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ARCHITECTURAL INVESTIGATIONS OF BUILDINGS AS SYSTEMS

By

John Linn Forbis
B. Arch., University of Oklahoma, 1964

SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER IN ARCHITECTURE
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15 June 1965

Pietro Belluschi, Dean
School of Architecture and Planning
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Dean Bellusch,

In partial fulfillment of the requirement for the degree of Master of Architecture, I hereby submit this thesis entitled, "Architectural Investigations of Buildings as Systems."

Respectfully,

Signed ______________________
John Linn Forbis

ABSTRACT

This thesis is concerned with the design of a prototype system for a research and development building. The two areas of concentration were a system of growth whereby a building can be expanded without compromising the life of the building and the structural subsystem within the building. The growth study compares one way or linear patterns with multidirectional or neutral patterns of growth. Accompanying these studies are three directly analogous systems from nature and mathematics. The second part of the thesis, the structural subsystem study, compares one way and two way structural systems and discussed the system finally adopted.

ACKNOWLEDGEMENTS

I am grateful to Professor Eduardo F. Catalano for his patient introduction to the concept and exploration of systems.

I want to thank Professor Waclaw Zalewski for guidance in structural systems and his affirmation of the creative engineer which he exemplifies.

TABLE OF CONTENTS

INTRODUCTION: Buildings As Systems

For the purpose of this paper a system is a set of relationships within or between entities. In architecture systems can be used at many lebels of organization with the entities being either material objects or subsystems. Nature can be interpreted as a system whereby phenomena is internally and externally organized. Some of nature's systems are directly analogous to the problems confronting architectural organization. Man has also uncovered systems of mathematical models which the architect can employ. The tree and the semi-lattice are mathematical models which can aid the architect in the formation of the design conception.

The cellular systems, see illustrations A and B, in Nature result when the forces shaping the body are all of similiar magnitude. These forms are similiar to the two way systems of buildings. When all factors are of similiar magnitude or when a neutral receiver is desired because the magnitudes of the eventual forces cannot be predicted, the two way system is

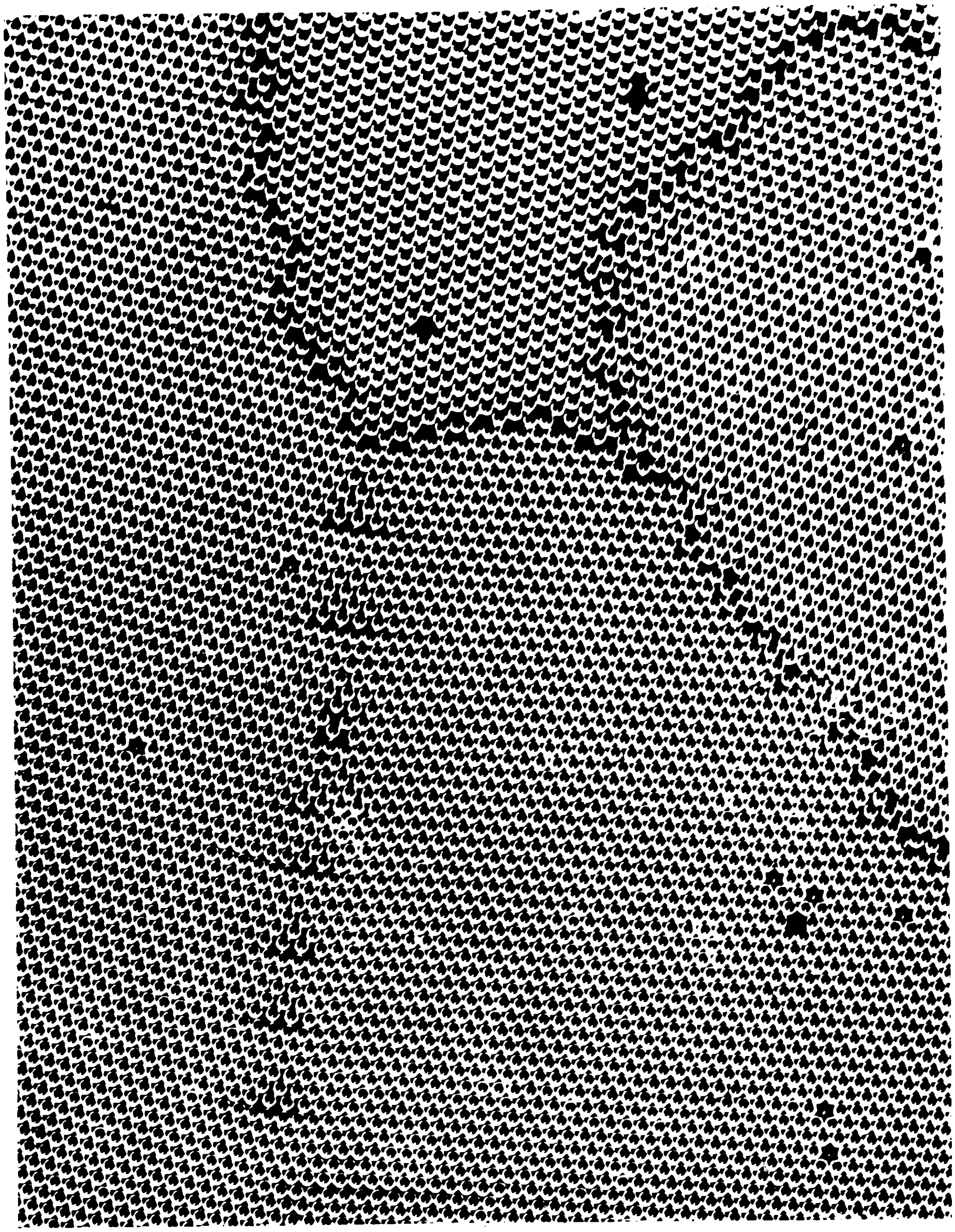

Fig. 2. Raft of tiny uniform soap bubbles showing "grain boundaries" where zones of differing orientation meet. Magnification x 7.

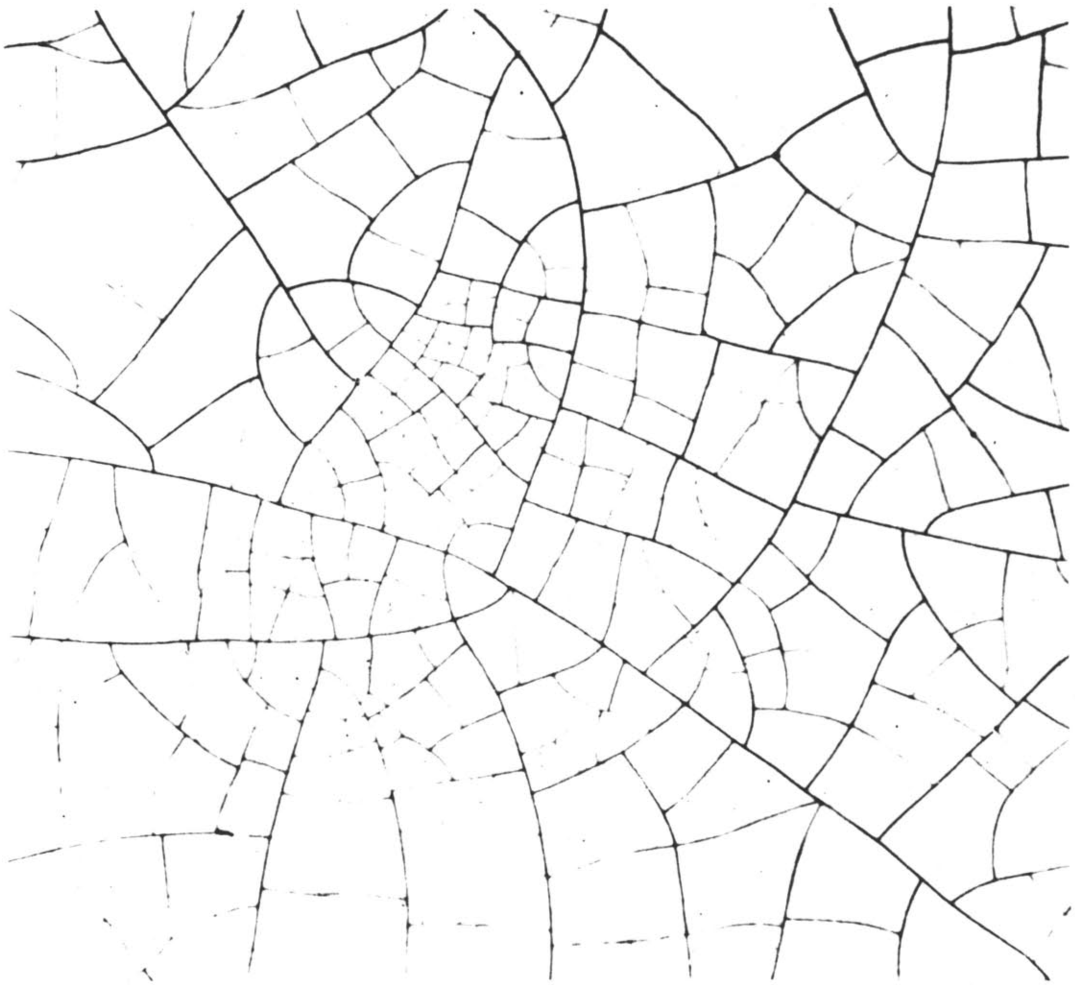

Fig. 7. Pattern of craze lines on a glazed ceramic surface. Magnification x 1.5.

a desirable solution. The second group of photographs, C and D, illustrate branched structures. According to Cyril Stanley Smith, "this occurs whenever a protuberance has an advantage over adjacent areas in getting more metter, heat, light, or other requiste for growth."[1] If a predominate factor can be singled out then a direction could be plausible in the building system, resulting in a linear system.

One of the difficulties of the prototype is the provision of unity to the resultant building. While the tree is the mathematical model generally used to organize a diverse group of subsidiary systems in a hierarchy, the prototype needs more unifying units. While Alexander bases his model upon the need to resolve the complexity of the city, it will also serve to organize this system. The semi-lattice model provides the necessary hierarchy in organization; yet, simultaneously, adds the subtle necessary interrelations between branches of the tree which a complex unit needs and uses.

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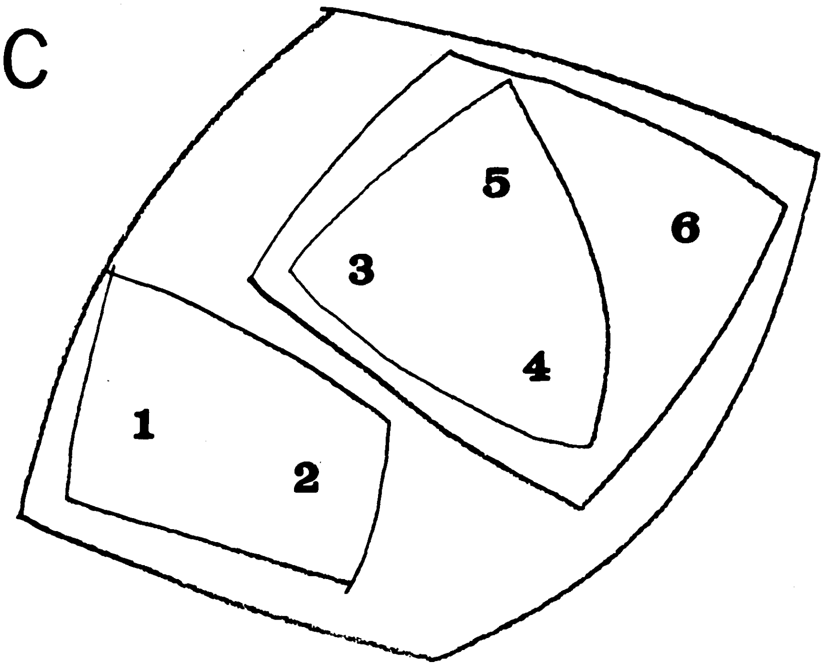
1. Cyril Stanley Smith, "Structure Substructure Superstructure", Structure in Art and Science, p.39

2. Christopher Alexander, "The City As A Tree", Architectural Forum, Vol.122, #1, p.58

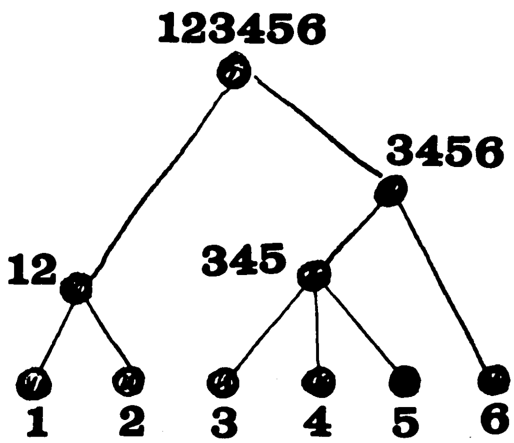
Fig. 15. The surface of an ingot of antimony, showing dendritic crystals which have grown to interference with each other. (This pattern was the mystic Star of Antimony of the alchemists.) About natural size. *(Photo Courtesy The Science Museum, London. Crown copyright)*

Fig. 16. Pattern of ridges formed by a crack moving in a crystal of a brittle compound of copper and magnesium, Cu_2Mg. The crack proceeded from the top to the bottom of the figure. Magnification x 300. *(Photo Courtesy Duane Mizer, Dow Metal Products Company)*

C

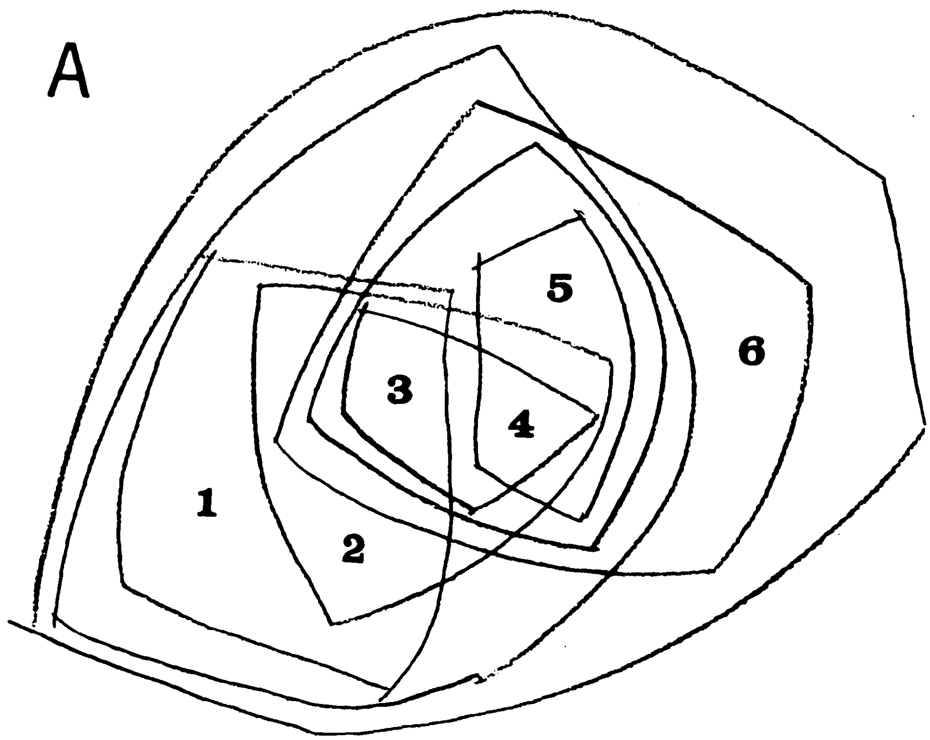


D

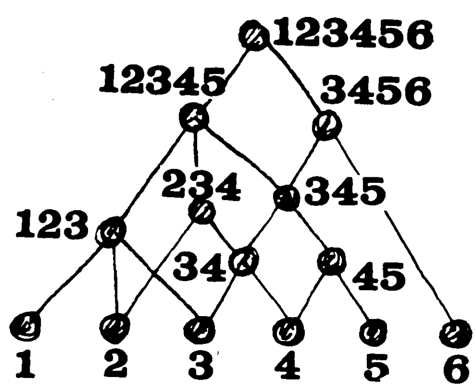


A collection of sets forms a tree if and only if, for any two sets that belong to the collection, either one is wholly contained in the other, or else they are wholly disjoint.

A



B



A collection of sets forms a semi-lattice if and only if, when two overlapping sets belong to the collection, then the set of elements common to both also belongs to the collection.

The adopted solution is based upon the integration of a two way structural system with multidirectional and neutral growth patterns. This system can fit the exterior local variables with a minimum of compromise to both the internal functioning of the building and its relationship with the surrounding environment.

The provision of unity to large and diverse prototypes requires more than the hierarchy of organization can provide. In this study the interaction of each subsystem becomes the basis for such unity. The predominate unifying factor is the structural system which has been transcended from its first purpose, and used to unify and enrich the space of the building.

Creative Engineering

Architecture Tomorrow

Close collaboration between creative architects and engineers is needed to solve the building problems, today and tomorrow. The demands that society is placing on the building industry, coupled with the rapid pace of society, requires total creative solutions by all members of the team. The problems can no longer be solved by an individual discipline nor can other disciplines hold their area constant while an individual explores and solves his specialty. The broad and the individual solutions must be a synthesis based upon the need and results of each field and the total problem. These needs can only be met when all members of the team, architect, engineer, and others are working as creative collaborators. Only then will solutions in one area aid in generating better solutions in the other areas of the problem.

In the future, when architects begin to integrally apply systems and teams, the architect will be freer to understand and control the application of the wealth of benefits which the technological revolution is providing. Equally the advances in the education process will provide him the time to completely understand his society and his responsibility. Then perhaps the complete integration and expression of man's productivity with man and his society will once again begin to mature in a culture of man.

AIM OF THE THESIS

The purpose of this thesis is to explore the concept of buildings as systems. The stated problem is a prototype building of about 600,000 sq. ft. gross floor as an integrated system of spaces, structure, and services to be used for research and development activities. Both simple flexible space for scientific and administrative personnel and more complex flexible space for laboratories and development of components were required. The building studies were divided into five major system areas: life systems, system of growth, circulation system, services system, and the construction system.

From these I studied two extensively. The building as presented is the result of examination of a system of growth which does not compromise at any time during the life of the building the other complimentary system. The second more extensive part of the thesis, is a study of a structural system which fulfilled the needs as established by the above requirements [illegible], the requirements of structural economy and the interaction with the above systems.

of the building, the requirements of structural economy and the interaction with the above systems.

Duration of Installation of the Components of a System

Constant or Permanent

Structural System

Cores

Mechanical Rooms

Electrical and Telephone Supply

Long Term Variables

Configuration of Building

Location of Life Spaces

Mechanical Supply

Intra Structural Bay Changes

Short Term Variables

Partition Position

Circulation Configuration

Acoustical Panels

Lighting Units

Mechanical Diffusers

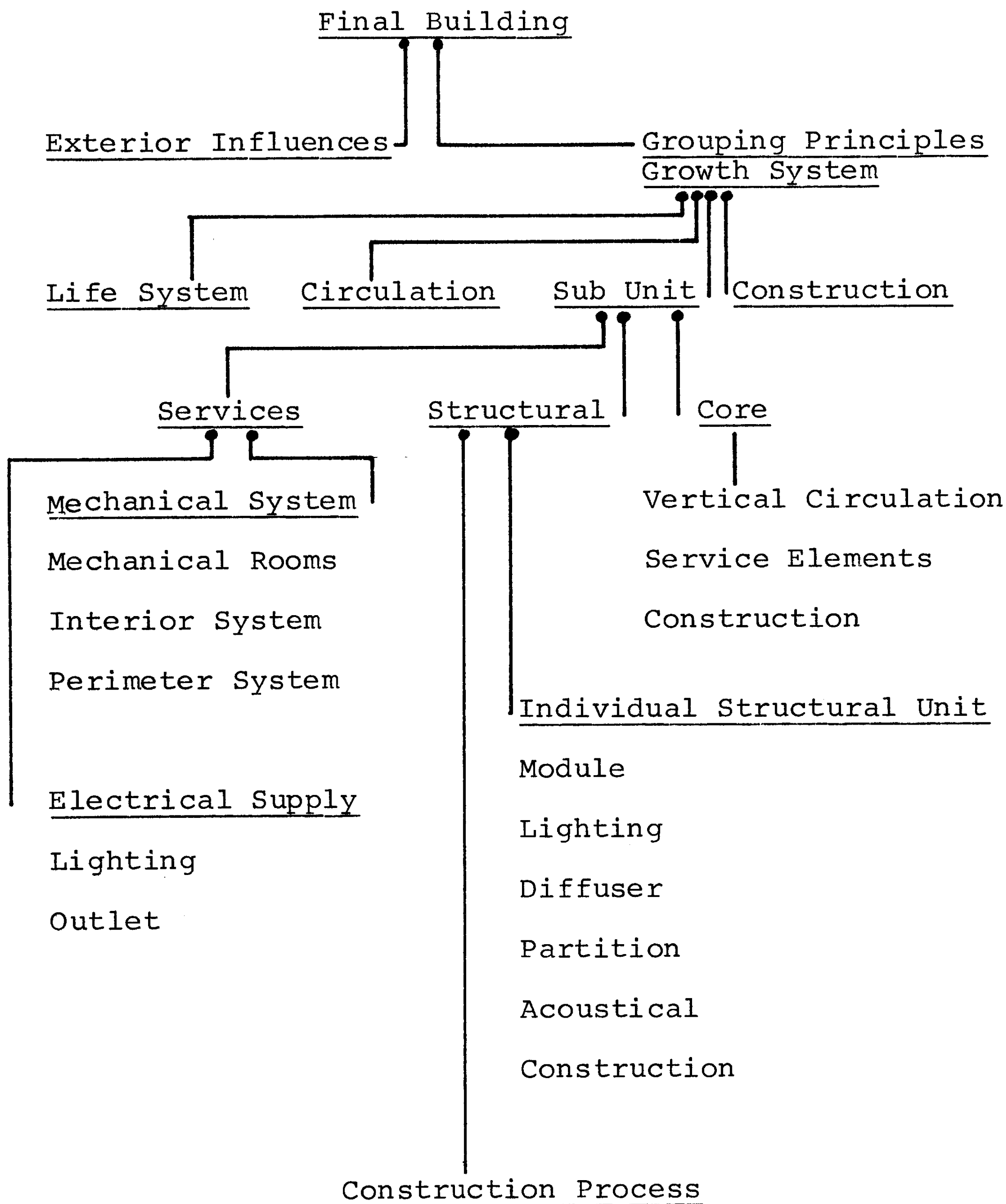
Exact Configuration of Life Spaces

FLEXIBILITY

Within the building system there are several modes of flexibility. The system of growth is that mode which meets the needs for large scale expansion. The growth system is based upon the independent unit which the core mechanical and structural systems determined and the needs of circulation and life spaces. While whole units can be added without alteration to the existing building the process is not reversible.

The next mode of flexibility is for the short time highly variable demands. These include the partition system, mechanical distribution, lighting units, and the partition panels. The placement of the core in a neutral area, the long span structural bays, the allowable changes in configuration, but not location, of the life spaces and increased flexibility. Between these modes the removability of the central sections of certain bays allows for vertical expansion on a medium scale, but once the section is removed the section cannot be returned to its original place. Finally, all subsystems are unitized so that units can be interchanged quickly without disrupting the overall system for long periods of time interchanged quickly without disrupting the overall system for long periods of time.

HIERARCHY OF SYSTEMS



SUB SETS

Structural Units

Life System   Lighting   Acoustical

Mechanical   Partition

Life Spaces

Grouping Principles   Circulation   Growth

Requirements as Given for a Five Story Building

Module 5' - 0"

Structural Spans not less than 30' - 0" in the shortest dimension.

Live Load - 125 psf.

Elevators 12 elevators 5' - 0" x 7' - 0"

Service Elevators 1 per floor 8' - 0" x 12' - 0"

Toilets per floor

	Men	Women
Urinals	20	
Waterclosets	20	20
Lavatories	15	15

Mechanical System Two Duct System - Supply and Return

Internal	Supply	3000 CFM / 1000 sq.ft.
	Return	1000 CFM / 1000 sq.ft.
External	Individual Fan Coil Units	

Electric Closet 5' x 10' every 15,000 sq. ft. of gross area

Telephone Closet 50 sq.ft. every 15,000 sq. ft. of gross area

Janitor's Closet 30 sq.ft. every 30,000 sq. ft. of gross area

Public Telephones One every 15,000 sq. ft. of gross area.

The Solution

Grouping Principles: The grouping principles are the conclusions derived from the observed relationships when the sub unit is grouped into desirable configurations.

Life of the Building: The life of the building is defined by three types of communal spaces. The first is the central space which passes up through the building. The next spaces are auxilliary courts about which the cores are grouped. These are only two stories in height and will have distinct circulation connections with the central space both at the main floor and the upper floor level. The third spaces occur at the perimeter of the main building. About these two story openings the growth of the building will occur.

The Sub Unit: The sub unit was determined by the core, specifically the area accessible to the stairs for fire safety, the linear pattern of the mechanical duct system, the structural system, and the construction system.

Structural System: The structural grid is a 10' - 0" square 5' - 0" deep, subdivided into 4 5' module units. All the units of the structure will be precast and light enough to be removed from the truck either with a small crane or a large fork lift. All assembly will be accomplished on the ground so that scaffolding will not be needed.

Construction Sequence

1. Parking floors are completed to serve as a flat surface for assembly.
2. Lower post tensioning cables are laid on the slab.
3. Columns are placed.
4. Structural members are placed.
5. Top panels are placed
6. Top chord post tensioning cables are laid in prepared slots.
7. Post tensioning sequence completed.
8. Individual floors are lifted into place.
9. Perimeter elements are placed.
10. Finishing is completed.

Mechanical System

Atop each core the fan room will be located for that sub unit. These will be supplied by a central basic mechanical equipment room.

Area of Basic Mechanical Room: 4% 700,000 sq.ft. = 28,000 sq. ft.

Area for Air Handling Unit: 6% 150,000 sq. ft. = 9,000 sq. ft.

Perimeter Individual Fan Coil Units hot and chilled water piped to each unit.

Cores

1. 2 elevators per core
2. 1 men's toilet
3. 1 women's toilet
4. 1 electric closet
5. 1 telephone closet
6. 1 stair
7. either a service elevator or a storage room
8. 1 janitor's closet
9. 400 sq. ft. of duct space based upon 320 sq. ft. for immediate use and 80 sq. ft. for expansion and pipes.

The Columns: The Columns will stop at the middle of a module unit to simplify the partition joint detailing because of the variety of partition thicknesses to be used.

The Acoustical Control: The acoustical control for economy and appearance in rooms up to 20' x 20' will be panels placed horizontally between the lower chords of the structural unit. For a 20' x 20' room local conditions will dictate the treatment. In rooms larger than 20' x 20' - 4 x 4 modules - vertical acoustical panels enclosed in the openings of the structural system will be used.

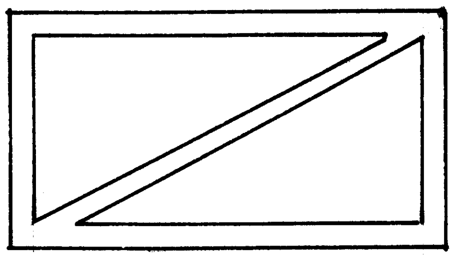
STRUCTURAL SUB SYSTEM

Consistency in expression is a major design task in a building of this magnitude. While a definite hierarchy of systems provides organizing consistency, common denominators are needed to intensify the unification of this large building. These should be drawn from the permanent consistent systems, instead of arbitrarily established conventions of design. In this building the structure is suited for its basic purpose, to unify the subsystems and to enrich and intensify both the communal and individual spaces.

Because of its simplicity of erection and compatibility with a definite mechanical distribution the one way system was first examined. Difficulties arise when mechanical feeds cannot be defined and the need exists for placement of large mechanical ducts through the girder from central core feeds. A double girder system resolved this problem, but the definite linear patterns of organization suggested by a linear system did not seem as desirable as a more multidirectional system where the influence of growth and the site could be resolved without excessive structural compromise. Furthermore, the need to support partition in both directions requires an infill unit in a one way structure.

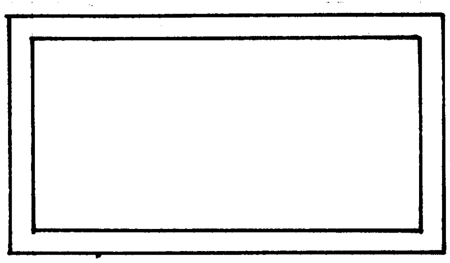
The next studies were various two way systems based upon the rule of constancy of forces whereby horizontal shear is eliminated. The double girders allowed sufficient openings for the passage of services in both directions, but the configuration of the openings was not completely satisfactory. Furthermore, as discussed in the joint section, a satisfactory joint could not be resolved.

Vierendiel Trusses provide optimun resolution of the mechanical duct requirement, but the extremely high moments at the chord web intersection makes them uneconomical. The following illustrations show the desirability of the final solution to resolve the mechanical requirements and to place enough material at the intersection to make the joint more economical.



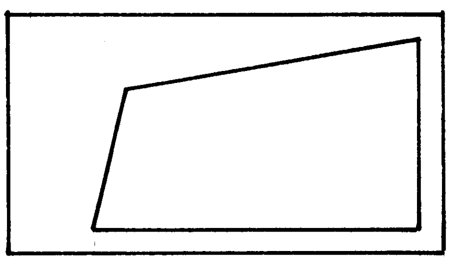
axial forces in member.

difficult for mechanical duct passage.



very high moments

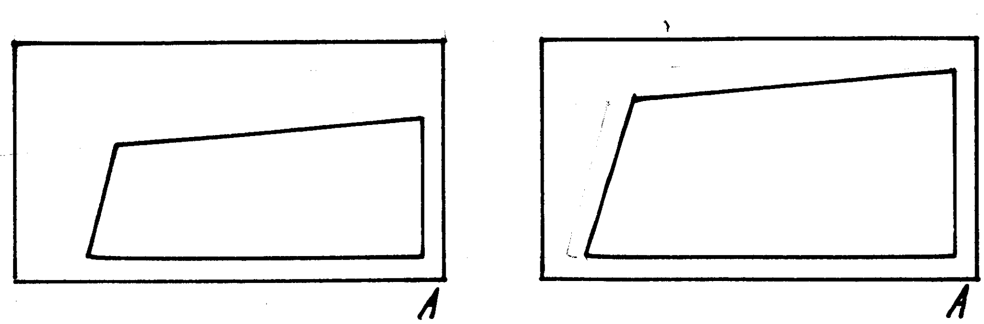
large openings for mechanical ducts.



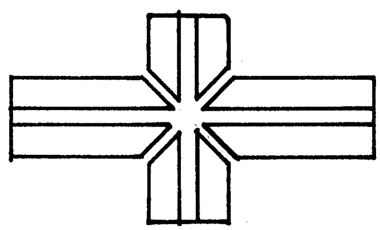
increased amount of material to resist moment

adequate openings for mechanical duct.

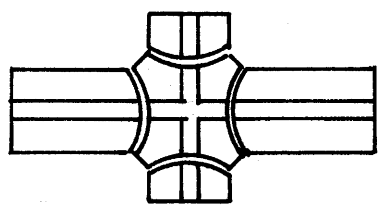
The unit below resulted after the third alternative was chosen.



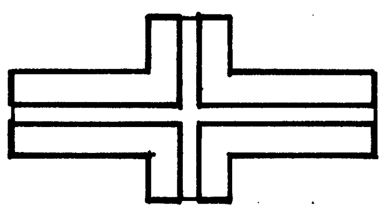
While the configuration provides sufficient material to resist secondary moment and vertical racking of the individual units, the material at ends A is wasted unless an exact full heigh connection is used. At the same time studies were made in assembly of the structure. Below are several joints with their advantages and disadvantages listed.



Poor construction-needs simultaneous 2 way post tensioning lack of centering device-if one member slips the joint will be off. Lines are not coexistent with needed partition joints.



The joint acts as centering device but lines of construction not commensurate with lines of partition.



Ideal resolution of joints but units 10' x 10' too large.

Furthermore, where a joint is necessary, it should be at the point of minimum stress to simplify the connection, and serve the needed centering for ease of assembly.

DESCRIPTION OF ADOPTED STRUCTURAL SYSTEM

Structural Bay: Size 70' x 70' with maximum cantilever of 25' - 0". Internal Openings - 60 x 60, 40 x 40, 20 x 20 or any 9 x 9 opening space between structural members. Depth of Structure - 5' - 0" constructed of 19'2" x 4'3" x 10" members placed as shown in drawings.

Process of Assembly:

1. Placement of Lower Chord Tendons - serves as grid for location and placement of members.
2. Placement of major structural units beginning with shear.
3. Floor Panels are placed on major structure element.
4. Top Chord Tendon is placed.
5. Concrete is placed in top channel.
6. Post Tensioning.
7. Bottom Tendon Channel is grouted.

Basketweave Assembly:

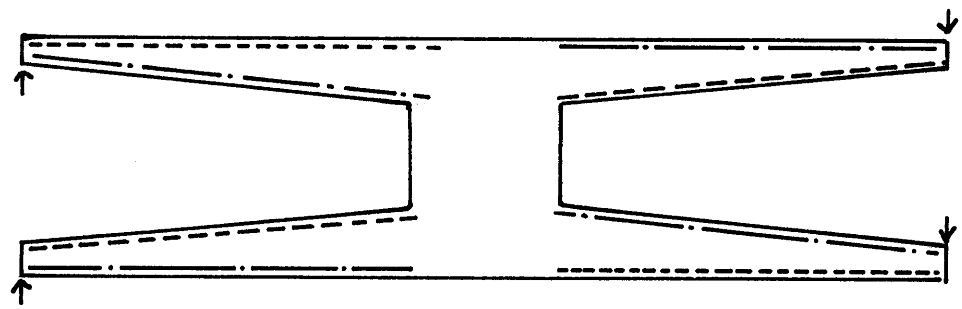
1. Reduces the number of members per unit.
2. Members meet large stable section of adjacent members - resulting in increased stability during post tensioning.

Coffered Panel: The coffered panels spanning between units serve as forms for concrete poured around post tensioning wires and provide a grid for attaching the mechanical equipment supports.

Steel Placement: Major Moments will be resisted by the concrete and post tensioning cable.

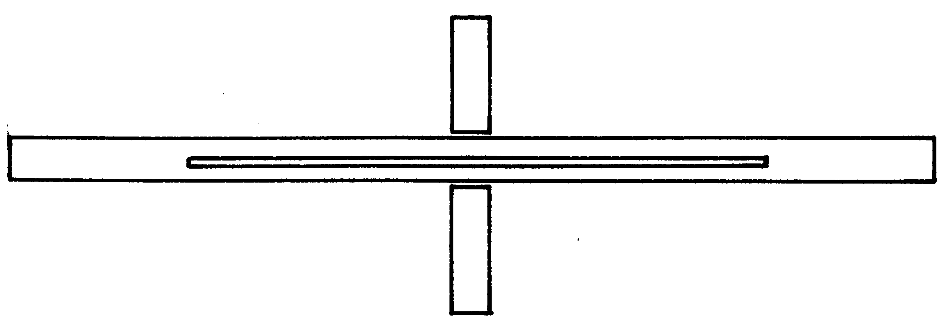
Shear is resisted by stirrups.

Secondary Moment In Arms.



Compression - - - - - - -   Tension ——— · ——— · ———

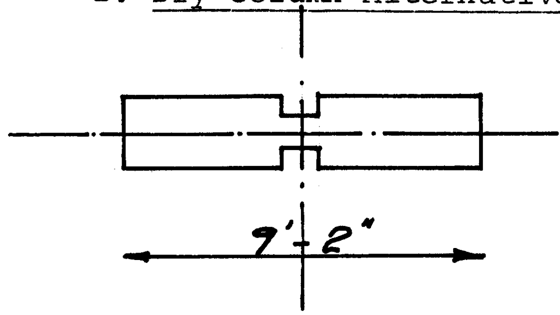
Expansion Joint: The expansion joint will be longitudinally slotted members as below. These members will extend across the entire structural bay.



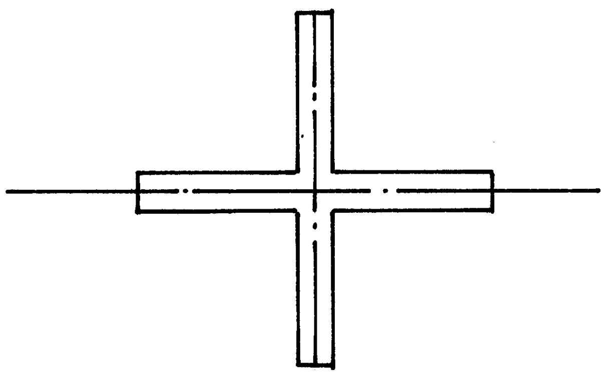
Column:

1. Wet Column - With 70 x 70 bays a column large enough to feed to critical interior 70 x 70 area was too large for the necessary planning freedom.

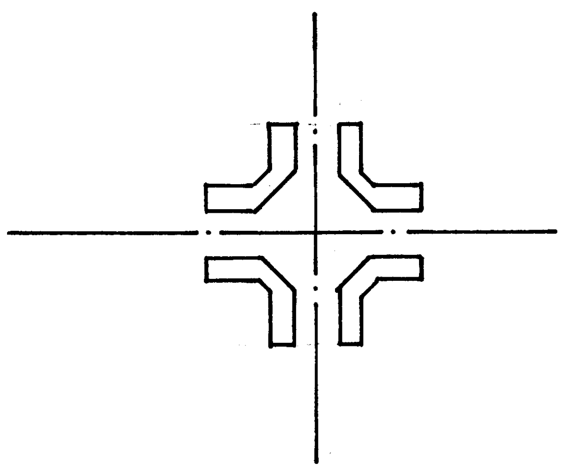
2. Dry Column Alternatives:



a. Too wide for planning



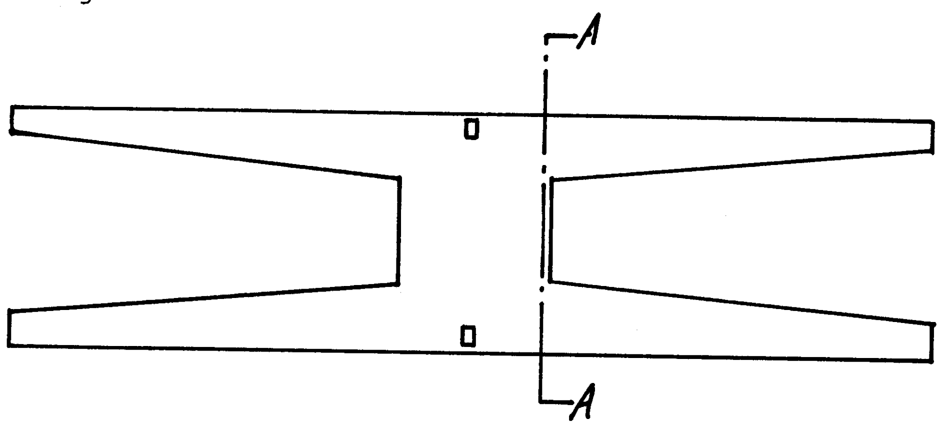
b. With variable thickness of partition the column should stop at next module rather than at the partition joint.



c. Ideal for lift slab - allows equipment to pull directly vertical without large eccentric extension.

Combined Area of 9 square feet - sufficient for upper-floors. After lift slab operation completed the middle section will be infilled with reinforced structural concrete making the total beam area 16 square feet on the lowest floor.

Individual Unit - See sheet #4 and #5 of final drawings.



1. The thick stem in the center provides enough concrete to resist secondary moments caused by the shear forces without added steel in the compressive zone.

2. The tapered arms concentrate the forces so that the small beaming plates, a 2" x 5" steel hemicylinders, will economically transfer the forces into the next member.

3. Before final stresses, a placed unit will move about its vertical centroid axis; therefore, a joint near this centroid will move less than one farther from the centroid. This means that joints #1 and #3 will be relatively stable points for joint #2 and #4 of another member to align with during assembly sequence.

4. Depth of the arms at section A-A are not equal. It is more efficient to make the arms of unequal depths because the resisting moment varies with the square of the depth of the section.

5. The floor panels are coffered, providing at equal distances supports for mechanical hangers and pipe fittings.

6. The placement of post tensioning cables in the slots uses the lower cable for member placement alignment and is a simpler operation than threading the tension through holes.

7. The bearing hemicylinders and the receiver angle forms a self aligning joint which greatly aids erection.

Sources of Illustrations

Page	Source
2.	Smith, Cyril Stanley, "Structure Sub-Structure Superstructure", *Structure in Art and in Science*, George Braziller, New York, 1965, p.30
3.	*Ibid*, p.33
4.	*Ibid*, p.37
5.	*Ibid*, p.38
7 and 8	Alexander, Christopher, "*A City is Not a Tree*", *Architectural Forum*, Vol. 122, No. 1, April, 1965

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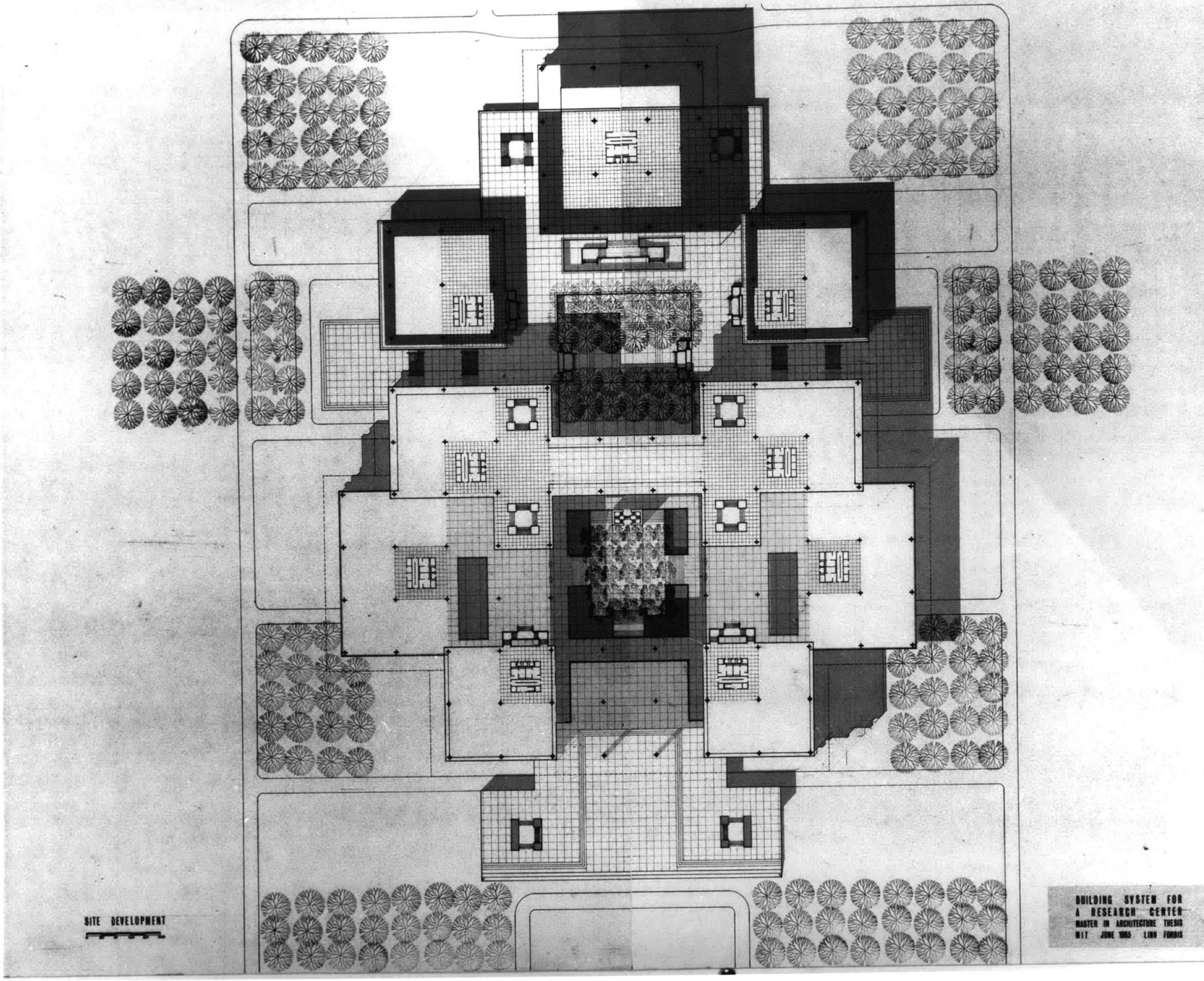
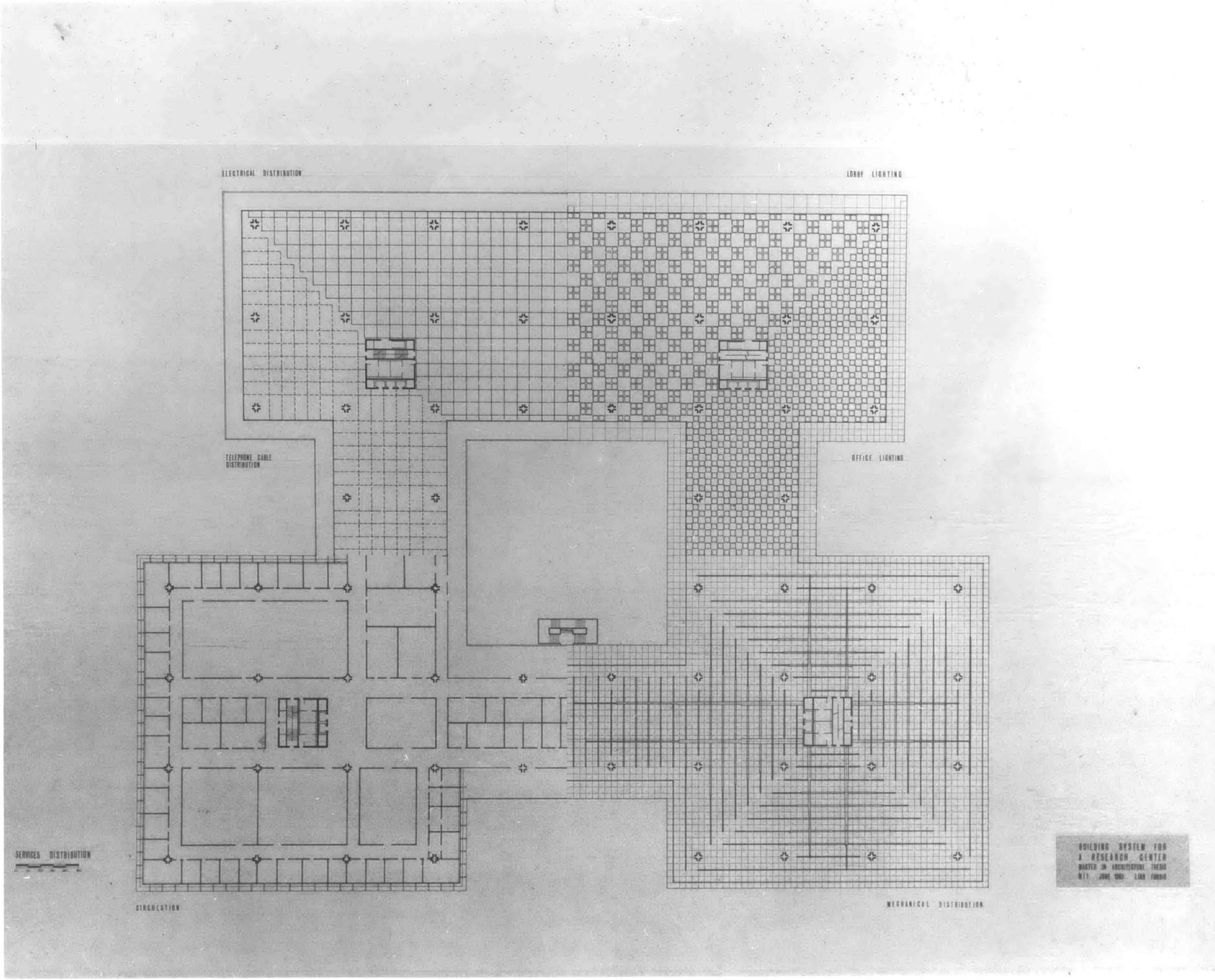
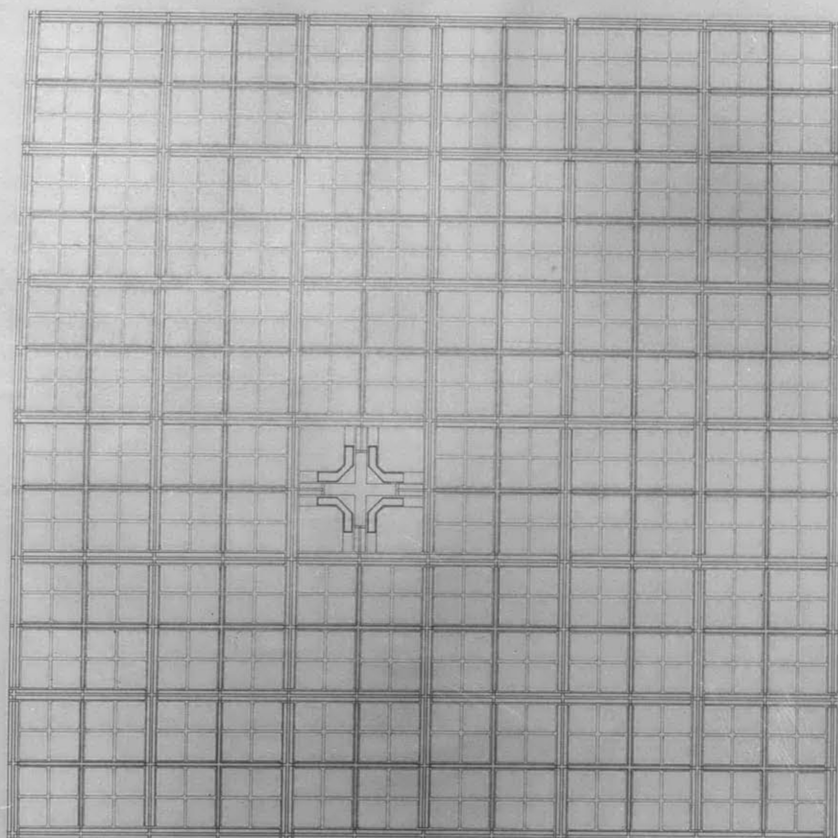
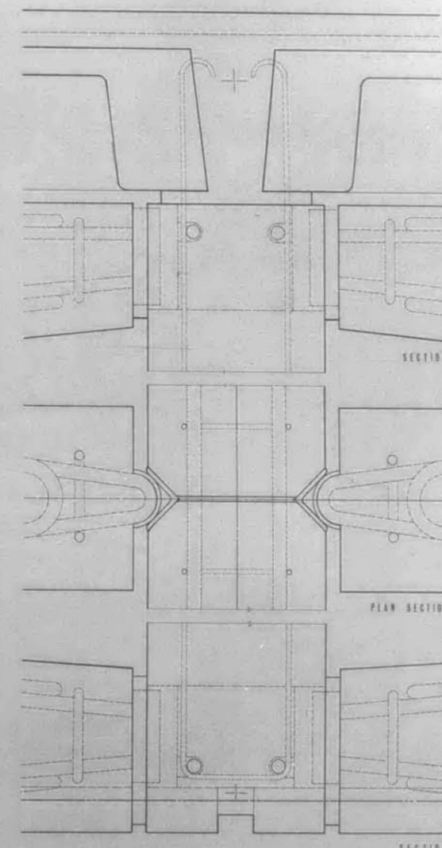


SITE DEVELOPMENT
BUILDING SYSTEM FOR
A RESEARCH CENTER
MASTER IN ARCHITECTURE THESIS
MIT JUNE 1965 LINN FORBIS


ELECTRICAL DISTRIBUTION
LOBBY LIGHTING
TELEPHONE CABLE DISTRIBUTION
OFFICE LIGHTING
SERVICES DISTRIBUTION
CIRCULATION
MECHANICAL DISTRIBUTION
BUILDING SYSTEM FOR
A RESEARCH CENTER
MASTER IN ARCHITECTURE THESIS



REFLECTED CEILING PLAN



CONNECTION

BUILDING SYSTEM FOR
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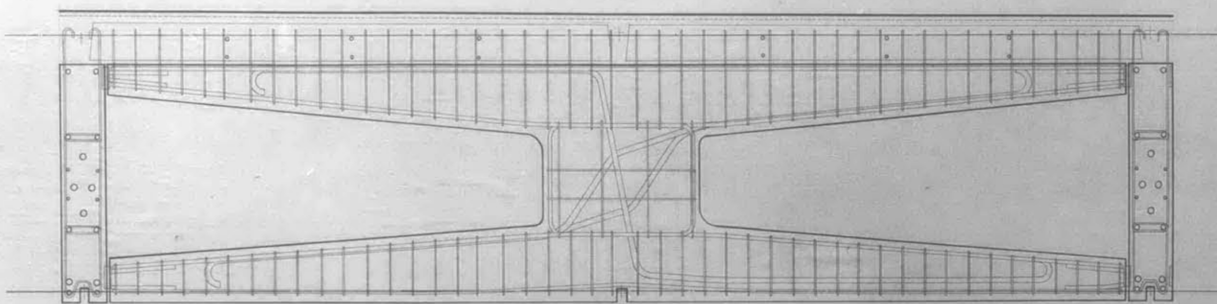
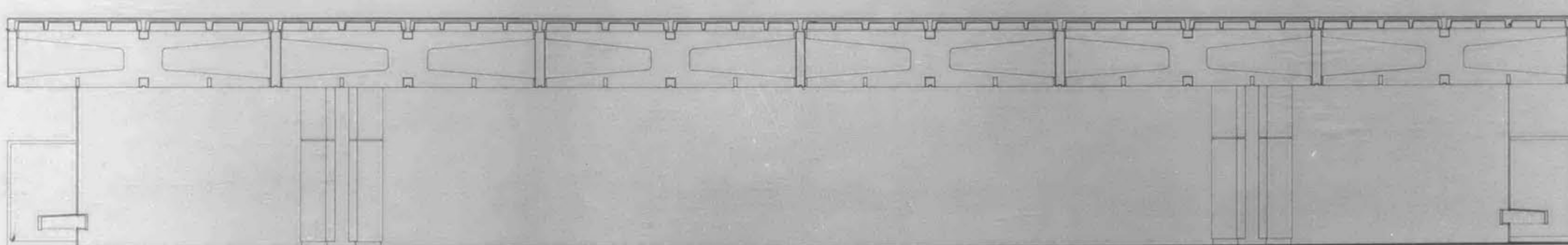


UNIT C REINFORCING

0 6" 1'-0" 2'-0"



STRUCTURAL SECTION

BUILDING SYSTEM FOR
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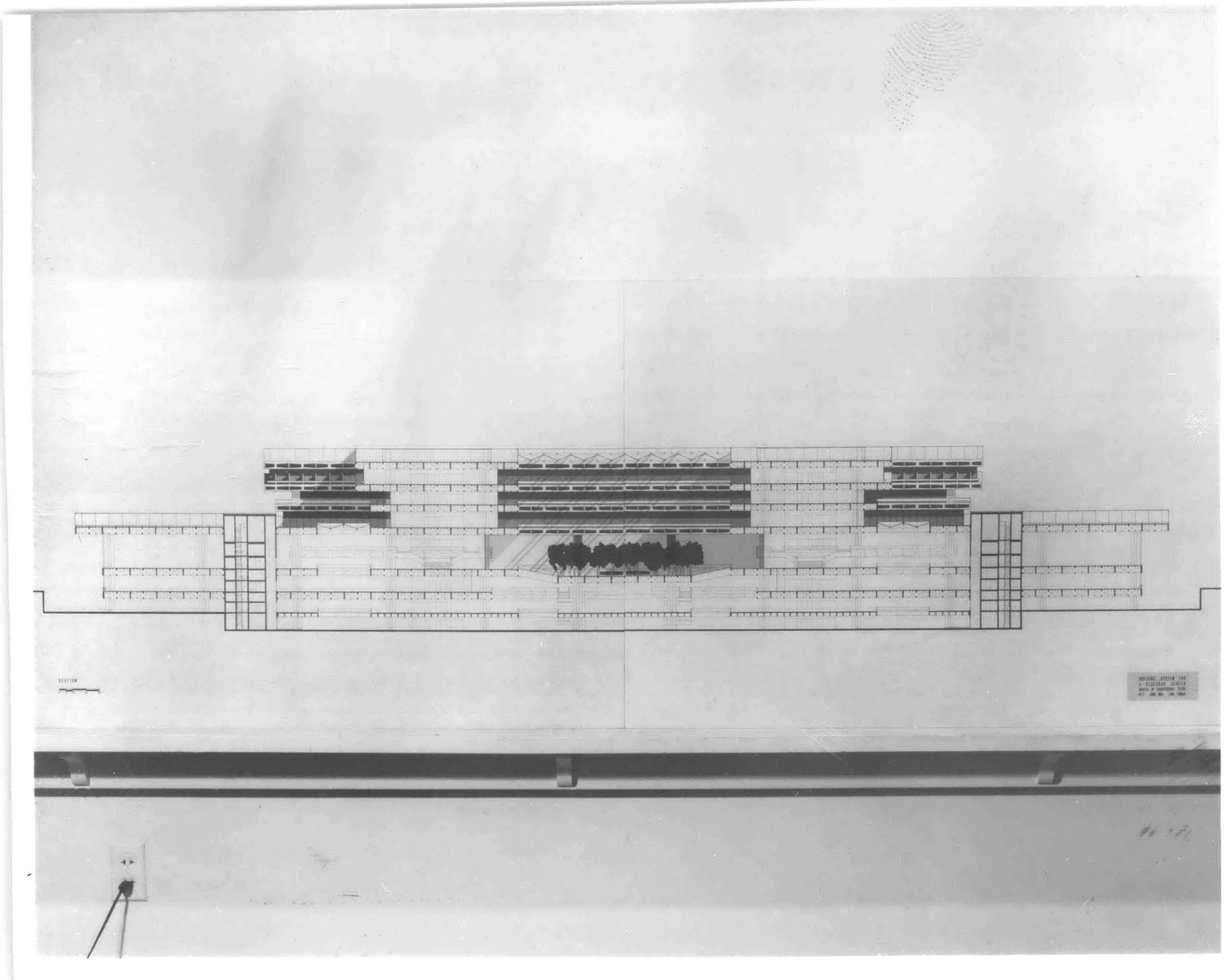
SECTION
BUILDING SYSTEM FOR
A RESEARCH CENTER
MASTER OF ARCHITECTURE THESIS