST UNIT - SCHEME "B"

While more than twice as heavy, each box unit in effect gives a structural coverage of 50 sq. ft. The pyramid on the other hand supports only 25 sq. ft. The second dissimilarity is the possibility of furnishing great shear resistance in the pyramidal system without destroying its visual uniformity or its capacity for mechanical integration. This can be achieved by providing a large amount of concrete in the valleys formed by the pyramids.

3. Comments

While recognizing the practicability of both systems, an appraisal of the preliminary proposal can lead to a more thorough and accurate final solution. The following comments and criticisms served as a basis for continued investigation, development and refinement of the original schemes.

a. Mechanical

Total reliance on utility core for vertical passage of services limits versatility of structure. Supplementary vertical chases which could be accommodated within hollow structural columns would permit greater mechanical and functional flexibility.

b. Structural

Shear is the critical problem in flat slabs of the proposed dimensions lacking capitals or solid panels over the columns. This is especially true in the case of Scheme "A" when the total shear force must be transferred through only 4 ribs. A detail study of special shear reinforcing for such sections is essential. The problem can be substantially reduced by utilizing a larger column which could distribute the shear forces over a greater number of ribs.

c. Details

Post-tensioning has clearance requirements which must be provided in final solution. Zones of post-tensioning and anchorage details should be clearly indicated.

Grouting of post-tensioned cables from beneath creates specialized problems of detailing especially in the case of the pyramidal system. A simplification of the precast element to allow grouting from above is desirable.

Dimensions of both precast elements should be revised to conform to approximate structural analysis. A general reduction of most dimensions is possible. Inclination of the faces of precast box complicates forms.

Cement-wood fiber panel used as slab form in the pyramidal system acts as a flat slab bearing on 4 corners. Reinforcement, by stiffening of the edge, is necessary.

Such conditions as the column to slab connection and the slab edge detail must be investigated. Insert panels for acoustic insulation, lighting fixtures, and a standard detail for joining partitions with the structure should be indicated.

4. Approximate Structural Analysis

The following analysis is made in conformance with the ACI code standards for flat slabs. Prestressing formulas used were taken from The Design of Prestressed Concrete Structures by T. Y. Lin. Calculations are made only for primary slab flexure & shear forces. Localized conditions have not been analyzed. While the analysis has been performed for the typical case, the system of intersecting Vierendeel trusses in a 50' square bay supported by hollow columns, the approach can be applied to the case with solid columns and extended to the pyramidal system.

a. Data

Dead load -	precast unit (2800 #total)		56.00psf
	3" floor slab		37.5
	cement-wood fiber panel		5.25
	ducts		5
			103.75psf
		use	105.0 psf
Live load			100.0 psf
		w =	205.0 psf

Dimensions of bay	50' X 50'
span (L)	50' or 600"
area	2500 sq. ft.
Total weight (W) 2500(205)	512,500 lbs.
Depth of column (C)	68"

b. Bending Moment

$M_o = 0.09\ WLF\ (1-2c/3L)^2$

$F = 1.15 - c/L \quad 1.037$

$M_o = 24{,}500{,}000$ in. lbs.

Middle strip, positive moment = $.16M_o$

= +3,920,000 in. lbs.

Middle strip, negative moment = $.16M_o$

= -3,920,000 in. lbs.

Column strip, positive moment = $.22M_o$

= +5,400,000 in. lbs.

Column strip, negative moment = $.46M_o$

= -11,300,000 in. lbs.

c. Flexural Calculations

(1) Middle strip, positive moment

F = prestress force

h = 48"

$$F = T = \frac{M_t}{0.65(h)} = \frac{3{,}920{,}000 \text{ in. lbs.}}{0.65\ (48")}$$

= 126,000 pounds

A_s (over 5 ribs) = F/fs (use fs = 125,000 psi)

$$= \frac{126,000 \text{ lbs}}{125,000 \text{ psi}} = 1.01 \text{ sq. in.}$$

use prestress cable 8-0.196

(.241 sq. in.)

Freyssinet System

(2) Middle strip, negative moment

$$T = \frac{M_t}{h} = \frac{3,920,000 \text{ in. lb.}}{44''}$$

$$= 89,000 \text{ lbs.}$$

$$A_s \text{ (over 25')} = \frac{T}{fs} = \frac{89,000 \text{ lbs.}}{20,000 \text{ psi}}$$

$$= 4.45 \text{ sq. in.}$$

use #4 bars 10" o.c.

(3) Column strip, positive moment

$$F = \frac{M_t}{0.65h} = \frac{5,4000,000 \text{ in. lbs}}{0.65(48'')}$$

$$= 173,000 \text{ lbs.}$$

$$A_s \text{ (over 5 ribs)} = \frac{173,000 \text{ lbs.}}{125,000 \text{ psi}}$$

$$= 1.48 \text{ sq. in}$$

use prestress cable 10-0.196 (.302 sq. in)

Freyssinet System

(4) Column strip, negative moment

$$T = \frac{M_t}{h} = \frac{11,3000,000 \text{ in. lbs.}}{44''}$$

$$= 257,000 \text{ lbs.}$$

$$A_s \text{ (over } 25') = T/fs = \frac{257,000}{20,000}$$

$$= 12.85 \text{ sq. in.}$$

use #6 bars 10" o.c.

d. Compression Calculations

Critical section (column strip, negative moment) is checked to determine safety of assumed area.

$f'c = 5,000$ psi

$fc = 2250$ psi

c_1 (5 ribs) = 5 (70") (3/4) 2250 psi

= 591,000 lbs.

c = 257,000 lbs.

Assumed section is safe

e. Shear Calculations

Area = 2500 sq. ft.

Total Dead load (B) = 105 psf X 2500 sq. ft.

= 262,500 lbs.

Total Live load (L) = 100 psf X 2500 sq. ft.

= 250,000 lbs.

$U = 1.2\,B + 2.4\,L$ (total load with safety factor)

$U = 315{,}000 + 600{,}000 = 915{,}000$ lbs.

Total shear force is distributed over 8 ribs which are supported by the column.

$$V = \frac{U}{8} = \frac{915{,}000}{8} = 114{,}400 \text{ lbs.}$$

$$v \text{ (ultimate)} = \frac{V}{bd} = \frac{114{,}400 \text{ lbs}}{8''(65')} = 220 \text{ psi}$$

$$v_c \text{ (allowable)} = 90 \text{ psi}$$

$$v_s = V - V_c = 220 - 90 = 130 \text{ psi}$$

$$V' = 67{,}6000 \text{ lbs.}$$

$$Av = \frac{V^1 s}{fvjd}$$

$$Av = \frac{67{,}600 \text{ lbs. } (12'')}{20{,}000 \text{ psi } (.875)\ 46''}$$

$$= 1.01 \text{ sq. in. per foot}$$

use #6 U type stirrups 10" o.c.

5. Final Proposal

a. Description

It has been assumed unnecessary to investigate both solutions in the same degree of detail. The system of intersecting Vierendeel trusses has been selected for the more thorough study, not out of preference for it as a structure, but because it had been chosen for structural analysis and can be more accurately detailed. Because of the dimensional similarity of the two systems, it is assumed that most details indicated for the first case could be adapted to the pyramidal system with minor alteration.

(1) Scheme "A" (intersecting Vierendeel trusses)

(a) Structure

In its final form, the floor structure is composed of intersecting Vierendeel trusses on an orthogonal grid having a module of 5' X 5'. Total depth of the floor is 4'. A typical square bay with columns on 50' centers has been studied although the system is considered practical for spans from 40' to 70' with few modifications. (see drawing 1)

The typical precast unit is a four-sided perforated box (see drawing 2) similar to the one described in the preliminary proposal, but certain dimensions have been altered to correspond more closely to demands arrived at through calculations. The result has been to produce a lighter structure of more delicate proportions. Inclination of the faces, present in the earlier study, has been eliminated to simplify pre-casting forms.

Reinforcement is minimal in typical units, although shear reinforcement is increased and voids in the ribs either reduced or omitted in units to be placed in the area of the column. Overall dimensions of precast unit and ribs has been maintained as a constant throughout the system.

While the considerable depth of the structural slab greatly reduces flexural problems, it is necessary to bind the units into a monolithic structure by a light post-tensioning cable extending along the recess in the lower ribs. To avoid increasing the already high negative bending moments, the cable is interrupted beyond the point of counter flexure and standard reinforcing steel is used in areas of negative moment. Grouting is done from below.

Steel ties are extended from the top of the precast unit to effect a connection with the simply-reinforced floor slab which is cast in place on cement-wood fiber forming panels.

Alternate solutions for the column (see drawing 4) are based on mechanical demands and the magnitude of shear forces. Where supplementary vertical chases are required for mechanical services in addition to those supplied in the utility core, the hollow column is a logical result. Furthermore, it offers structural advantages in longer spans where shear forces are unusually great; maximum shear can be distributed over 8 solid ribs as apposed to 4 in the solid column solution. The solid column finds reasonable application in structures of moderate dimension (40'-50') having few special mechanical needs. Even so, special reinforcing details are necessary (over the column) for shear and continuity. Both columns are cast in place and vertical continuity is achieved by overlapping reinforcement according to standard practice. (see drawing 4)

(b) Techniques of Construction

1) Precasting

In order to achieve a high degree of efficiency, the precasting operation must be placed on a twenty-four hour cycle. This could be accomplished and a good finish obtained through the use of steel or plastic, fiberglass reinforced, forms. A base platform and eight connecting side forms, 4 interior and 4 exterior, would be required. The forms could be quickly stripped and re-used many times.

2) Post-tensioning

Post-tensioning is accomplished by means of the Freyssinet system described in section . Allowances are made for the jack clearance and special surfaces are provided in the precast units for cable anchorages. (see drawing 5)

3) Erection

The most efficient procedure of erection for such a structure is an involved calculation requiring the cooperative counsel and knowledge of the contractor, engineer, and architect. The following step-by-step procedure of erection is a proposed outline which could guide a more detailed investigation of the problem (see drawing 3):

1. Placement of footings, foundations, basement.
2. Erection of column formwork and

pouring of column up to ceiling level.

3. Erection of scaffolding
4. Placement of principal precast structural units.
5. Pouring of grout to form vertical keys and pouring of column to floor level.
6. Post-tensioning operation and grouting of lower ribs.
7. Placement of cement-wood fiber panels.
8. Slab reinforcement placed and slab poured.

At this point procedure reverts to step 2 and is repeated for as many floors as desired. Mechanical and architectural services are installed independently of principal construction.

(c) Mechanical Services

This system affords generous and orderly network of voids to receive mechanical services. Air ducts, pipes, and conduit can be carried with minimum obstruction along the axes of the structure or on diagonal lines. Vertical branch service for electrical wires can be made downward into partitions through sleeves cast into ribs.

Specially cast panels in the floor slabs permit the passage of services upward.

The hollow column, which has knockout panels, and the floor system itself allow easy access for installation and alteration of mechanical services. Ducts of 8' to 10' can be installed from beneath.

The structure provides little visual "cover" for mechanical services. In the areas where the function requires a high degree of finish and elegance, recessed panels could be installed in the structural grid to hide unattractive mechanical facilities.

(d) Architectural Services (see drawing 5)
Acoustical treatment is integrated into surface geometry of structure. The cement-wood fiber panels used as forms for the floor slab provide a uniform surface with a high coefficient of sound absorption, especially useful where a lowering of the sound intensity level is desired.

For purposes of sound isolation, insert panels rigidly fixed to the lower grid furnish the needed barrier. This position is preferable to the vertical as it does not interfere with the free passage of mechanical facilities. Though not illustrated, reflective panels could be installed with similar details in spaces where sound reinforcement is desirable.

Lighting fixtures are mounted between the lower ribs of the structural frame. The dimensions of the structure accept fixtures using standard 4' long fluorescent bulbs. The fixture may serve as a return air intake and be joined to a duct.

A recess has been provided in the underside of the lower ribs to accommodate the partitioning system. The standard detail developed would maintain the visual independence of the structure, accept expected deflection of the slab without damage to partitions, and allow the use of a variety of partitioning materials.

(2) Scheme "B" (Pyramidal frame)

(a) Structure

The structural characteristics of this system are similar to the alternate proposal and will be descibed only where they vary. Illustrated is a typical 50' bay (see drawing 6) having a two-way modular grid of 5' square.

The precast pyramidal unit has been modified chiefly by reducing the sections of web and chord members and by altering the lower rib conformation. Openings have been slightly enlarged.

The units are positioned during the post-tensioning operation by steel channels which also act as forms for the grout. In contrast to the preliminary proposal, grout is poured from above into the space formed in the lower ribs by the steel channel and adjacent units. After the structure is completed, the channel is removed leaving a 2" wide reveal between units to receive the standard partitioning detail.

The cement-wood fiber panel has been stiffened along the edge since it lacks a continuous support. The floor slab is poured to form a continuous structure as in the previous example.

Both column solutions (the solid cruciform and the hollow column of one module dimension) can be applied to the pyramidal system and a satisfactory shear detail can be conceived. Whether over four or eight ribs, a large section of concrete with shear reinforcing is easily provided in the valleys created by the geometric system.

(b) Techniques of Construction

Precasting would be carried out with inner and outer forms of steel or plastic with fiber-glass reinforcing. Possibly the casting would be done in an inverted position. If a higher degree of hand labor is acceptable in the precasting operation, the outer form can be eliminated and those surfaces finished by a screed.

The general procedures for post-tensioning and erection would follow those described for the alternate proposal.

(c) Mechanical Services

The ducts, pipes and conduit necessary for the various mechanical services would generally be accommodated in the voids found above the ribs. This has the advantage of creating a visual cover for the services and retaining the most exposed portion of the ceiling visually uncluttered. It allows direct vertical access into partitions without intersecting structural members. This layout of service facilities, however, complicates their installation and alteration because of the size limitations of ducts which can be passed through the openings of the pyramids. In fact, installation of the air system before the floor slab is poured might be expedient with only alteration of the original system done from beneath.

In cases where visual considerations are unimportant or where lighting fixtures are to be suspended in the lower grid, the entire system of voids may be used for mechanical services.

(d) Architectural Services
Details for acoustical treatment, lighting facilities and partitioning have not been illustrated for the pyramidal system. Those indicated for the alternate proposed can be modified for use with this system.

6. <u>Comparative Evaluation of the Two Systems</u>

a. Structural Efficiency

An accurate comparison of structural capabilities without more thorough analysis is impossible. In general it appears that the pyramidal system offers definite advantages over the system of intersecting Vierendeel trusses in longer spans because of its lightness and the possibility of providing a better shear condition at the column without disturbing the visual uniformity of the slab. If dropped panels are permitted, this advantage disappears.

b. Precasting

While both units can be readily mass produced, the open box requires half as many units as does the pyramid for the same area. This consideration could result in a saving in forms, but a final evaluation must wait until the exact design of the forms and the casting operation.

c. Integration of Mechanical and Architectural Services

Visual considerations aside, the Vierendeel truss scheme is the more flexible system, providing large openings which allow easier installation of bulky services. The pyramidal system incorporates twice as many openings of a more limited size. When the visual problem is important, the advantage is somewhat reversed. Cover panels must be inserted in the lower grid in the first proposal while the pyramidal system provides its own cover for the services. In addition acoustical panels need not destroy the visual pattern of the system as they conform to the surfaces of the pyramids.

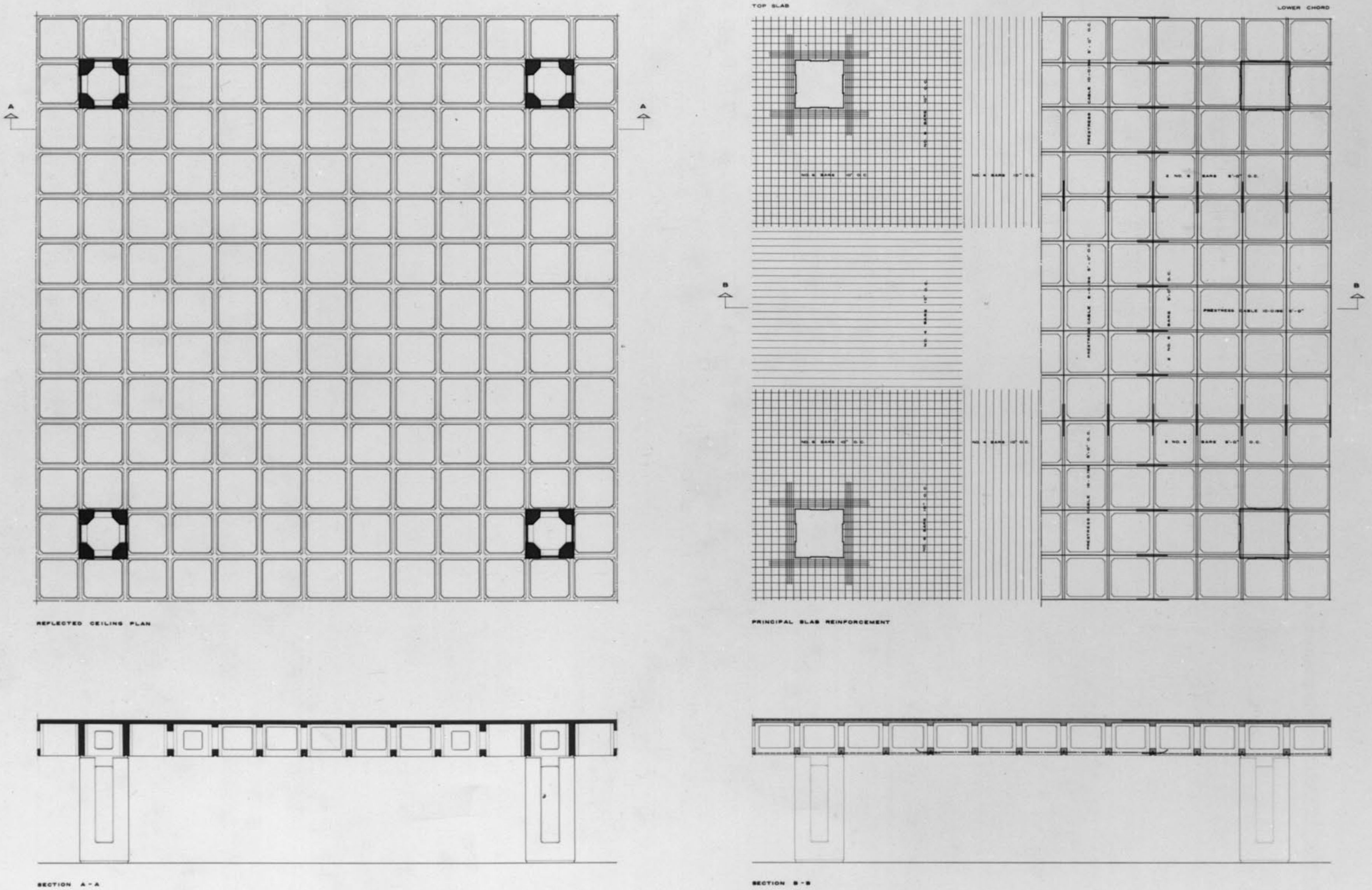
d. Weight of Floor Structure

Weights of the two systems are determined from the units as detailed in Drawings 2 and 7. Since dimensions of certain members were estimations, the weight comparison must be considered an approximation.

	Scheme "A"	Scheme "B"
precast unit lbs.	2800	750
lbs/sq. ft.	104	90
lbs/50'X50' bay	262,000	218,000

e. Visual Expressiveness

While to a large extent a matter of personal judgment, the pyramidal system presents a richer and more varied character which is more easily maintained with the intrusion of mechanical services than in the alternate proposal.

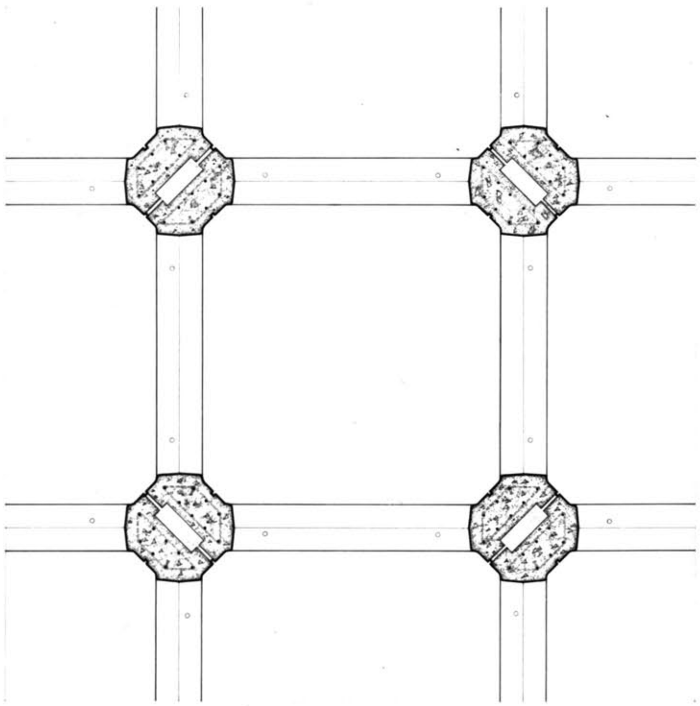


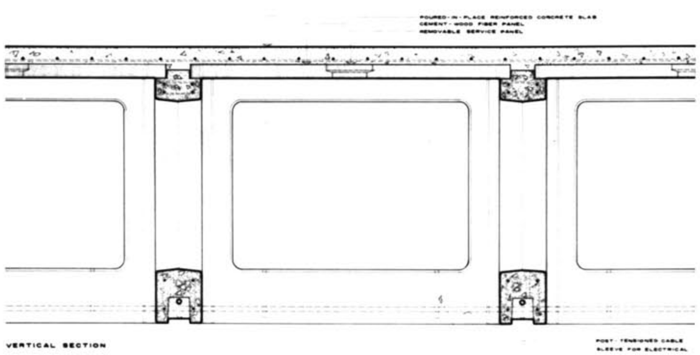
TYPICAL STRUCTURAL BAY

PRECAST FLOOR SYSTEM

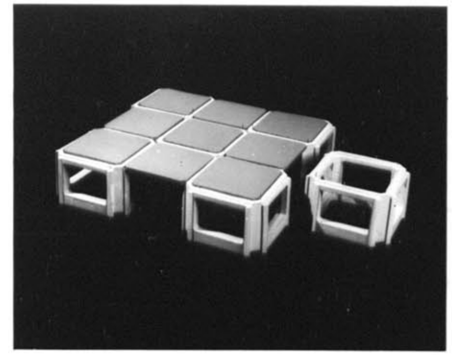
MASTER IN ARCHITECTURE THESIS
ROBERT P. BURNS M.I.T. 1962

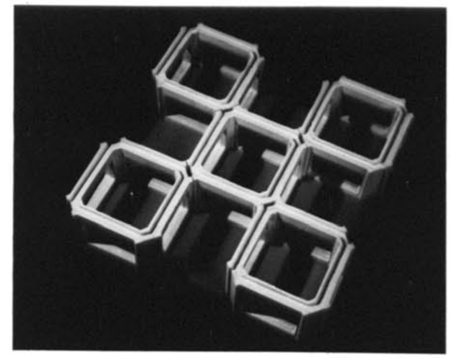
1

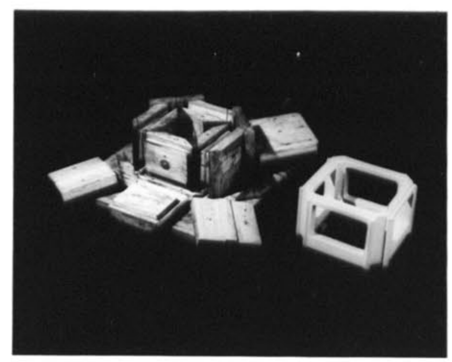




TYPICAL PRECAST UNIT







PRECAST FLOOR SYSTEM
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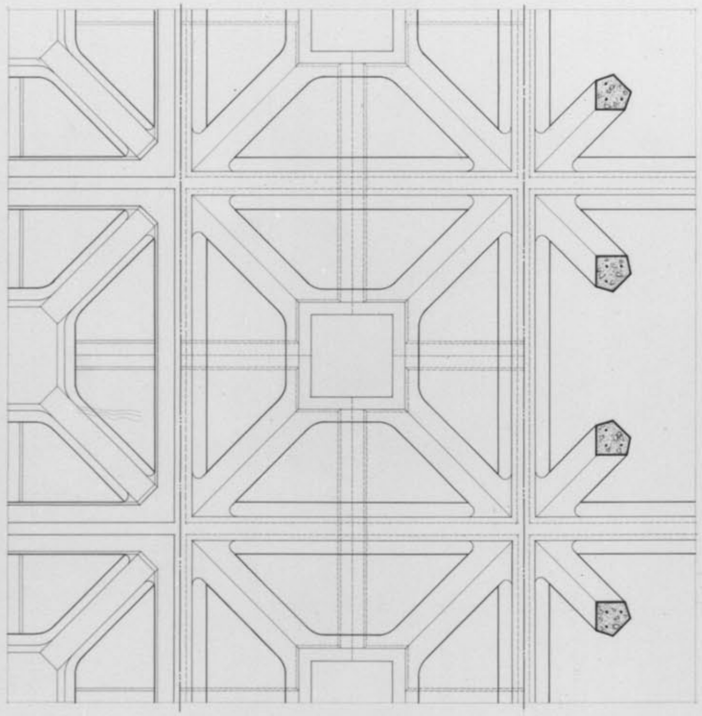

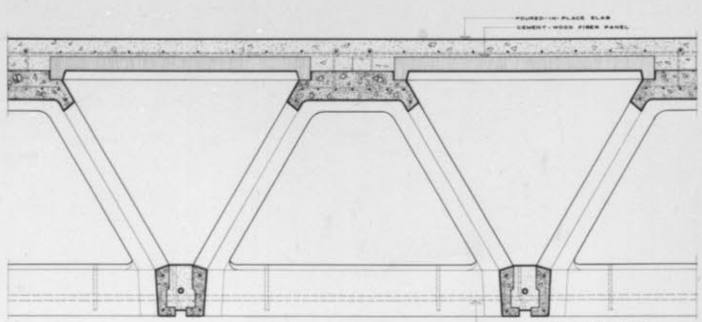

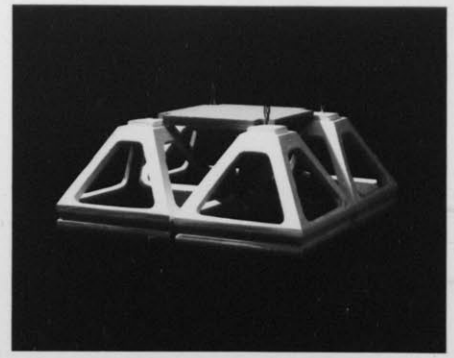

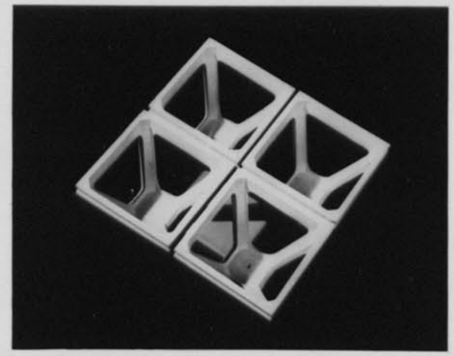

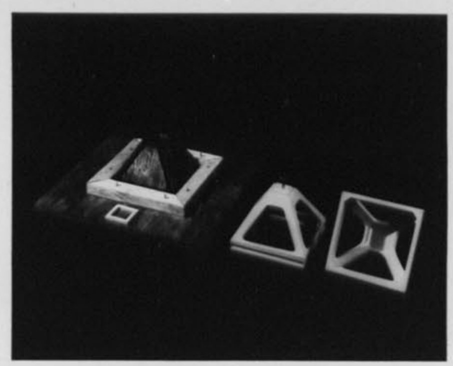

TYPICAL PRECAST UNIT - ALTERNATE SCHEME

SCALE FEET

PRECAST FLOOR SYSTEM
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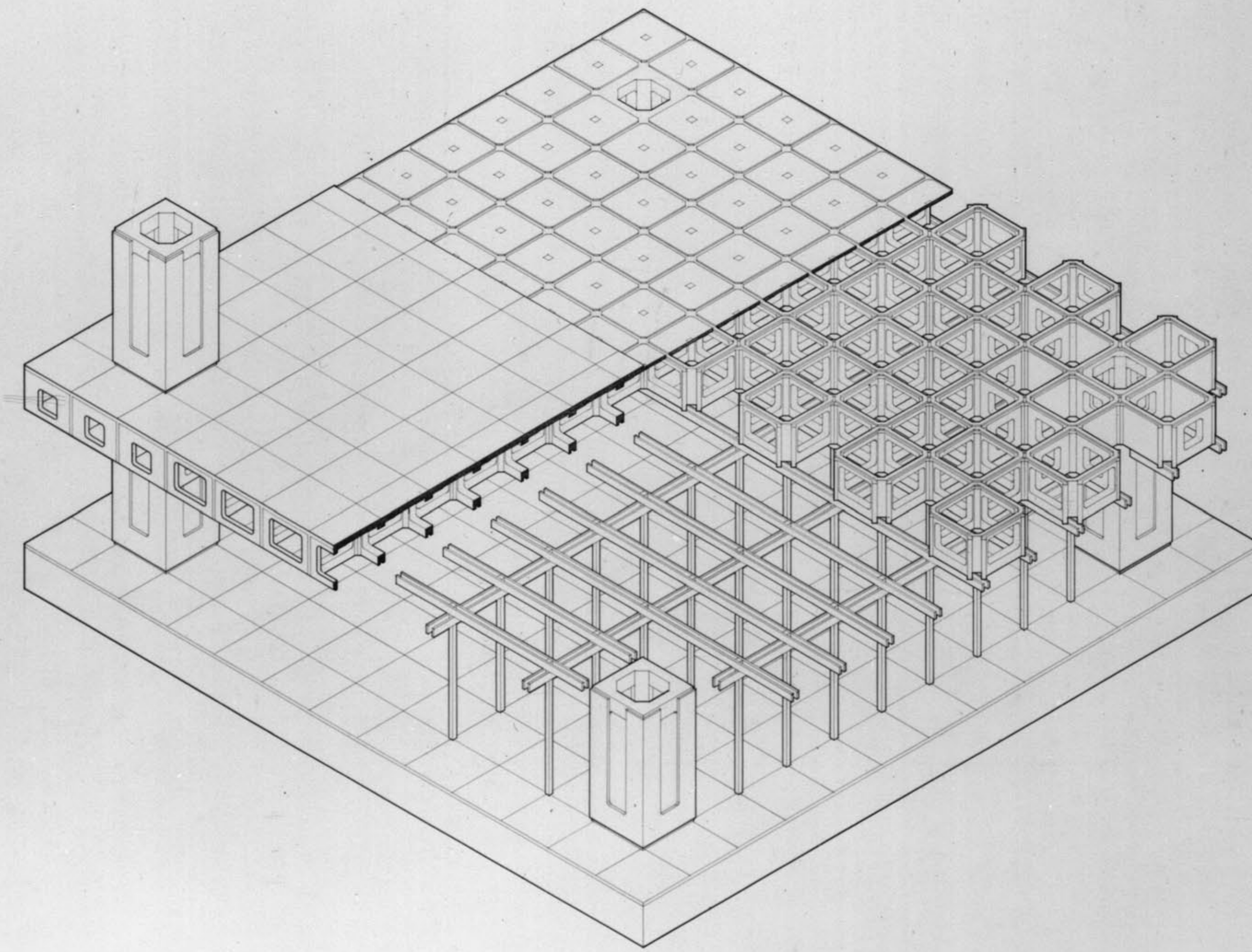

ISOMETRIC VIEW SHOWING FOUR STAGES OF CONSTRUCTION

0 5 10 15 20

SCALE FEET

PRECAST FLOOR SYSTEM

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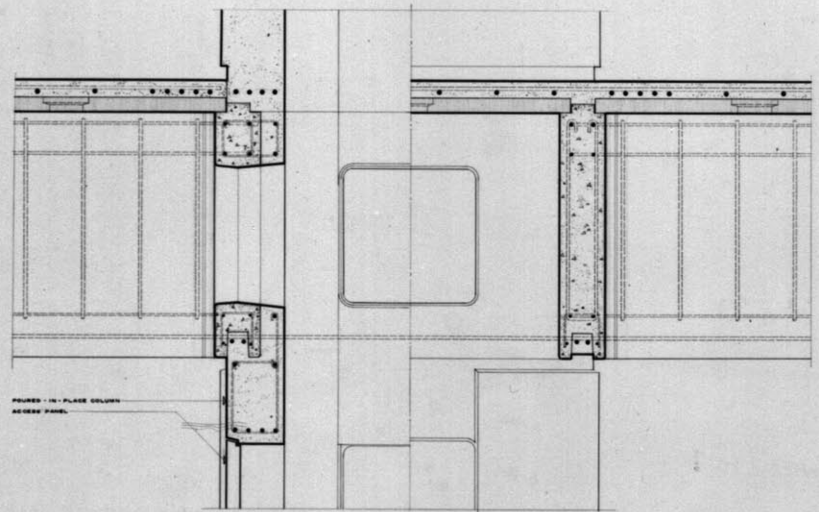
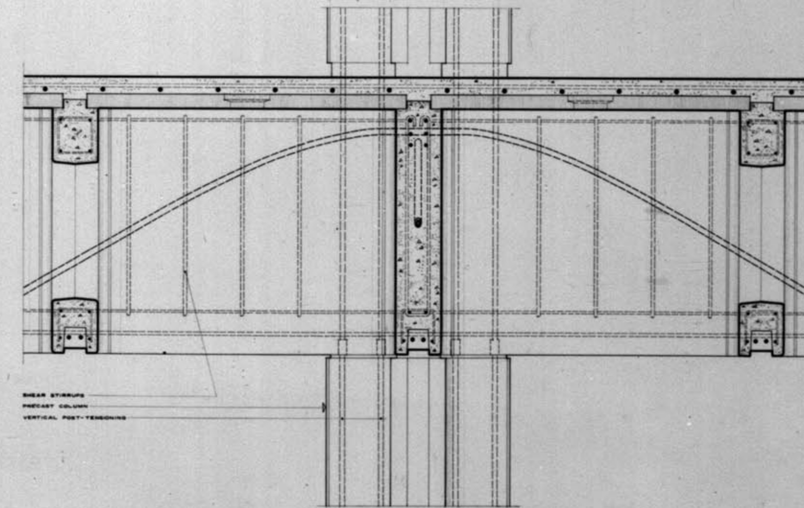
4

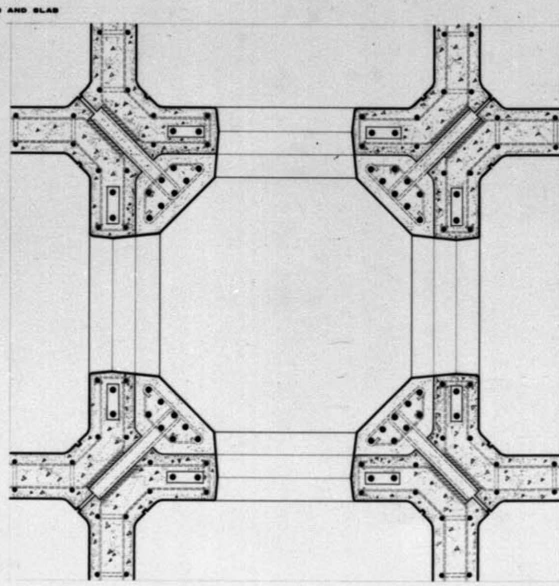
HOLLOW COLUMN

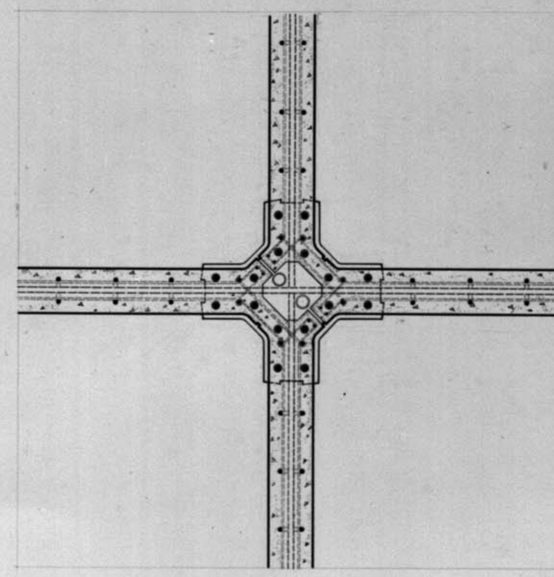


SOLID COLUMN



JUNCTURE OF COLUMN AND SLAB





HORIZONTAL SECTION

COLUMN - SLAB DETAILS

0 1 2 3
SCALE FEET

PRECAST FLOOR SYSTEM
MASTER IN ARCHITECTURE THESIS
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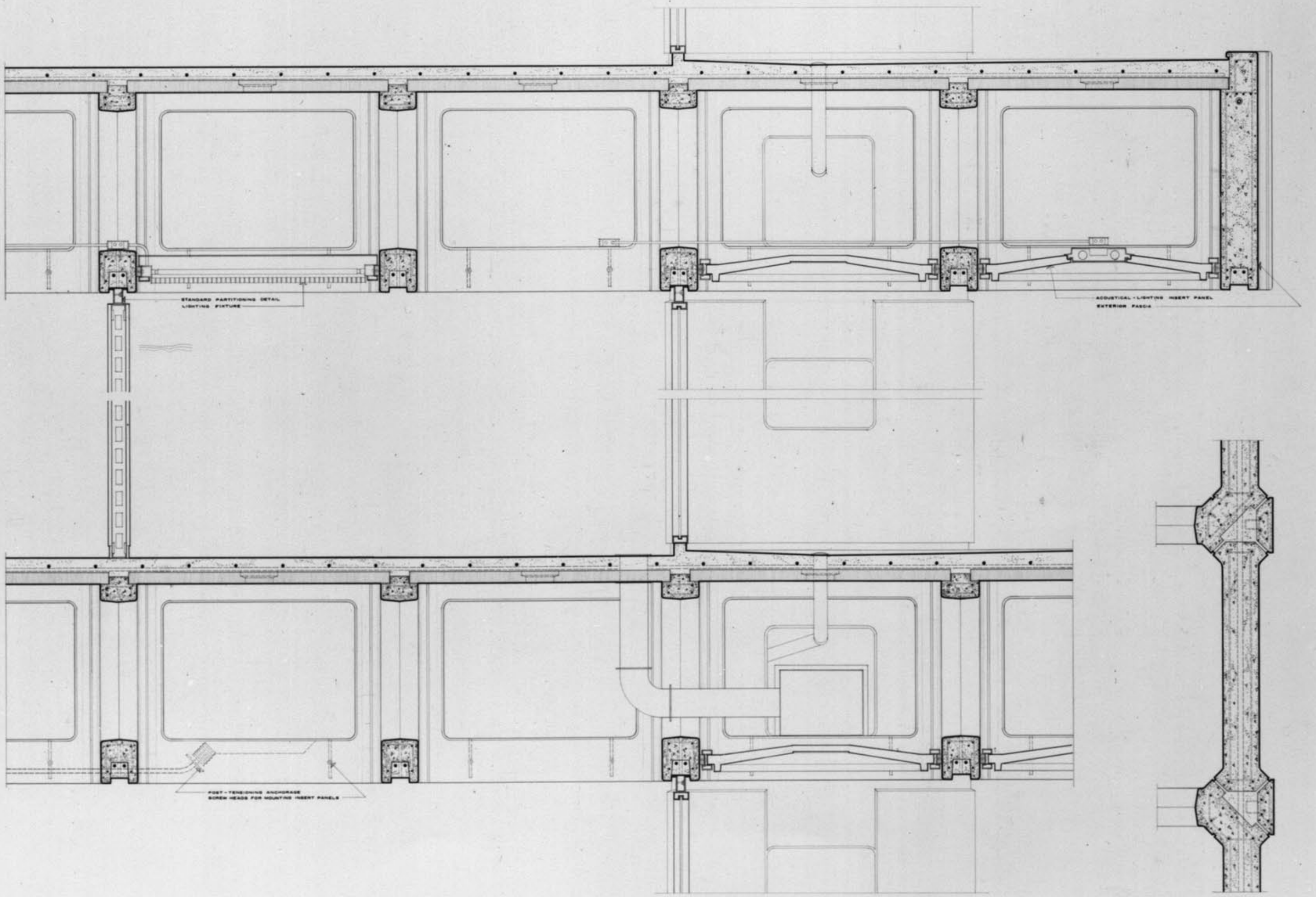
5



DETAIL SLAB SECTION

DETAIL PLAN OF FASCIA

MISCELLANEOUS DETAILS

SCALE FEET

PRECAST FLOOR SYSTEM
MASTER IN ARCHITECTURE THESIS
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6

1. General Description of Floor System

a. Introduction

The method of bringing sticks of wood and bags of cement to a site that is usually incapable of storing materials is difficult when viewed in terms of construction and economics.

Today's building industry is slowly becoming accustomed to the technology and machinery available. This is especially true of large size concrete buildings. Slip form construction, precast elements, and heavy machinery provide a scale of time for erection that is in the same spirit as the scale of the structures built.

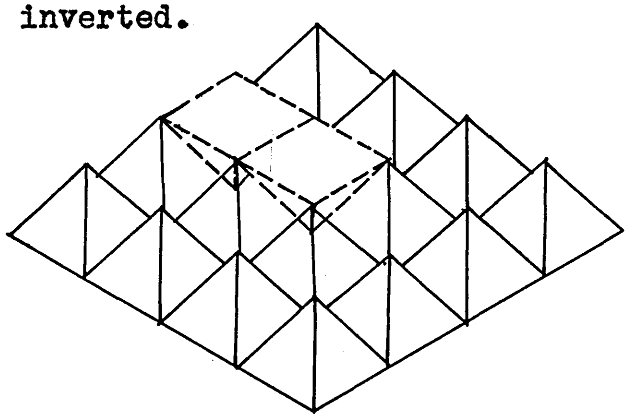
b. Direction of Study

To reduce costly site labor, simplify construction, and obtain a greater control of the materials used for strength and architectural expression, a floor system component in the form of a linear precast trussed beam is studied.

Often there are decisions which have to be made during the advancing of an idea. Because many of the deciding factors directing these decisions are not based purely on economics or more real and specific planning instances, ideas may be eliminated even though there is merit in them. The following report will present the problem and then the choice for certain elements considered.

c. Description of Completed Floor

The floor is composed of a series of pyramids open from beneath. The floor slab placed at their apex creates a second series of pyramids which are inverted.



The linear trussed floor component collects a number of pyramidal forms to make use of their structural capability for transportation and handling as a larger scaled unit. Formwork and on the site labor is reduced to that of a large precast unit.

Inherent within the system of geometry selected are basic structural and architectural qualitites.

The use of the upper inverted pyramids for mechanical utilities allows the lower, visible pyramids to be always uncluttered for architectural requitements. The separating of the ducts to keep them from interrupting rods holding light fixtures and from perforating acoustical panel's is another primary benefit.

The triangulated geometry provides web members which are able to act in a more truss-like manner. Because bending is greatly taken out of these members, a more efficient system results.

A disadvantage of the geometry is the reduced passage for mechanical ducts. The pivoted members forming the pyramids provide a more restricted opening than that of a vertical web.

Further advantages and disadvantages are clarified later in the context.

d. <u>Floor Component</u>

It is possible to create the trussed member in several configurations by cutting the pyramidal system at different intervals. Only two systems are considered within this proposal because of these units' greater architectural, erectional, and structural advantages.

(1) <u>Unit I</u> (see drawing of typical unit)

This unit provides for an entire floor strip equal to the length of the beam to be placed in one operation.

Along the unit would be legs, which when joined, would form the system of pyramids seen from the floor below. When the beams are made integral with the floor system, a construction joint within each pyramid and along the bottom chord member perpendicular to the component, will be visible.

The extended legs would also serve a secondary purpose for they provide stability of the unit during construction.

By cutting the pyramidal system at this interval, a unit with the structural behavior of a tee beam is acquired.

Because of the void contained within the center of the truss beam and because of the extended legs, formwork would prove to be very difficult.

(2) <u>Unit II</u> (see drawing of typical unit)
This scheme consists of two basic units, a trussed beam and a top slab.

Inherent within this truss shape is the distribution of mass closer to the prestress wire. This wire is needed for structural purposes and is described later. Having the property of a lower centroid, this scheme becomes almost as efficient as the tee beam (Unit I), even though it has much less area to prestress. The lighter weight may prove more desirable to lift for longer span structures.*

The shape provides the compactness and stability desired. Construction joints will occur along a grouted recessed partition provision. The pyramids visible from beneath will be extremely smooth from the precast operation.

The casting of the unit is described in detail, as well as the structural implications, later in the report, for this is the final proposal for the beam shape.

e. <u>Description of Support</u>

Since the triangulated geometry reduces the size of duct possible, extended runs

* 50' unit weighs 8.5 tons vs. 12 tons for scheme I
70' unit weighs 12.0 tons vs. 16.75 tons for scheme II

would begin to have excessive friction for low velocity air systems. Shorter runs of ducts would work to the advantage of the system.

A hollow column, one module in dimension, was therefore more seriously considered than was the solid support.

A column of a 5' X 5' dimension is easily accepted on the exterior of a building. This five foot zone provides the possibility for the transition of light from the exterior to the interior and also provides space for the air conditioning equipment.

The interior column presents a formidable mass, especially when the area is partitioned. It may often prove inconvenient to have one face of a column as a finish for an ordinary room dimension. Provision for paneling to conceal the column is considered necessary.

2. Detailed Description of Floor System

a. Structure

For a fifty foot bay supported by a hollow column one module in dimension, component beams of forty-five foot lengths will span the entire distance (see plan of hollow column scheme). Between the columns in both directions will be placed the floor components. The area left to be covered in the center of the bay is also of the smaller clear-span dimension. With this reduction in length of beams used, the undesirable bending moment during transportation and the number of anchorages needed for post-tensioning are reduced.

The intended placement of the components for the solid column requires units of the span selected to be used. The trussed elements will be placed parallel to each other to form rows (see plan of solid column scheme). This avoids awkward connections at the column.

Although the floor system does not need a prestress force for strength, structural unity between precast members is achieved. As stated in the structural notes, this force is needed primarily in the bottom chords. Tension cables placed in the bottom chord will span the entire middle strip and be anchored in the column strip beyond the inflection point. Ordinary reinforcing placed uniformly across the top slab provides the negative reinforcement. This condition is only for the hollow column.

Post-tensioning will be used in the top slab to accept the condition present in the smaller solid column. Because of geometric incapability of the triangulated system to pass the stressing cable (in the plane of its major stressing) from the inferior to the superior slab, a completely separate cable system is used.

The pretensioning of the beam units is done such a way as to insure a proper variation of stress at any section. The prestressing cables are forseen placed in tubes to allow for the possibility of applying stress in several steps.

Sufficient prestress will be provided to meet load requirements for transportation and final loading moments. The precast members will have two basic pretensioning forces, for the middle strip elements and the column strip.

High stresses on prestress cables often cause considerable contraction of the unit accepting this forc. The span and the prestress force used for this study of the floor components are sufficiently small to provide a reasonable amount of tolerance for construction.

The prestress force is desirable in handling for it makes the unit a more elastic member capable of sealing itself if cracks occur.

The dimensions of the bottom ribs and the intermediate web members are the result of minimum concrete coverage for steel reinforcing rather than the result of structural necessity. Because more concrete is present in the bottom ribs than is needed, the added mass gives the section a greater strength capacity and thereby reduces the steel originally necessary.

To decrease the need for added steel and concrete to accommodate shear conditions within the slab, all the web members were slanted at an angle to direct their lines of force to meet at the centroid of the bottom steel and at the upper portion of the compression slab.

The economical strength of concrete is around 3,000 psi when lower strength steel is used.[6] "The use of higher strength concrete resulting in a smaller section will increase the amount of reinforcing."[7]......if that steel is not also of high strength quality. High strength concrete of a 5,000 psi flexural strength is compatible with high strength prestressing steel.

Lightweight concrete will not accept shear as well as heavy aggregate concrete does. Although it is true that the lighter concrete aggregate produces less load concentration at the column, the lightness of the floor does not compensate for the reduced allowable shear. Heavy aggregate concrete of 5,000 psi strength is used for the following calculations:

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[6] T.Y. lin, <u>Design of Prestressed Concrete Structures</u>, p. 395

[7] <u>Ibid</u>., p. 395.

b. Casting

Present prestressing plants have geared their operation to a twenty-four hour cycle. Work that has been completed from the previous cycle is removed from the forms. The forms are cleaned, steel is set, and concrete is placed. Automatic steam curing on the prestressing bed during the last part of the process raises the concrete strength to accept the prestress force for early removal of that member from the forms.

Essential is the number of forms necessary for accomplishing production to meet building schedules. Casting beds are made sufficiently long to form many members at once with only one set of prestress wires.

Complicated forms may cause a member to be poured more than once, thereby using the form work longer. If, also, the form is too intricate, the ability to place a stiff mix of high strength concrete is extremely difficult. Special controls or a longer pouring process is needed.

Because the trussed beam chosen is pierced many times to provide passage and articulation for services, the formwork required is relatively complicated.

The components which are needed to transform the individual pyramids to a beam are the top horizontal continuous ridge and the continuous tension members in the bottom legs of the unit.

To form the finely finished pyramids that comprise this beam and ultimately the floor system, a series of concrete pyramidal forms with provision for the desired openings necessary to obtain access to mechanical space will be used. These forms will serve as the basis for three possible methods of casting presented. Only after a thorough 'field' study can one tell which of these methods will be more economical. Scheme I follows the structural action of the slab closely, whereas Schemes II and III are more approximate.

(1) Scheme I

This scheme conceives the entire beam as being cast in one operation. To accomplish this, side forms as well as inserts between the pyramids are used. The forms are covered with a sprayed wax solution or wax panels and releasing agents. Tension is applied and the concrete cast. When the concrete has set sufficiently, steam curing will quickly strengthen the beam and melt the wax.

After the steam curing process, the casting cycle is near its completion. The tension wires will be cut. Because of the space created by the melted wax, the extremely small, but troublesome contraction of each concrete pyramid will not hinder the lifting of the unit from the casting bed. Without a tetrahedron insert used between the concrete form pyramids, two pours will be necessary, producing a longer use of the forms.

(2) Scheme II

It is possible to save formwork by pouring the beam in two stages, freeing the form after the first pour.

The first pour would form the pyramids and the bottom ribs. Ordinary reinforcing will be placed instead of prestressing cables. After the first pour has cured, a steel beam will be bolted onto the tops of the pyramids cast. This beam will act as the compression flange and provide the continuity needed to lift the casting from the bed. The unit will have many points of support to reduce bending of this composite beam during lifting.

The second pour would occur at a post-tensioning bed. The steel beam will be removed and a concrete ridge poured in its place. After the beam is cured again, post-tensioning is applied. Even though the tensioning will run from one end of the unit to the other approximating a uniform moment diagram, there is enough compression area in the lower ribs to handle the small prestress overload.

(3) Scheme III

Casting individual pyramids with short extensions at their top is a third method of arriving at the linear component. When the units are placed in a linear fashion, post-tensioning can be applied to form a beam and then lifted into place. This scheme is similar to 'Proposal A' for it provides the possibility of gathering a number of small units at the construction site.

This third method of casting does not take advantage of handling; however, the scale of the individual elements may make form work easier.

c. Erection

Since the erection of the floor system is dependent upon the use of ordinary reinforcing and poured concrete to obtain continuity, the advantage of working at the speed possible with precast elements is limited.

Because the floor system is dependent upon flat slab structural action, the speed of erection is again limited. This limitation stems from the methods used to construct one-way precast floor systems which are virtually independent structurally from their neighboring structural unit. To allow the crane with its limited reach to place beam units in the interior of the structure, one structural bay or a row of structural bays are filled to their height with a number of floors. This method uses the structure as shoring and is extremely rapid.

The erection procedure of the solid and hollow column proposal for the components used would be as follows:

1. The initial rows of columns at the base would be securely anchored to a foundation with provisions made for a plenum to serve the hollow column if necessary.

2. Shoring will be erected to support the beam units at one-fifth the length from the beam ends.
3. Trussed beam units will be placed in the appropriate positions. The next column and column steel will be placed.
4. Post-tensioning cables will be positioned and made ready for stressing.
5. The lower ribs will be grouted and the concrete placed around the column for shear condition.
6. Top slabs will be placed.
7. Top steel protruding from precast units will be bent to lie on slab panels. Slab steel for negative reinforcing is placed.
8. Three inch top slab is poured.
9. Cables will be post-tensioned after the slab has gained strength.
10. The same procedure is repeated for floors above.

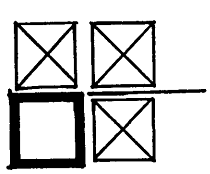
d. Column

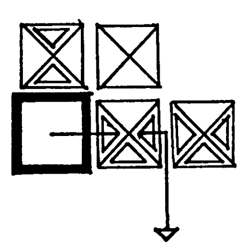
Continuity of the bottom slab is needed over the hollow collumn to pass added steel for shear and provide for continuity of the lower reinforcement.

Ideally, at the four corners where the structural grid crosses the column, a post should be placed to carry axial load and provide for the most efficient placement against punching shear.

Because the mechanical space runs directly over the bottom structural grid, any attempt to leave the hollowed column, with a mechanical duct for direct entry into the space intended, will run into difficulty. At the point where the duct should leave the hollow support, a column is located. Any duct that leaves at this point would be immediately split in two (see sheet), and its air carrying capacity reduced by much more.

To keep the duct intact, either a transformation of axial load is necessary or the duct must travel through the first finished pyramids adjacent to the column.





The column selected transforms the load. This transformation of the loads makes the column more unified. Instead of the axial forces traveling directly down each post at the corners creating four separate columns with a void in between, the forces transfer in many directions simulating a tube with perforations to handle mechanical equipment and structure.

This column is not as structurally efficient as the separated posts, but it does provide a totally uniform finished ceiling with a visually unified support.

A cruciform shape to obtain extra dimension in overcoming punching shear is used for the solid column. The only service carried through it are the roof drains. The solid column is much more appropriate for smaller spans.

e. Lighting and Electrical Services

The geometry selected allows any type of the many suspension systems used for lighting. The support that is most commonly used is a fixture suspended by a rod from the apex of the pyramids. Inserts may be provided in the precast units to handle the wiring for, the raceway system often is in the mechanical space. The placement of the raceway in this space places the electrical service directly below the partition of the floor above and in an accessible position to the floor below. To make access to the floor above reasonable, knockout panels can be provided.

f. Acoustical

A layer of acoustical material will be placed above the fixture and formed around a rubber gasket for a close fit if the necessity of transmission loss from one divided area to another is necessary. This layer of acoustical material provides a surface which sound must immediately en-

e. Lighting and Electrical Services

The geometry selected allows any type of the many suspension systems used for lighting. The support that is most commonly used is a fixture suspended by a rod from the apex of the pyramids. Inserts may be provided in the precast units to handle the wiring. A channel is provided in the mechanical space for the raceway system to follow. The placement of the raceway in this space places the electrical service directly below the partition of the floor above and in an accessible position to the floor below. To make access to the floor above reasonable, knockout panels can be provided.

f. Acoustical

A layer of acoustical material will be placed above the fixture and formed around a rubber gasket for a close fit if the necessity of transmission loss from one divided area to another is necessary. This layer of acoustical material provides a surface which sound must immediately encounter before it enters the dead air space above. When no suspended panel is desired, a pyramidal insert with leveling legs can be provided or individual panels can be gasketed into place.

g. <u>Air Conditioning</u>

The installation of the mechanical air duct will occur after the floor structure is completed, as is common with typical installations.

The largest fabricated duct in 5' lengths able to penetrate the voids provided by the openings of the finished pyramids is an eighteen inch diameter or a 15" X 15" square duct. The length of run these ducts may have is dependent upon individual conditions.

The mechanical space can easily pass a twenty-two inch duct. Insulation will have to be placed after the duct has been inserted into the mechanical portion of the floor system in order to retain an eighteen inch diameter for flow of air.

3. Structural Analysis

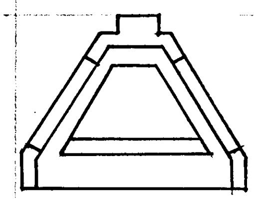
The calculations in this proposal attempt to:

a. arrive at preliminary sizes of major elements in the structure. (Ultimate flexural design was not contrasted to the elastic design because of the approximate nature of the calculations.)

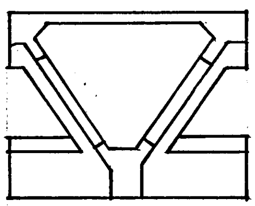
b. analyze the efficiency of the system component selected in contrast to the one that was considered inappropriate because of casting and detailing problems.

c. to check compressive stresses if post-tensioning is applied as suggested from possible casting simplifications.

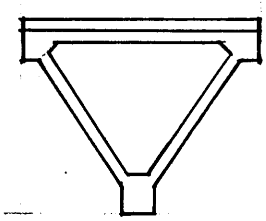
Properties of Structural Sections



Centroid	22.5" from base 22.0" from top
Inertia	47,000 in^4
Area at section	156 sq. in.
Wt. of beam	360#/lin. ft.



Centroid	36.0" from base 9.0" from top
Inertia	88,000 in^4
Area at section	213 sq. in.
Wt. of beam	453#/lin. ft.



Centroid	40.0" from base 8.0" from top
Inertia	112,500 in^4
Area at section	351 sq. in.
Wt. of floor	125#/sq. ft.

Floor Loads to be Carried

LL 100#/sq. ft. (including partitions)

DL 5#/sq. ft. ducts
125#/sq. ft. structure and finished floor
230#/sq. ft.

Total Panel Load (50 foot panel)

$W = 570^k$

Design Moments

$M_o = .09\,WFL\,(1-\frac{2c}{3L})^2$

M_o hollow column $= 2350'^k$
where $F = (1.15-\frac{c}{L})$

c = dimension of column

L = length of bay

$M_{46} = 1080'^k$

$M_{22} = 515'^k$

$M_{16} = 375'^k$

M_o solid colum $= 2540'^k$

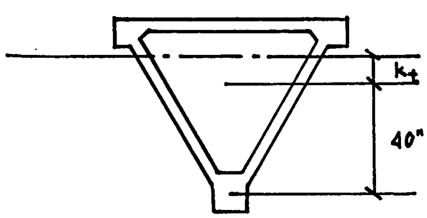
$M_{46} = 1165'^k$

$M_{22} = 560'^k$

The more critical moment of a solid column support is used to size the material necessary for the strength of section.

Final Prestress Forces

(continuous loading moment for maximum load on prestressing cables)



I final = 112,500

$r^2 = \frac{I}{A_c} = 320\ in^2$

$k_t = \frac{r^2}{c_b} = \frac{320}{40} = 8$ in.

Net moment to be carried by prestress

for column strip mid-span = 560'k

$\frac{560}{5 \text{ units}}$ = 112'k/unit

k_t + (40 in. - 4 in.) = 44"

$F = \frac{112 \times 12}{44} = 30.5^k$ (Design Load)

$f_s = .75 f'_s = .75(150) = 112^k/in^2$

F initial $= F_o = 30.5 \left(\frac{150}{112}\right) = 40.7^k$

Pretension Wire Selection (Data sheet 2)

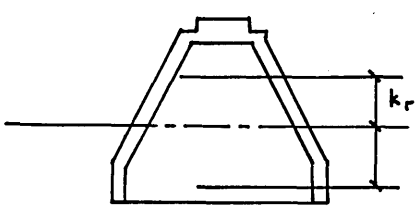
Select 6-¼" wires = 30^k

Post-tension

$A_s = \frac{F_o}{f_s} = \frac{40.7}{112} = .363$

Select (Data sheet 1) 12-.196 cable

<u>Prestressed Forces' Effect on Component Beam Selected</u>



I = 47,000

$r^2 = \frac{I}{A_c} = 301 \text{ in}^3$

$k_r = \frac{301}{22.5} = 13.4$ in.

Fo from requirements for final moment $= 40.7^k$

$$Fo = \frac{M'^k \times 12}{31.9''} \; ; \; M = \frac{40.7^k(31.9)}{12}$$

$108'^k$ max. allowable

M of beam simply supported

$$\frac{wL^2}{8} = \frac{.360(45)^2}{8} = 91'^k$$

∴ Beam safe during lifting

<u>Prestress Effect on Component Beam</u>

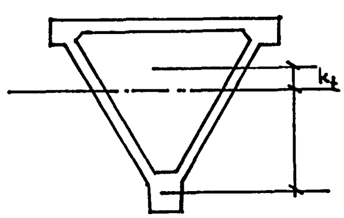
<u>Not Selected</u>

$I = 88{,}000$

$$r^2 = \frac{I}{Ac} = \frac{88{,}000}{414 in^3} = 234 \text{ in}^3$$

$$k_t = \frac{r^2}{c_b} = \frac{234}{34} = 11.5 \text{ in.}$$

$32 + k_t = 32 + 11.5 = 43.5$



Fo from requirements for final prestress moment $= 40.7$

$$M = \frac{40.7(43.5)}{12} = 147'k$$

Both the component beams have adequate stress from the final pretension force to not require additional reinforcing for transportation. The added area for the tee beam provided this component, which was not selected, with a greater structural capability during lifting.

Check of Compressive Stresses at Column

(to see if post-tensioning cable as suggested in casting methods II and III are feasible for solid and hollow columns)

M = 1080'^k for 5' column

column strip = 25' or 5 units

Compression load

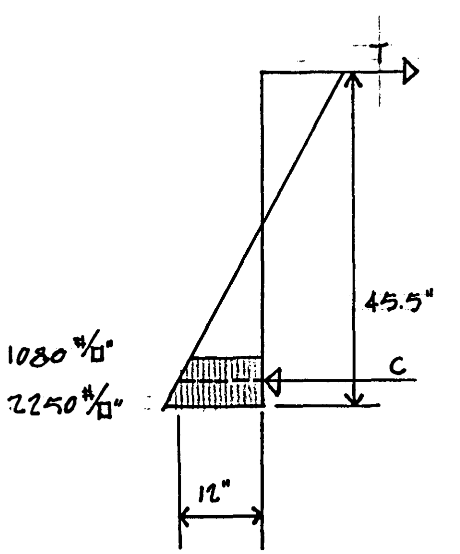
$$\frac{M}{jd} = C = \frac{1080 \times 12}{45.5} = 285^k$$

C + post-tensioning forces =

$$= 285 + 5(40.7)$$

$$= 473^k$$

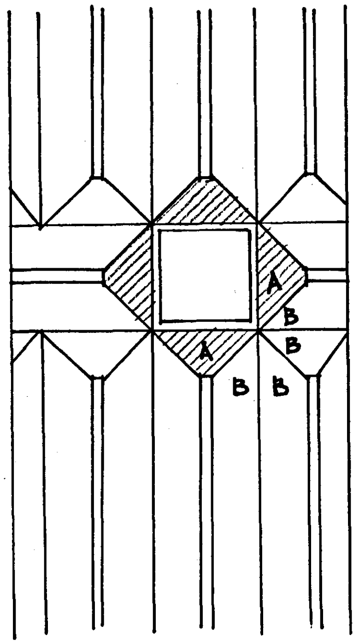
The area of the column strips' lower flange is only 3/4 effective as suggested by ACI code (1957), Design Procedure 1002 (c)



Compression possible at lower flanges

$$[480 \text{ sq. in.}] \frac{(1080 + 2250)}{2} (3/4) = 600^k$$

It is therefore feasible to prestress the beam component uniformly with the nominal 40.7^k/unit force.



Shear, Ultimate Design for Hollow Column

Panel load by code

1.2 DL + 2.4 LL where DL = 130 #/ sq. ft.
LL = 100 #/ sq. ft.

156 + 240 = 396#/ sq. ft.

V ult. = 980^k

Shear/ rib
980/8 = 122.5^k

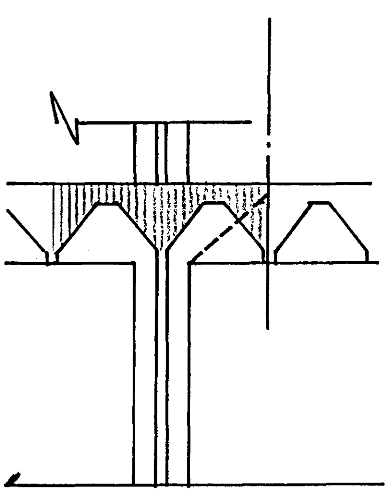
Assume 50% of shear carried by 'A' which is filled solid. This assumption is based on the expected rotation of the slab. 'B' will carry 25% of shear. Because 'B' has relatively less area, 'B' is more critical

A_B = 240 sq. in.

$v_B = \frac{V}{A_B} = \frac{30.6}{240}$ = 127#/sq. in.

Use vertical stirrups

#3 bars in 10" grid



Shear, Ultimate Design for Solid Column

For area shown filled

V area = 3360 sq. in.

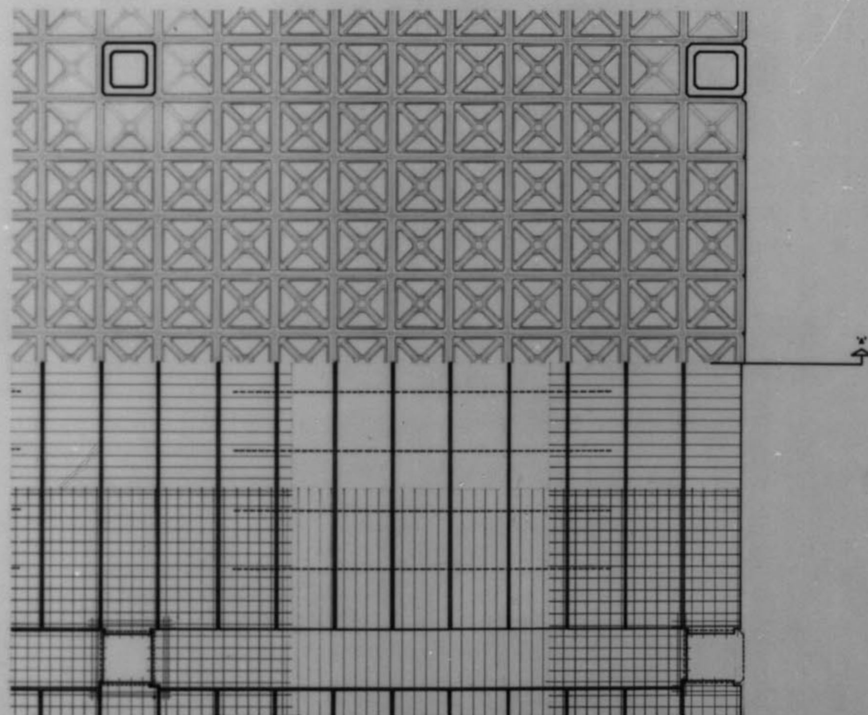
V allowable = 240 (3360) = 810^k

no good: 990^k is needed

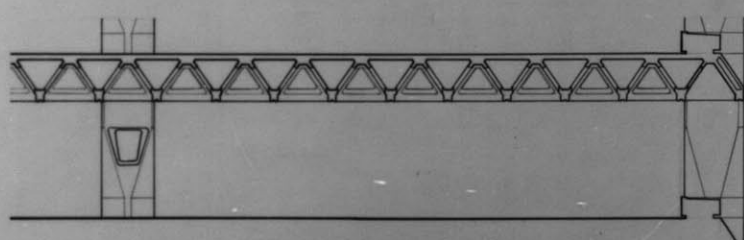
to develop V ultimate

At this point it is possible to add additional concrete at the column head to develop 990^k or decrease the concrete at the column and post-tension the top slab. Because more concrete would block access to the finished pyramids with services and because it was desired to eliminate the column head (as stated earlier), post- tensioning is preferred. Only if smaller spans are used is it feasible to use the solid column and ordinary reinforcing in the top slab.

The design of the column and the design of the component panels that form the top slab have been omitted from the design calculations. The emphasis was placed on the floor structure itself.



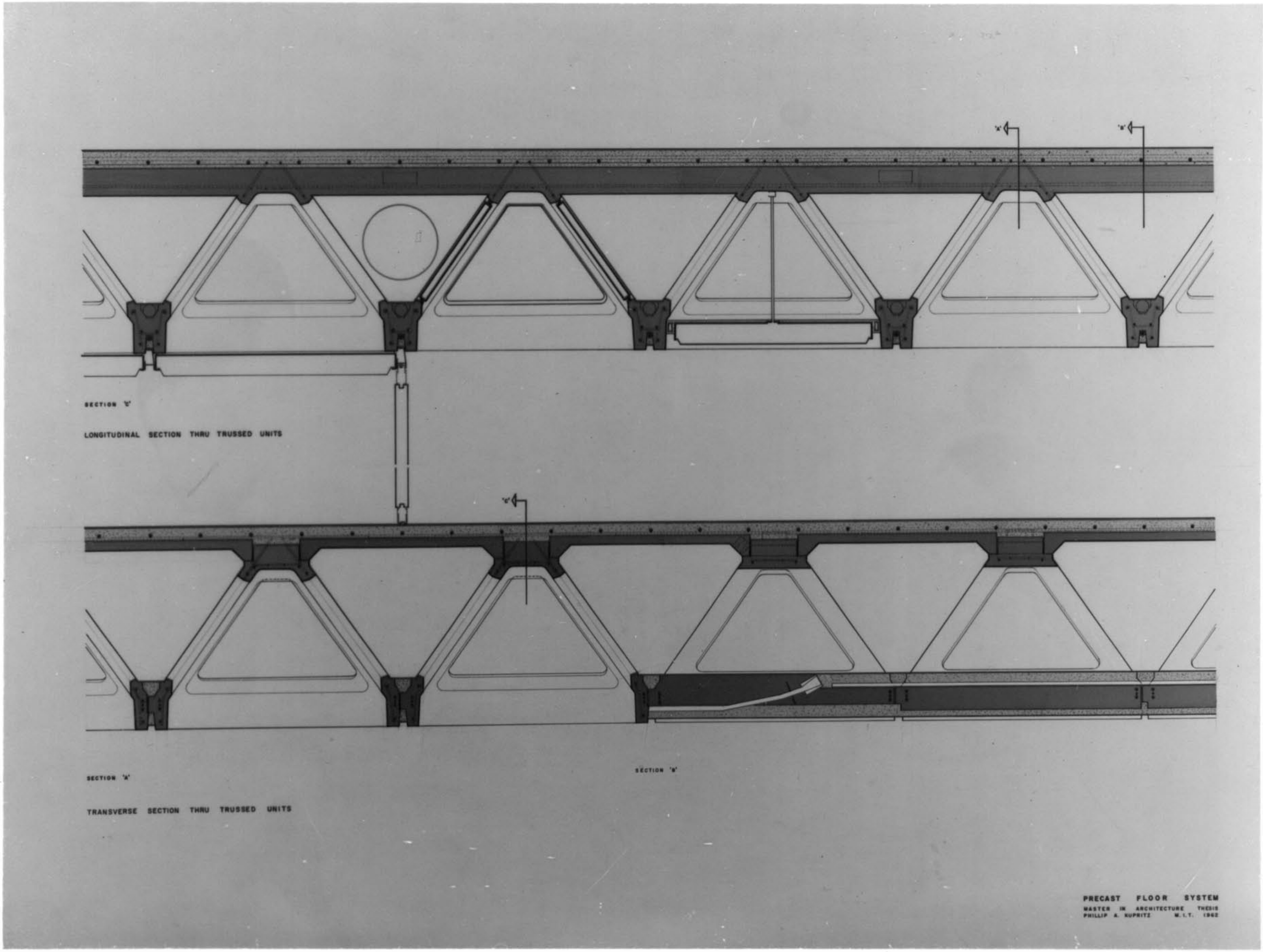
REFLECTED CEILING PLAN, COMPONENT PLACEMENT, PRINCIPAL REINFORCEMENT

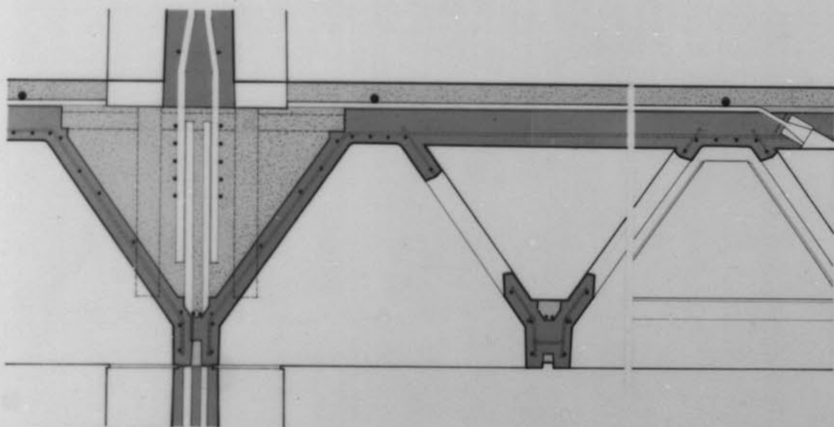


SECTION 'A'

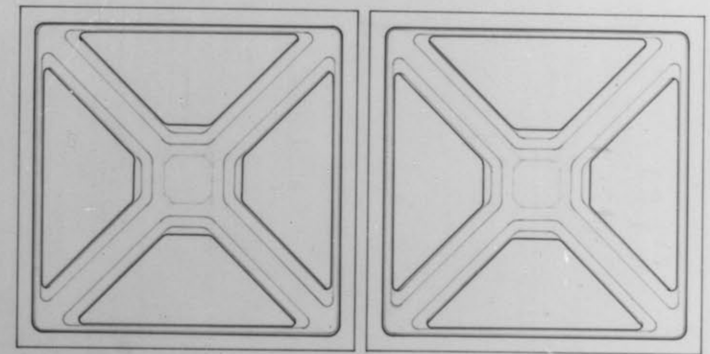
PRECAST FLOOR SYSTEM

MASTER IN ARCHITECTURE THESIS
PHILLIP A. KUPRITZ M.I.T. 1962

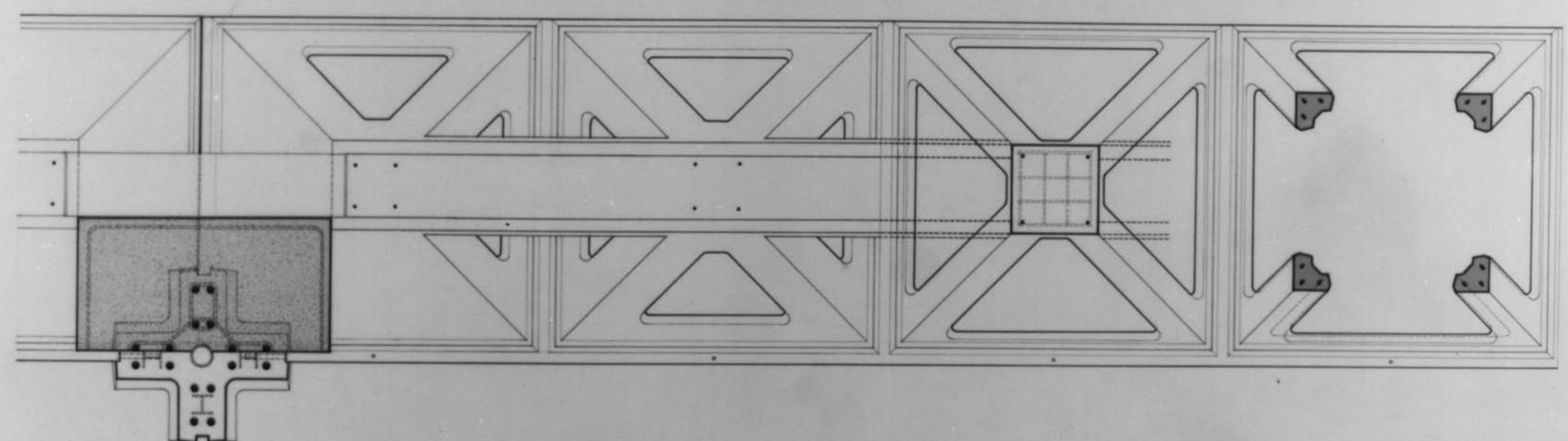

'A'
'B'
SECTION 'C'
LONGITUDINAL SECTION THRU TRUSSED UNITS
'C'
SECTION 'A'
TRANSVERSE SECTION THRU TRUSSED UNITS
SECTION 'B'
PRECAST FLOOR SYSTEM
MASTER IN ARCHITECTURE THESIS
PHILLIP A. KUPRITZ M.I.T. 1962



SOLID COLUMN SECTION



REFLECTED VIEW OF CEILING

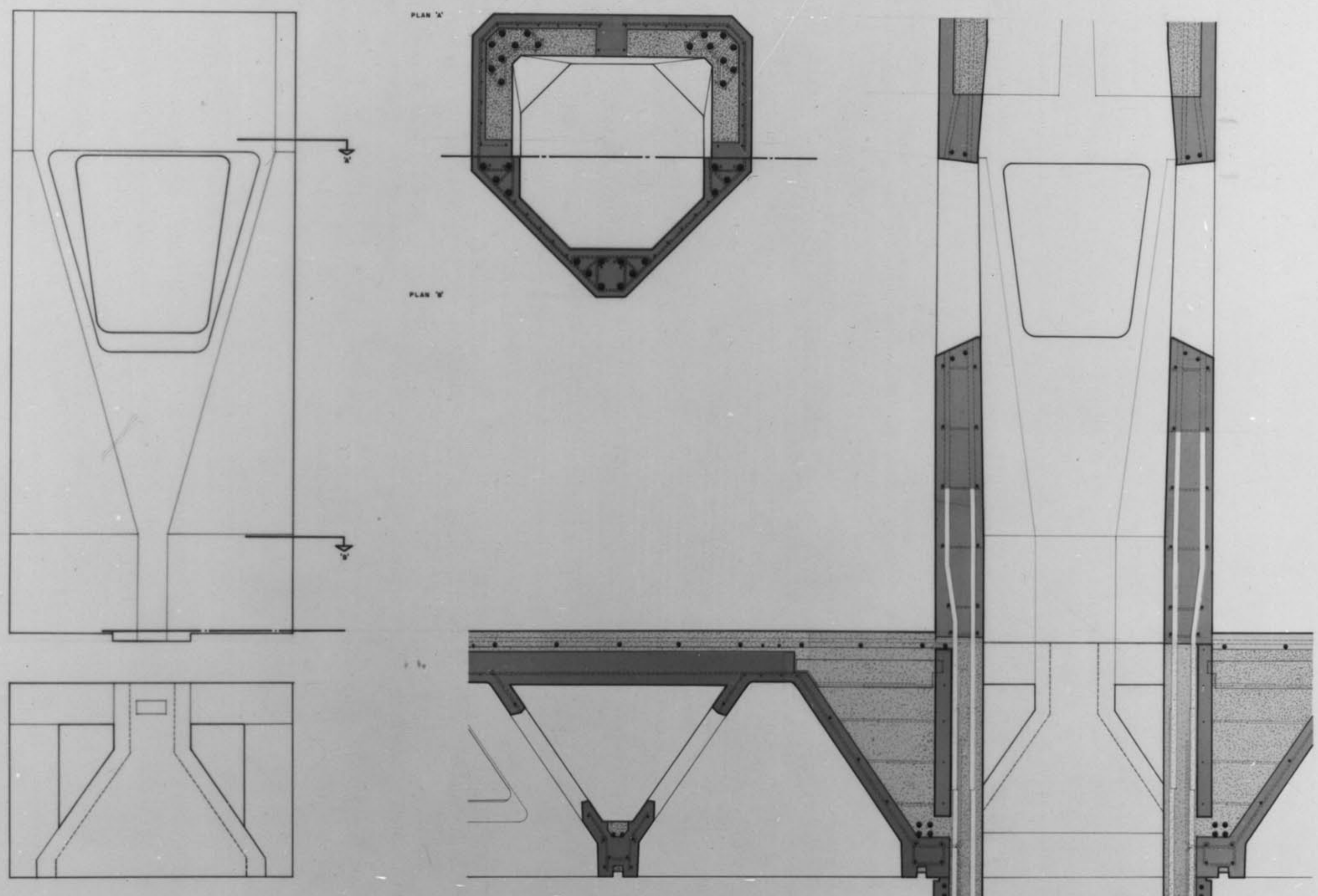


LINEAR BEAM COMPONENT AND SOLID COLUMN CONNECTION

PRECAST FLOOR SYSTEM

MASTER IN ARCHITECTURE THESIS

PHILLIP A. KUPRITZ M.I.T. 1962



HOLLOW COLUMN

PRECAST FLOOR SYSTEM

MASTER IN ARCHITECTURE THESIS
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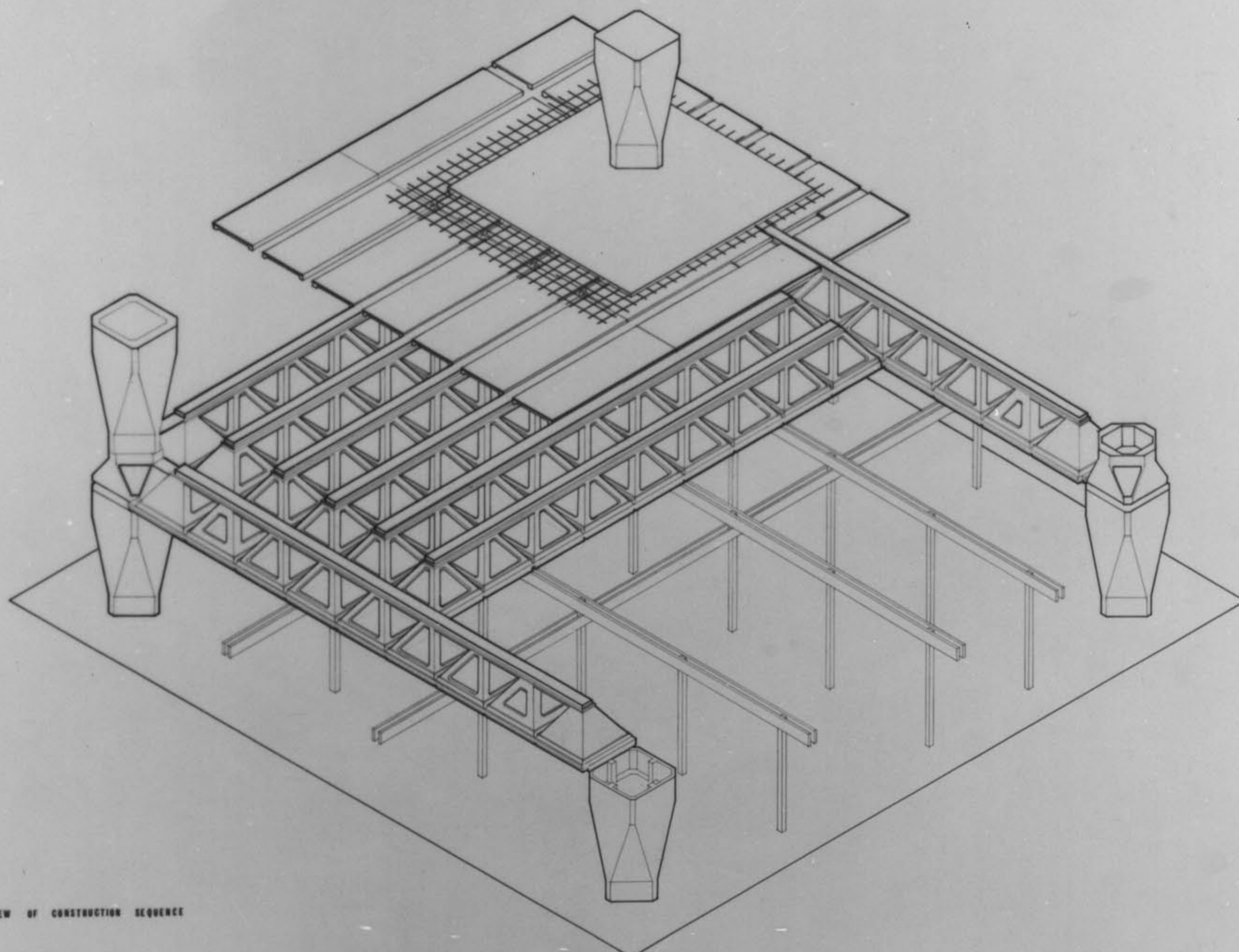
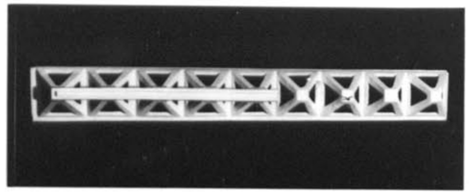
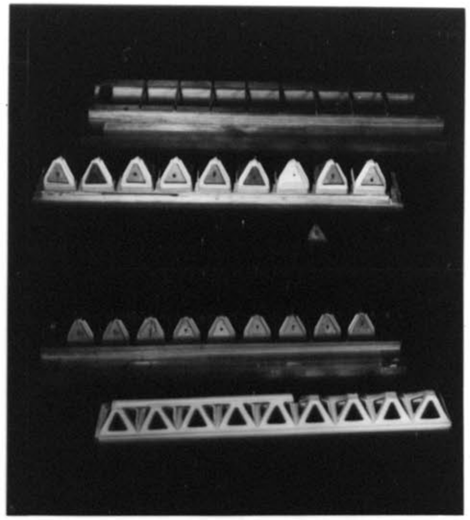


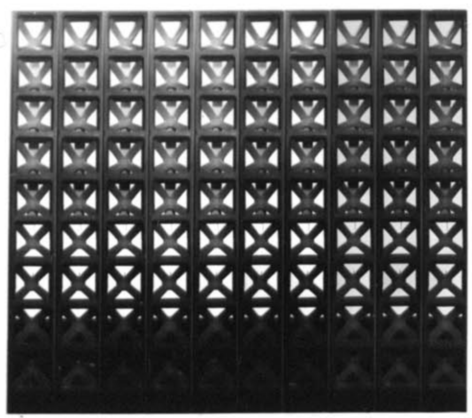
ISOMETRIC VIEW OF CONSTRUCTION SEQUENCE

PRECAST FLOOR SYSTEM

MASTER IN ARCHITECTURE THESIS
PHILLIP A. KUPRITZ M. I. T. 1962







PRECAST FLOOR SYSTEM

MASTER IN ARCHITECTURE THESIS
PHILLIP A KUPRITZ M I T 1962

C. PROPOSAL 3 John E. Rudquist

1. Introduction

This portion of the thesis study is devoted to the development and assembly of precast units one bay long and one module wide. These units, when assembled, would form an orthogonal, open-web, concrete floor structure based on the principle of intersecting Vierendeel trusses.

The unit would be precast in the same manner as a "T" beam with the top flange connected.

In addition, the proposed unit would have a perforated web and outstanding legs. These legs would be used to connect to adjacent members to complete the intersecting Vierendeel geometry.

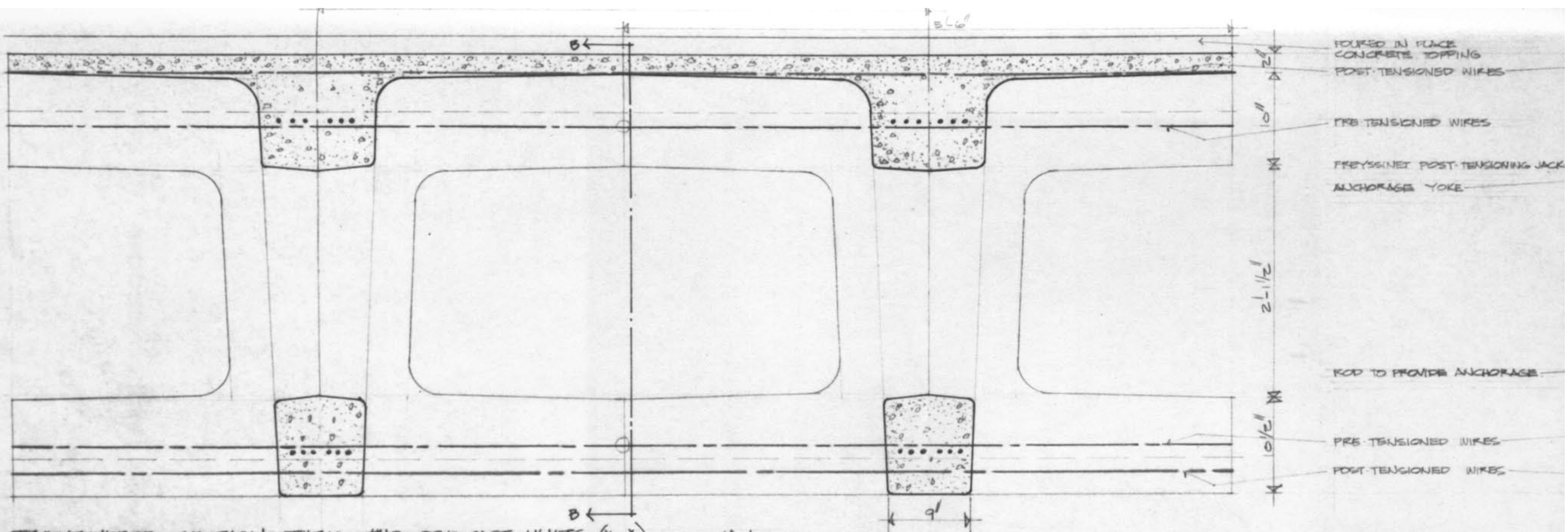
The development of this unit is aimed at a precast unit which would eliminate much of the usual required staging necessary in concrete construction, provide a reasonably small section with as large a perforation as possible, and act as a flat slab without a column capital in its final erected state.

2. Preliminary Proposal

The precast unit was assumed to be 4' - 0" high to provide enough space for mechanical services, 55' - 0" long, and 5' - 0" wide. The poured-in-place topping slab was additional to the height. The typical perforation was 2' - 1½" high by approximately 3' - 4" wide, and was placed 9" above the bottom face of the unit. The width of the web was 9" at the bottom tapering to a width of 14" at the flange. Eleven units placed side-by-side would form the floor structure for one bay.

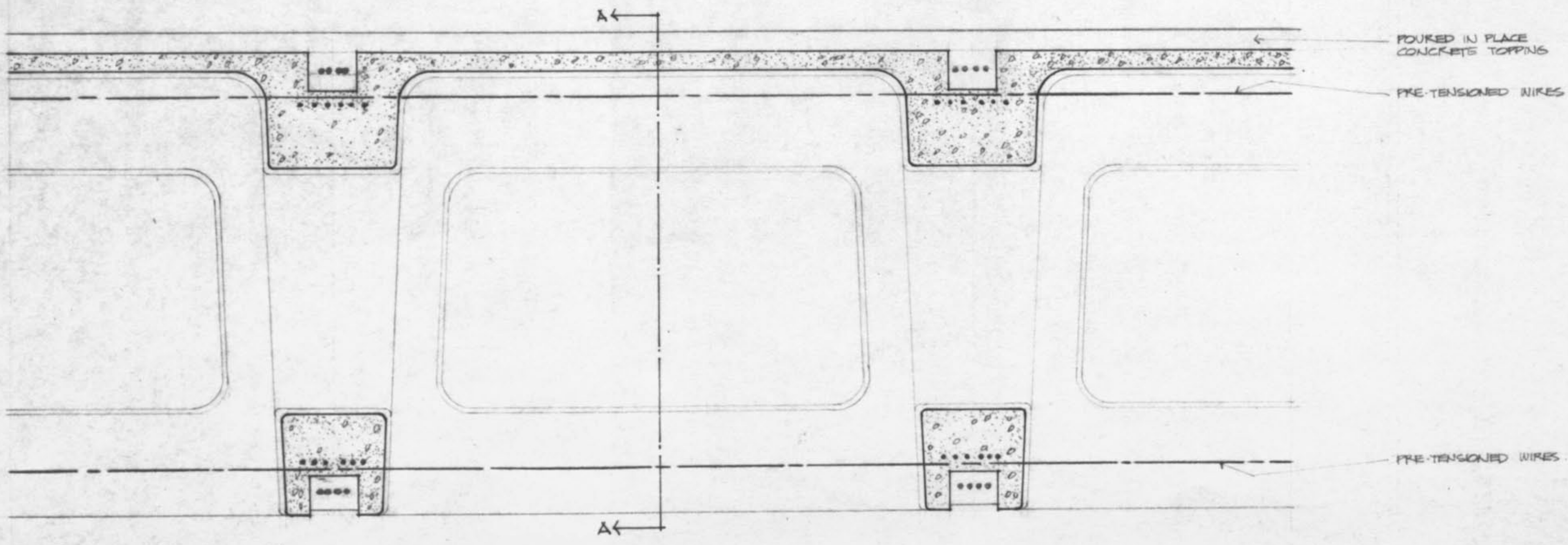
In order to maintain the smallest section reasonable with as large a perforation as possible it was felt necessary to prestress both top and bottom of the unit in both directions. (see figures 14, 15)

The column was assumed to be cruciform in shape to conform with the intersection of



TRANSVERSE SECTION THRU TWO PRE-CAST UNITS (A-A) SCALE: 1½"=1'-0" MAY 23, 1962

(A)



PARTIAL LONGITUDINAL SECTION (BB) SCALE: 1½"=1'-0" MAY 23, 1962 FIG. 14 PRELIMINARY PROPOSAL

(B)

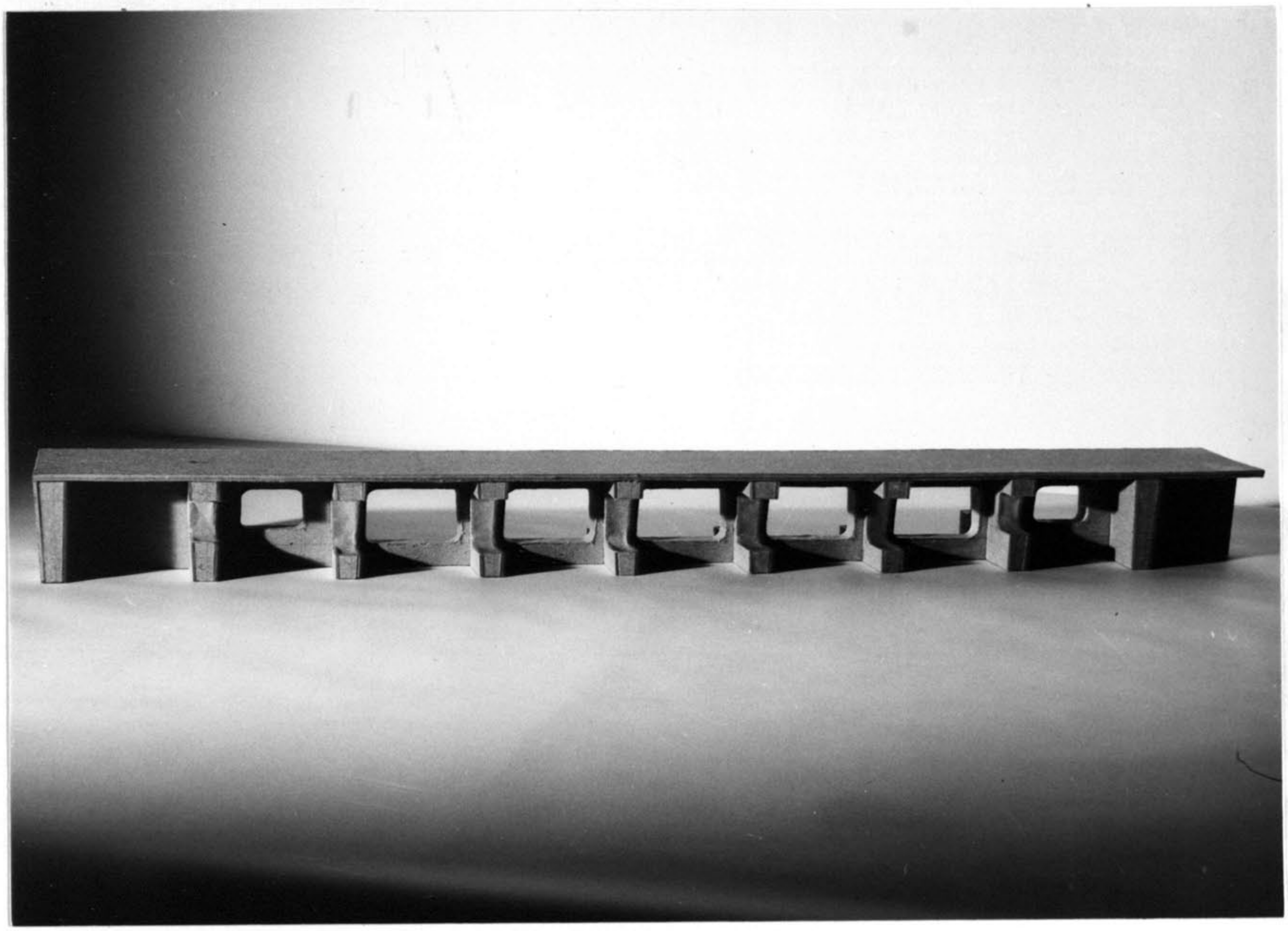


FIG. 15 MODEL PRELIMINARY PROPOSAL

the lower ribs. The column was 2' - 6" face-to-face and solid poured-in-place concrete with a roof drain in the center.

The shape and size of the column means that all of the shear, which is at a maximum at this point, had to be taken on four ribs. This, coupled with the concentration of maximum negative bending over the column due to the flat slab characteristics, seemed to be far more than could be accommodated with the size of the members assumed.

During the preliminary jury it was suggested that due to the large spans, it might be feasible to use larger columns which were hollow. The shear might then be reduced and air handling or other services could make use of the resulting void.

The column was expanded to 5' - 8" square which meant the shear could be taken on eight ribs instead of four. This reduced the shear problem considerably but did not eliminate it from consideration.

With the enlarged column a slab connection was assumed in which there was no continuity of the lower rib across the column, the assumption being made that the column could provide the necessary continuity. (see figure 16) This was so designed to get as large a perforation through the top of the column for passage of mechanical services as possible. This proved unfeasible. There must be the through continuity for true flat slab action.

To get the continuity in the slab itself from unit to unit there was to have been grooves, in the bottom and top of each outstanding leg, in which post-tensioning wires would be laid and stressed. The units themselves were to be pre-tensioned in the longitudinal direction of the unit to obtain the most effective use of a concrete section.

Continuity from unit-to-unit end-to-end provided another problem. For the purposes of the preliminary proposal it was assumed that this could be taken care of by horizontal

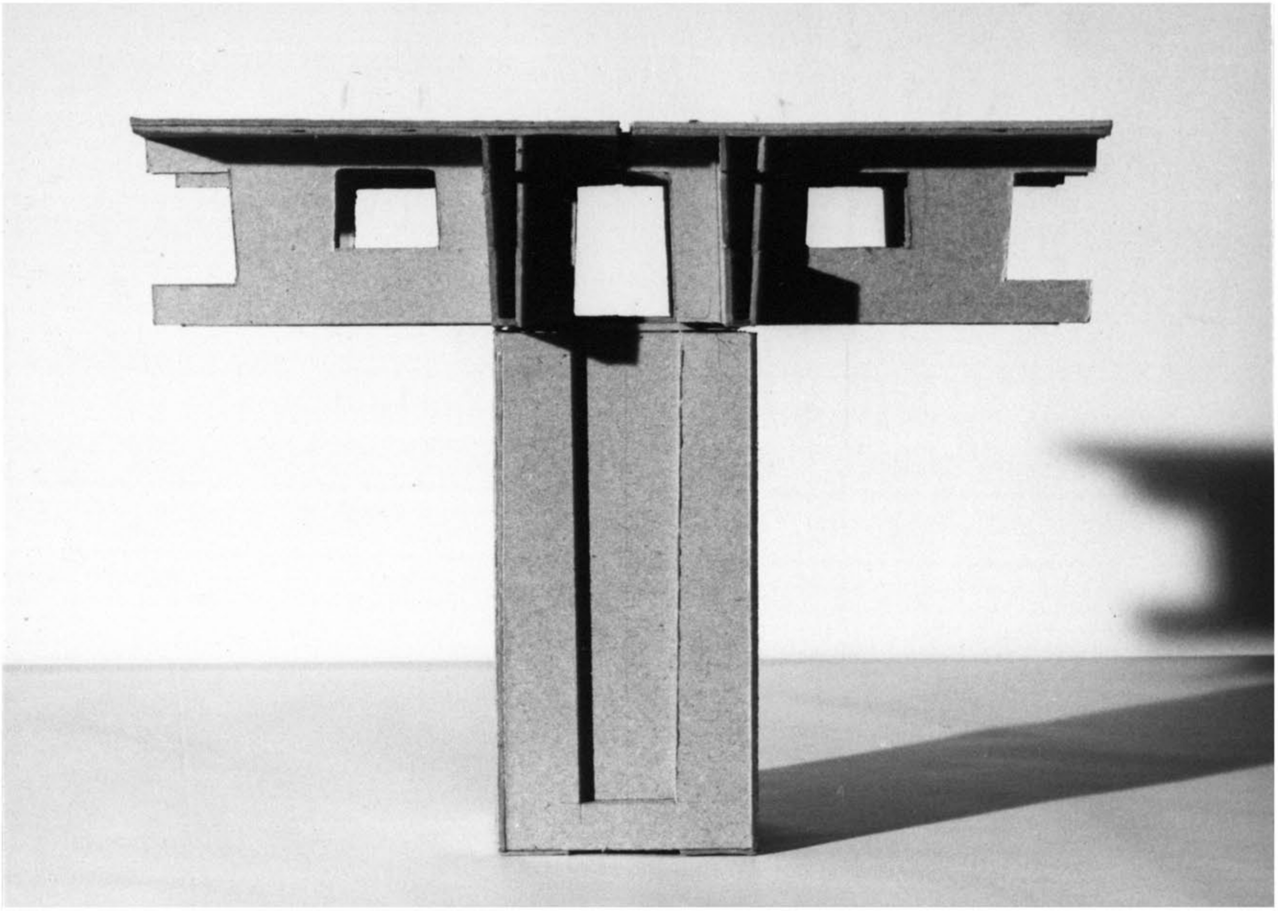


FIG. 16 MODEL PRELIMINARY COLUMN-FLOOR CONNECTION

post-tensioning across the joint.

During the structural analysis and consultation with the available structural engineers, it became apparent that the units were oversized and the prestressing had greater capabilities than had been assumed. It was also pointed out that if one can reduce the amount of post-tensioning on the job it would be desirable because of the labor costs today and the fact that the procedure requires trained personnel.

3. <u>Structural Analysis</u>

The structure is analyzed as a flat slab according to the ACI code of 1956. The amount of calculation presented is not intended to be all inclusive or finely detailed but rather to indicate to the author and the reader that the sections proposed are in the realm of reality.

a. Bending Moment

Live load 100psf

Dead load 130psf

$w = 230psf$

Total area of bay 3025 sq. ft.

Total weight $W = 3025(230) = 696{,}000$ lbs.

Bay dimension 55' - 0" square

$L = 55' - 0" = 660"$

Depth of Column $c = 68"$

$$M_o = 0.09WLF(1-\frac{2c}{3L})^2$$

$$F = 1.5-\frac{c}{L} \qquad F = 1.047$$

$$(1-\frac{2c}{3L})^2 \qquad = 0.867$$

$M_o = 36{,}000{,}000$ in. lbs.

$-.46M_o$ = Moment of support panel in column strip

$= -16{,}600{,}000$ in. lbs.

$+.22M_o$ = Moment of center of span in column strip

$= +8{,}050{,}000$ in. lbs.

$\pm.16M_o$ = Moment of center of span in middle strip and support panel in middle strip

$= \pm\ 5{,}850{,}000$ in. lbs.

b. Determination of prestressing force and cable sizing

$+.22M_o = +8,050,000$ in. lbs. over five ribs

$+.16M_o = +5,850,000$ in. lbs. over five ribs

F = prestress force

$= T = \frac{M}{0.65h}$

h = 48"

F at $+.22M_o$ = 258,000 lbs.

F at $+.16M_o$ 191,500 lbs.

F at $+.22M_o$ on one rib $= \frac{F}{6} = 43,000$ lbs. (F_1)

F at $+.16M_o$ on one rib $= \frac{F}{5} = 38,400$ lbs. (F_2)

Pre-tensioning strands for F_1 = 6 strands at $\frac{5}{16}$"diameter.

Pre-tensioning strands for F_2 = 5 strands at $\frac{5}{16}$" diameter (See Freyssinet data sheet 2)

$A_s = \frac{F}{f_s}$

$f_s = 0.75\ f_s'$ for post-tensioning 93,700psi

(See Freyssinet data sheet 2)

$f_s = 125,000$psi f_s'

Post-tensioning $A_s(1) = 0.460$ sq. in.

Use Freyssinet unit 18-0.196

Post-tensioning $A_s(2) = 0.410$ sq. in.

Use Freyssinet unit 18-0.196, this unit requires a hole of 1½" diameter. (See Freyssinet data sheet 3)

c. Tensile Stresses

Support panel at column strip

$$A_s = \frac{M(\text{in.lbs.})}{jdf_s} = \frac{16,600,000}{.866(46)20,000} = 20.8 \text{ sq. in.}$$

Use #6 bars 7" o.c. in 27' - 6" wide strip

Support panel in middle strip

$$A_s = \frac{5,850,000}{866(46)20,000} = 7.35 \text{ sq. in.}$$

Use #4 bars 9" o.c. in 27' - 6" wide strip

d. Compression Stresses

Critical section at support panel in column strip

Area of one lower rib (which would be subjected to this compression) equals 68 sq. in.

$C_1 = \frac{M}{h}$ compression force applied over five ribs

$C_2 = Af_c$ compression able to be taken over five ribs

$$C_1 = \frac{16,600,000}{42} = 396,000 \text{ lbs.}$$

$f'_c = 6000$ psi

$f_c = 2700$ psi

$$C_2 = 68(5)2700(.75) = 688,000 \text{ lbs.}$$

Section acceptable

e. Shear

Dead load 130psf

Live load 100psf

Area 3025 sq. ft.

$U = 1.2B + 2.4L$ = total load with safety factor (formula from page 983 ACI code)

B = total dead load $130(3025) = 394{,}000$ lbs.

L = total live load $100(3025) = 302{,}500$ lbs.

$U = 472{,}500 + 731{,}000 = 1{,}203{,}500$ lbs.

$V = \frac{U}{8} = \frac{1{,}203{,}500}{8} = 150{,}000$ lbs. shear on one rib at col.

$v = \frac{V}{bd} = \frac{150{,}000}{9(64)} = 260$psi

v_c (allow.) = 90psi (ACI code)

$v_s = v - v_c = 260 - 90 = 170$psi

$v_s A = V' = 170(9)64 = 97{,}800$ lbs.

s = stirrup spacing $= \frac{A_v f_s d}{V} = \frac{.88(20{,}000)64}{97{,}800} = 11.5''$ with #6 U-shaped stirrups

Web reinforcement can be reduced greatly by prestressing the section subjected to shear. (see example reinforcing drawing on final proposal drawings)

f. Analysis of unit as simple supported linear member during transportation and erection

55' - 0" member supported 7' - 6" in from each end

40' - 0" clear span

Unit weighs 645 lbs./ft.   total weight 35,500 lbs.

Moment at mid-span = +111,150 ft. lbs.

Moment at support = -114,850 ft. lbs.

$A_s = \frac{M}{f_s jd}$ = 1.9 sq. in. of steel in top flange

Use a 2 X 12 - 0/6 mesh

$C = \frac{M}{h}$ = 328,000 lbs. force applied to the bottom rib

$C = Af_c$ = 918,000 lbs force which section is able to resist.

Section acceptable

4. Final Proposal

a. Description of Unit

From the structural analysis, the depth of the unit is determined to be 3' - 9" with a 3" topping slab making a total dimension of 4' - 0". The typical perforation is 2' - 7" high by approximately 3' - 4" wide and is placed 8½" above the bottom face of the unit. The width of the web is 8" at the bottom and tapers to 11" at the flange.

b. <u>Formwork</u>

One of the major problems in the forming is the tendency of the unit to shrink when the prestress force is applied. The forms must be designed to accommodate this shrinkage or the outstanding legs will be snapped off.

For ease in removing the unit from the forms, the unit must be tapered slightly in the proper places. (see drawings) The formwork would be most effectively made out of steel.

c. <u>Tolerances</u>

Due to the nature of concrete, the curing processes, ways of forming and prestressing, it is difficult to get tolerances any finer than $\pm \frac{1}{4}$".

d. <u>Continuity From Unit to Unit</u>

Continuity is affected from unit to unit by means of prestressing in the positive bending moment areas. In the negative bending moment areas continuity is affected by means of ordinary reinforcing bars placed in the topping slab.

e. <u>Description of Prestressing Cable and Post-tensioning Anchorage</u>

The calculations also showed that a very nominal prestress force is required. To accommodate the post-tensioning cable, which runs transverse to the unit length, a hole of $1\frac{1}{2}$" in diameter is required through the center of the outstanding legs.

The pretensioning can be done with five wires 5/16" in diameter. These wires would be imbedded in the lower rib section in the longitudinal direction of the unit.

In the units that frame into the column, which all the shear is taken on, the prestressing wires and cables will be draped as shown in the finaldrawings to resist the diagonal tension force. This reduces the ordinary type reinforcing in this section to a minimum.

A detail for anchorage of the post-tensioning cables is shown in the final drawings. This is the standard detail of the Freyssinet system for anchorage. Because the prestress force is so nominal, the jack required is one of the smaller ones manufactured by the Freyssinet Company. There is ample room within the structure to accommodate this.

f. Results of Increased Prestress

It is conceivable the sections of the unit could be reduced somewhat with the use of a larger prestressing force. However, greater care than is now needed would have to be exerted during transportation and erection so as not to damage the unit.

g. <u>Erection Sequence</u>

(1) Pouring of columns, curing, and stripping of forms(or setting up of tensioning rods, placing of precast columns,and stressing rods within the columns.)

(2) Erecting of staging for floor units

(3) Placing of units on staging

(4) Post-tensioning procedure

(5) Column connection secured

(6) Laying of steel for top slab

(7) Pouring of top slab

(8) Formwork for next floor columns while mechanical is being put in floor just completed.

h. <u>Description of the Column</u>

As indicated in the preliminary proposal, the column is hollow and is 68" square to correspond to one module. The column shown in drawing no. 2 is poured-in-place. The center of each side of the column has knock-out panels which provide access for service connections, maintenance and grilles. There is also a hole at the top of the column corresponding to the holes in the structure which allows the passage of mechanical services to the floor structure.

Through the use of vertical prestressing, it is possible to use precast columns which would eliminate more poured-in-place work. The prestressing would, of necessity, have to be by high tension rods with couplers at each floor to enable a nominal prestress force to be made as each floor went up to maintain a certain stiffness until the final stress could be made. The general shape and dimensions are the same as with the poured-in-place column.

i. <u>Lighting Facilities</u>

It is conceivable that an air duct and the position of a light fixture might conflict which would interfere with the usual means of suspended support for light fixtures. In the interest of greater flexibility, inserts would be imbedded into the sides of the lower ribs of the unit to receive screws, bolts or other attaching devices. Fixtures attached to these inserts would leave the upper regions free for passage of ducts and other services.

j. Noise Transmission Control

Panels of reflective or absorptive material, whichever the particular requirements may be, would be supported by the inserts imbedded into the sides of the lower ribs. A neoprene gasket could be used to insure a tight seal.

In the areas where maximum control is to be exerted, the light fixture will be sound insulated also.

k. Electrical Services

Regularly spaced holes through the top and bottom ribs allow passage of conduit into the walls for connection to switches and outlets.

l. Partitioning

Illustrated in the final proposal is a 4" concrete block partition in place.

The bottom rib of the unit contains a 4" by ½" groove which would accommodate the anchorage for partitions.

m. Miscellaneous

Holes can be cast into the flange where ever necessary for services to rise to the floor above.

5. Observations

a. Advantages

The precasting of the units to the length of one bay reduces the amount of staging necessary for erection as opposed to those units of one module size.

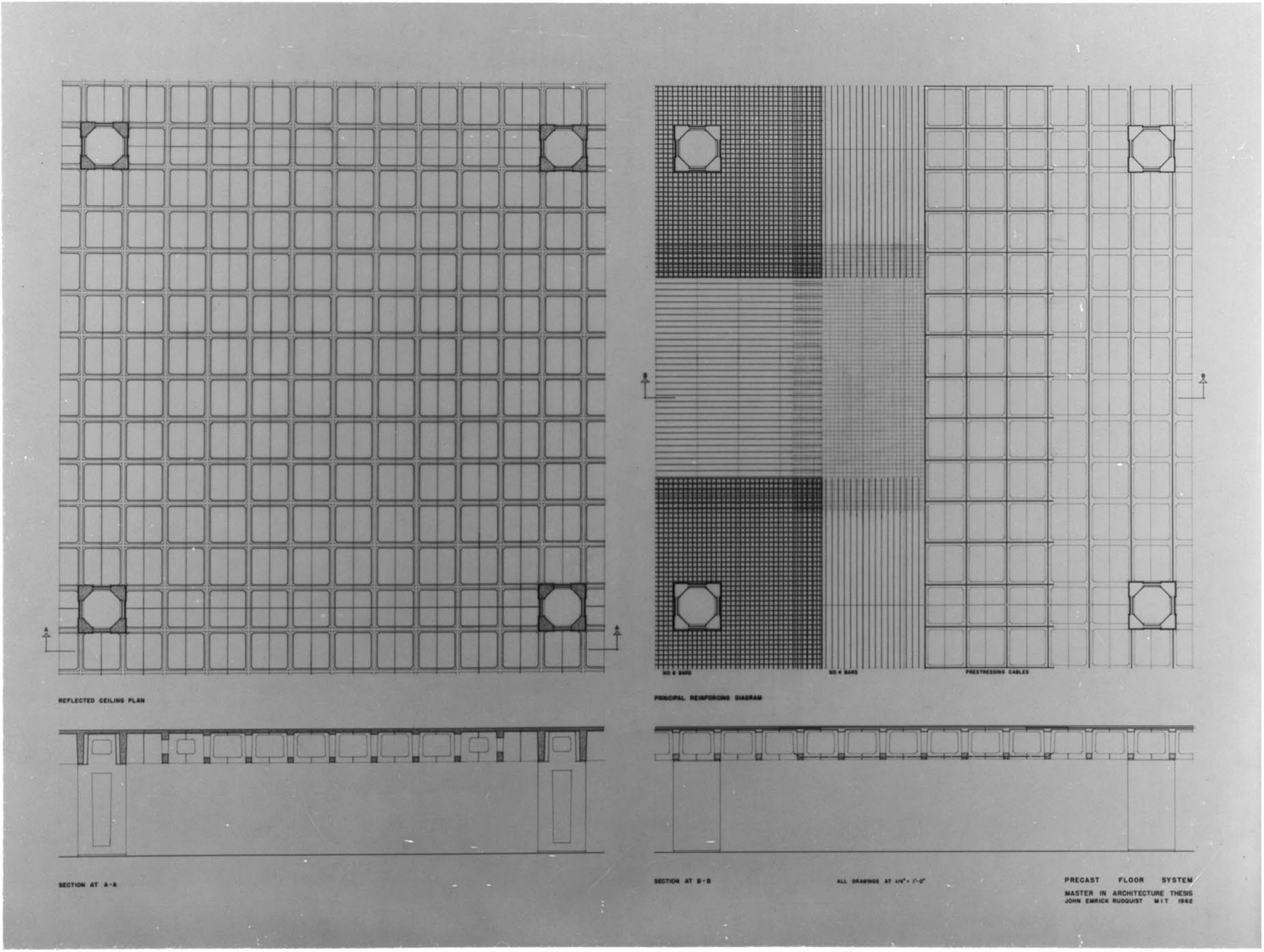
Using units of this magnitude also reduces the amount of post-tensioning by using pretensioning in the precasting yards which is desirable because of the better control that can be had in the yard.

The total weight of this unit is 17.75 tons which utilizes crane capability more efficiently than the smaller units. The fact that the rough slab is a part of the unit is another desirable feature in that it eliminates costly formwork for pouring the slabs which other systems need.

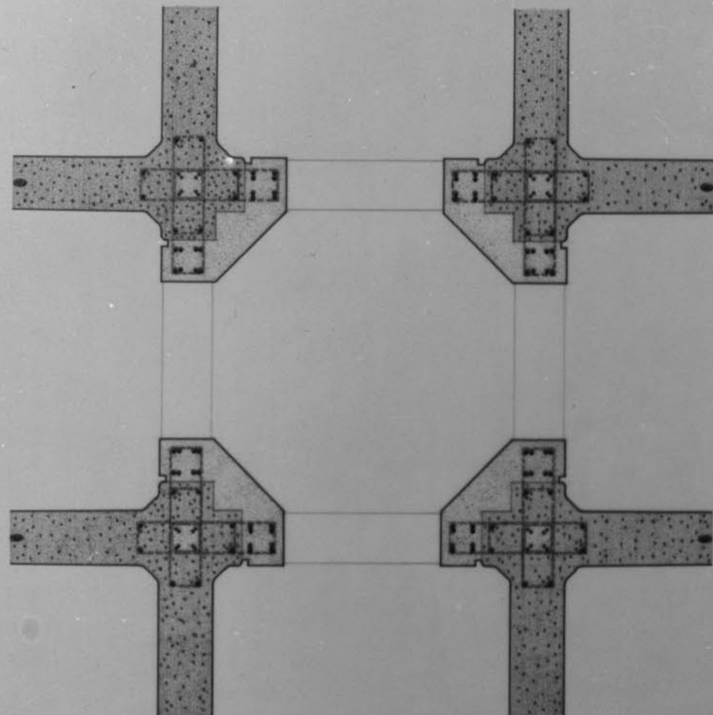
Rectangular perforations allow the passage of mechanical services more easily than the triangulated geometries.

b. Disadvantages

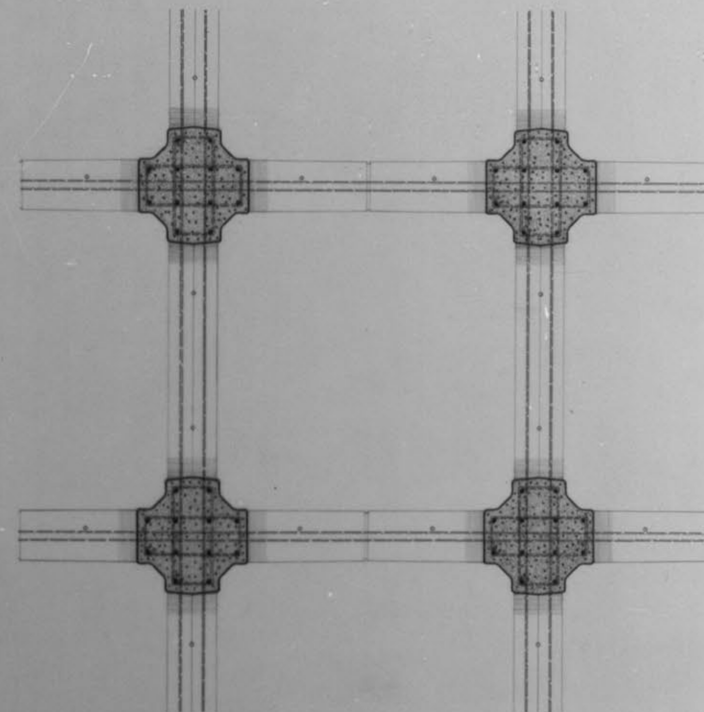
The size of the bay has a possibility of being somewhat limited by the capability of cranes available for erection and/or the transportation limitations due to truck sizes or local regulations on load restrictions.



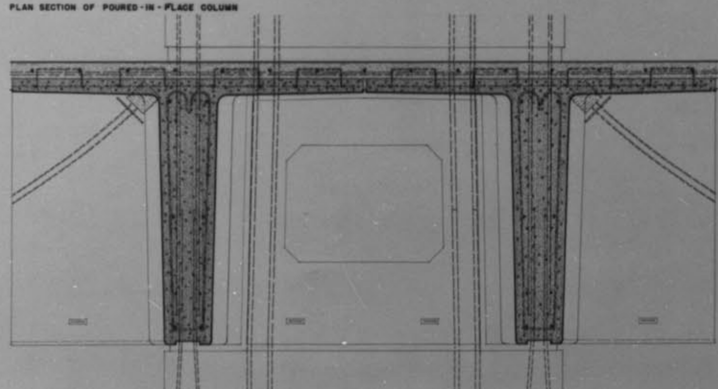
NO 6 BARS
NO 4 BARS
PRESTRESSING CABLES
REFLECTED CEILING PLAN
PRINCIPAL REINFORCING DIAGRAM
SECTION AT A-A
SECTION AT B-B
ALL DRAWINGS AT 1/4" = 1'-0"
PRECAST FLOOR SYSTEM
MASTER IN ARCHITECTURE THESIS
JOHN EMRICK RUDQUIST MIT 1962



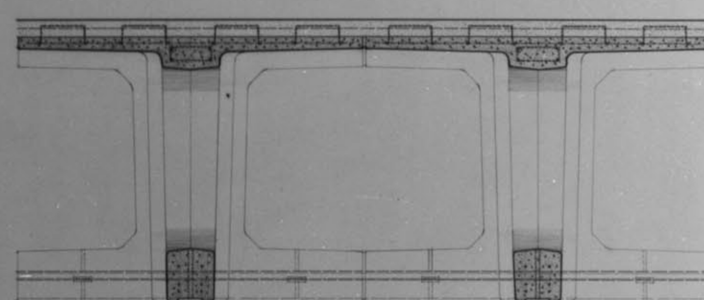
PLAN SECTION OF POURED-IN-PLACE COLUMN



PLAN SECTION OF TYPICAL UNIT



DETAIL OF POURED-IN-PLACE COLUMN



DETAIL OF TYPICAL UNIT

ALL DRAWINGS AT 1 1/2" = 1'-0"

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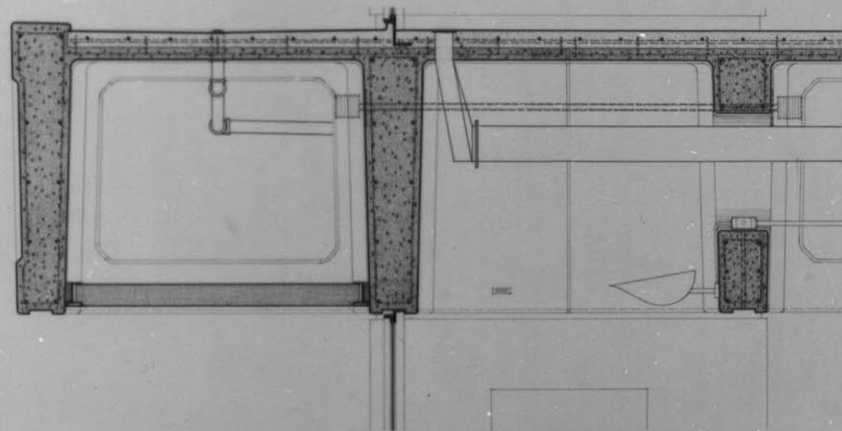
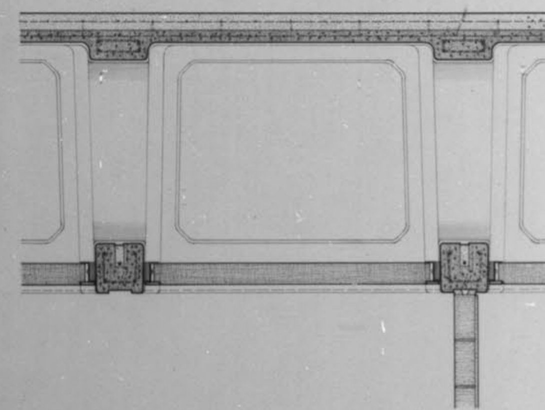
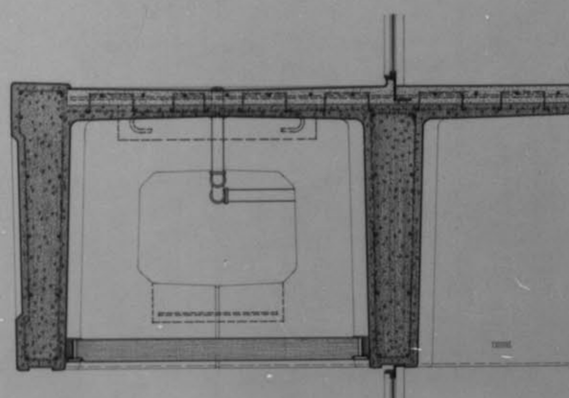


EDGE CONDITION AT END OF UNIT



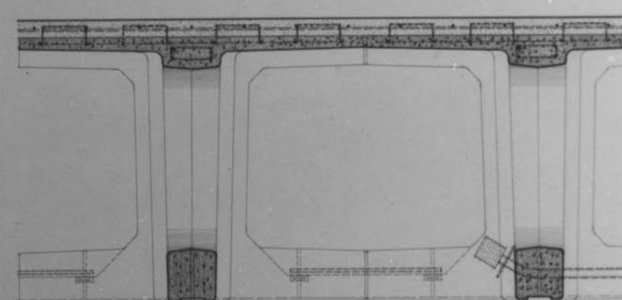
DETAIL OF FINISH CEILING PANEL

4" CONCRETE BLOCK WALL



EDGE CONDITION AT SIDE OF UNIT

ALL DRAWINGS AT 1 1/2" = 1'-0"



DETAIL OF POST-TENSIONING ANCHORAGE & STEEL FOR CONTINUITY

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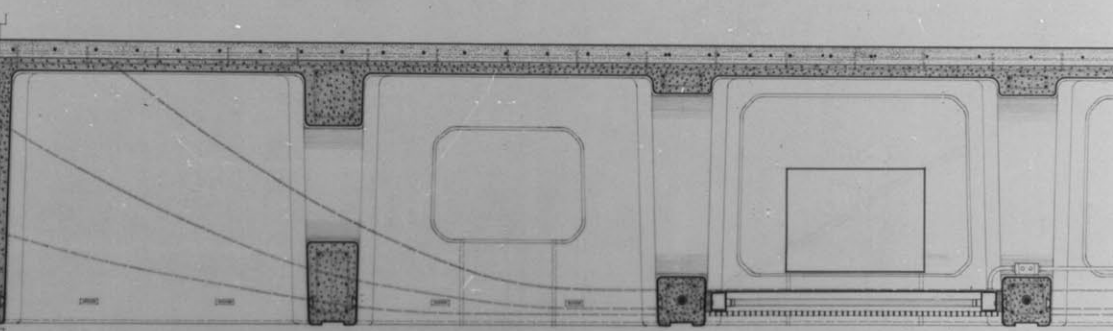
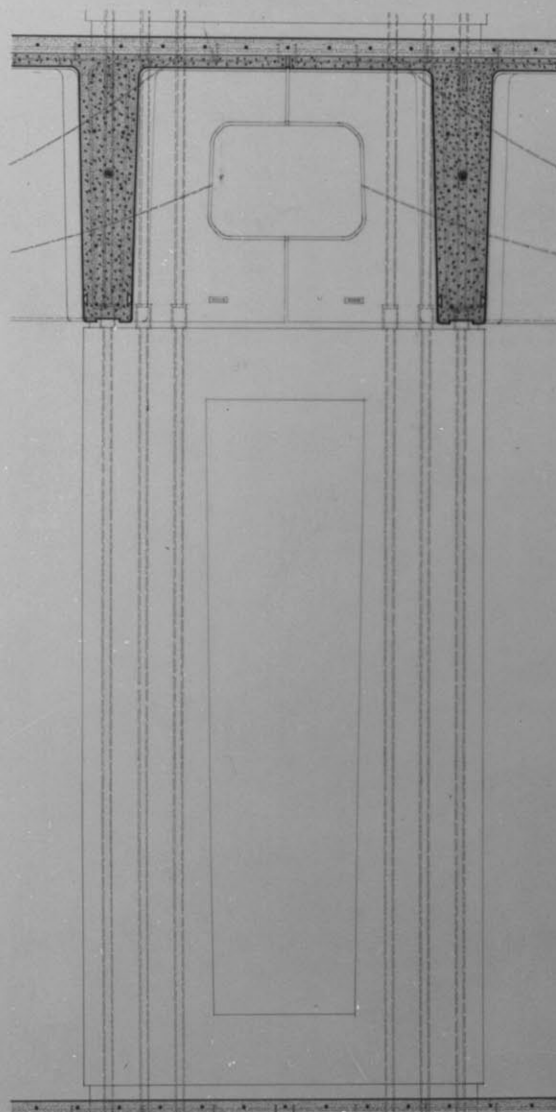
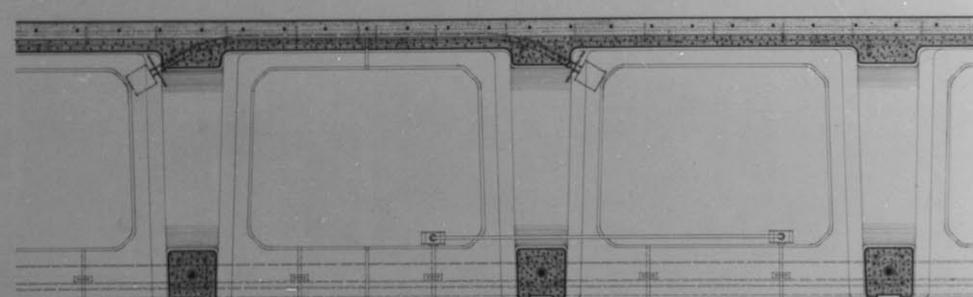


DETAIL SHOWING DRAPED PRETENSIONING STRANDS

LIGHT FIXTURE



DETAIL AT PRECAST COLUMN



DETAIL OF JOINT AT END OF UNIT

ALL DRAWINGS AT 1 1/2" = 1'-0"

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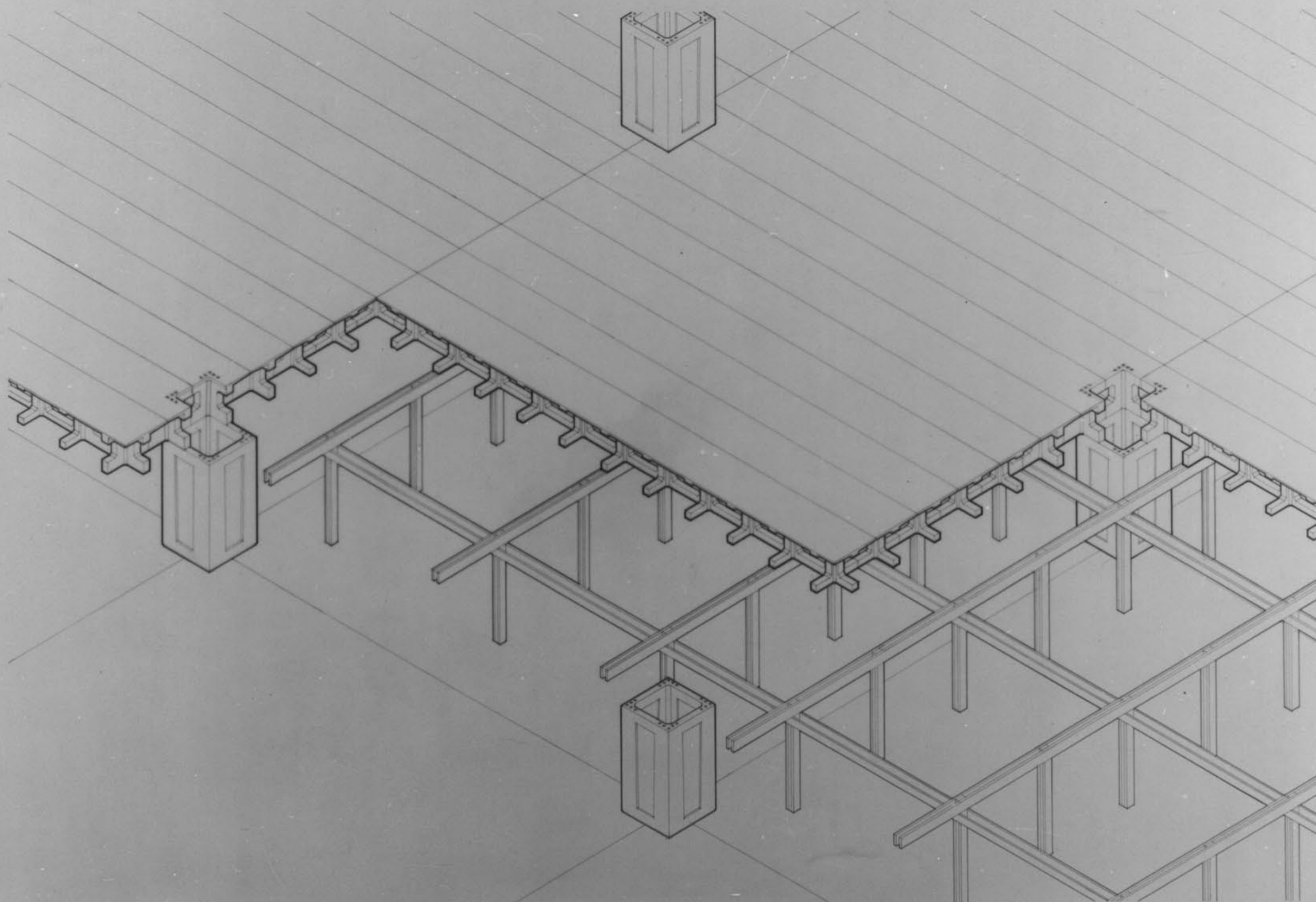

ISOMETRIC VIEW ERECTION SEQUENCE SCALE: 1/4" = 1'-0"

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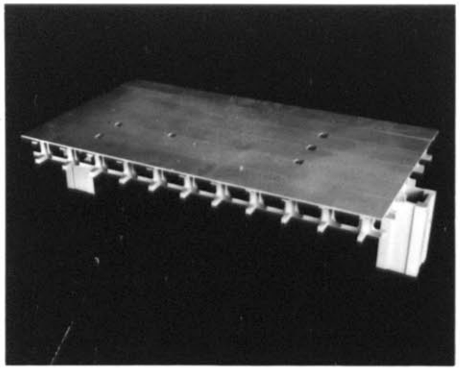
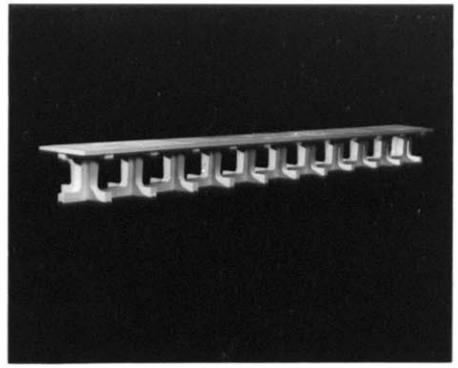
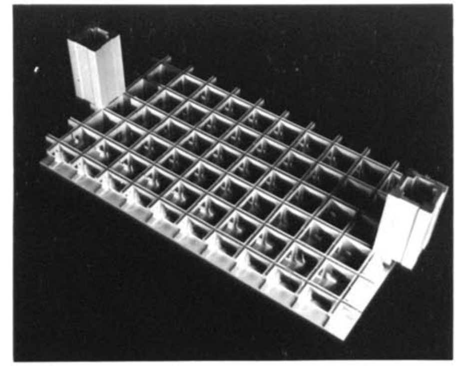
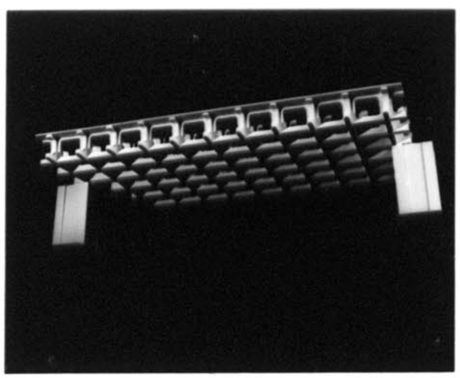
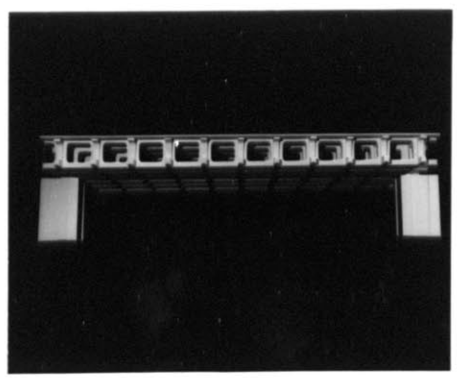
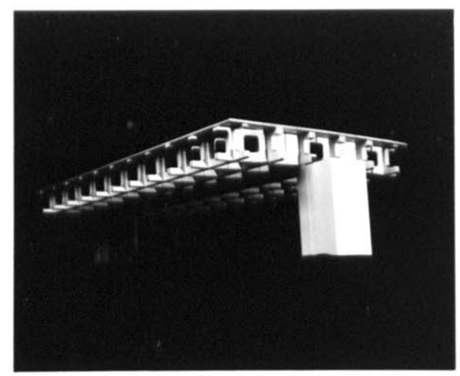

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