PRECAST COMPONENTS FOR UNIVERSITY BUILDING DESIGN AS SYSTEMS

by

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Signature of Author. . . . .
Department of Architecture, June 17, 1968

Certified by. . . . .
Thesis Supervisor

Accepted by. . . . .
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DISCLAIMER

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ABSTRACT:

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Reinhard J. Schneider

Submitted to the Department of Architecture on June 17, 1968 in partial fulfillment of the requirements for the degree of Master of Architecture.

Within the context of the component-systems concept of industtialized building a design development of a university building prototype is presented.

An attempt is made to dimensionally coordinate the subsystems of structure, heating and ventilating, lighting, and partitions such that planning and design flexibility can be achieved in terms of function, circulation and growth within the constraints of the program requirements.

Specific concentration is placed on the development of the structural subsystem and its program requirement of material optimization. The floor structure is essentially a triangulated space frame composed of post-tensioned precast units within which the mechanical and utility subsystems are contained. The dimensions of the bay, structural module, and planning module are 60'-0 x 60'-0, 10'-0 x 10'-0, and 5'-0 x 5'-0 respectively. The supports consist of clusters of four in-situ columns, which also contain the vertical mechanical and utility elements. The fragmented core concept is adopted in the circulation system.

Design and planning flexibility is achieved within the constraints of the 60 foot bay, the initial floor-to-floor dimension, and one self sufficient bay as the minimum element of addition.

Thesis Supervisor: Eduardo Catalano

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Dean Lawrence B. Anderson,
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Dear Dean Anderson:

In partial fulfillment of the requirements for the degree of Master of Architecture, I hereby submit this thesis entitled, "Precast Components for University Building Design as Systems".

Respectfully,

Reinhard J. Schneider

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I am grateful for the valuable advice and assistance to the following in the development of this thesis:

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CHARLES CRAWLEY	Mechanical Engineer

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1.0 Introduction

It is important to note at the outset that there is nothing new or revolutionary in the idea of system building. In the great majority of systems now offered both in the U.S. and especially in Europe, the methods and materials employed are the rationalized version of what has been the practice for many years. An example of this is the ordinary wood-frame house, which through an evolutionary process over many years incorporated the properties of a successful system building process. These properties include dimensional standardization, relation to local economy, and flexibility and adaptability to a wide variety of plans.[1]

There are no rigid lines between traditional, rationalized-traditional, and industrialized buildings; they merge imperceptably into each other. However, with the growing concentration on industrialized methods, progress in the process of rationalized building has been greatly accelerated in its application on building types other than low-rise housing, especially in the areas of educational and high-rise residential building.

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[1] William J. LeMessurier, "Building Systems", from Plastics in Architecture, ed. by Albert G.H. Dietz and Marvin E. Goody. Proceedings of a Summer Session at the Massachusetts Institute of Technology, 1967, p. 266.

1.1 Definition

Christopher Alexander defines a system as a kit of part and a book of rules.[2] Similarily, according to William LeMessurier a building system is not just structure, it is a kit of parts which will solve the problem of making the whole building. Thus it must include a mechanical system, electrical system, and an understanding of the relationships between these subsystems and the structural system. Additionally it must include an adaptability to change of function and growth.[3] To Moshe Safdie systems are a means to an end. "They are a means to achieve more for less...systems are a design tool...They are a way of approaching the environment as a total complex organism; of discovering an order which once established would preserve those aspects of the environment which we consider essential...Total structure is the structure of light and air and growth and reproduction and stability and all aspects essential to the survival of an organism."[4]

These definitions, among others, substantiate the problem of semantics when an attempt is made to differentiate between prefabrication, pre-engineered, pre-constructed, industrialized building, building systems, and system building. These terms and definitions are almost synonimous and imply that an

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[2] Ibid.

[3] Ibid.

[4] Safdie, "Anatomy of a System", RIBA Journal, Nov. 1967, pp. 489.

industrialized procedure has been applied to the building process and more generally, that the application of modern management techniques to coordinate design, manufacturing, site operations, and overall financial and managerial operations into a disciplined method of building.

1.2 Building Systems in Europe

In Europe building systems are initiated by four types of organizations; contractors, engineers, clients (mainly governmental), and manufacturers. Applications of system building are in the areas of residential, industrial, educational, and commercial building types.

The European systems can be classified into two categories, "open" and "closed". In "open" systems components are interchangeable with dimensionally coordinated components in other systems. They may be applied to a variety of building plans and are not particular to one organization. Conversely, in "closed" systems the components are applicable only to one system. They are usually associated with specific plan forms and are particular to one contracting organization. Currently there appears to be a trend, in most European countries, away from the rigidity of "closed" systems toward the more "open" systems, which provide the architect with greater flexibility. The architect must be versed and knowledgeable, both in defining the situation for which he is designing and also in the technical performance or limitations of the components which are available to him, so that he will come to rely less on the specialist assembler to undertake the design functions on his behalf.

The building systems as used in Europe encompass the entire construction process. It begins with the basic design and concludes with the finished structure. All the inherent operations such as site preparation, manufacturing of components, materials handling, and assembly are included in the system. The responsibility for the building system as well as the entire construction process is usually concentrated in one organization. The contractor is usually the coordinator of the design, manufacturing, transportation, and erection functions. Thus, better control is achieved over the total project.

Due to the large number of systems available the competition is very high and only a few are successful. The key to success seems to be the systems sponsor's ability to manage, organize and market its system.

1.3 Building Systems in the United States

The emphasis in the United States has been on the development of somponent systems; specifically the development of interior subsystems to integrate heating, cooling, lighting, structural ceiling, and partition components. As such they differ from the European approach where a building system usually encompasses the entire construction process from the design stage through the assembly and erection of the finished structure. This difference in approach between American and European systems resulted from differences in the social, economic, political, professional, industrial, and administrative context.

One of the most influential developments in component-system design in the United States has been the School Construction Systems Development program (SCSD) in California. The Goals of SCSD were:

1. To develop new products designed specifically for schools.
2. To encourage manufacturers to work together so that their products would create a system.
3. To guarantee a sufficiently large market for the products such that manufacturers would be willing to initiate research and development efforts.
4. To find a satisfactory way to bring producers and purchaser together.

These goals were accomplished by the coordinating architect in that he translated prospective user's needs into performance specifications. These were submitted to a number of manufacturers who were responsible through team effort to develop modularly coordinated sub-systems within the limits of the specifications. The design of each individual school was eventually performed by the local architect.

1.4 Requirements for an Effective Industrialized Building Process

In order for mass-production in building to be economic and thus able to match the resources available to the consumer, certain principles have to be followed by the building industry.*

Continuity of operation is required if the building industry is to amortize any great increase in capital investment. This has been the cause of failure of many attempts in the U.S. In fact, the lack of continuing demand for the SCSD System has been of great concern to its manufacturers. Only the mobilehome industry has so far been able to achieve a consistent nation-wide market.

Variations in the composition of demand must be decreased in order to make standardization possible in a particular building type.

A distinction has to be made between the products suitable for mass-production under industrialized conditions, and those that are not, from a market point of view. This was realized during the development of the SCSD system, in that the performance specifications submitted to the manufacturers excluded exterior wall treatment, floor coverings, interior finishes, foundation work, plumbing, and base electrical as part of the system components.

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*These are based on a paper which Dr. Gunnar Myrdal presented at Third Congress of the International Council for Building Research, (CIB) in 1965 at Copenhagen, Denmark.

Another requirement is to allow the existing division of work to provide the best possibilities of standardization and mass-production, not of identical buildings, but of identical components which can be combined into a great variety of buildings and thus satisfy a range of functional and aesthetic requirements. However, specialization demands coordination. To obtain real economic gain a specialized production process divided into a large number of independent sub-processes demands greater special effort for coordination than a process integrated within the framework of one single organization. As such, the best partial solution must give way to the best total solution that can be economically realized.

Finally, it is Dr. Myrdal's view that some of the major obstacles toward the application of what is today considered industrialized building are not of a technical nature, but rather economic, organizational, and political in character.

2.0 The Program

It is evident that universities today are undergoing constant changes in their physical and functional organization to provide for an ever increasing number of students and changes in curriculum. Within this context the objective of this problem is the development of a system of construction and planning that anticipates change, and therefore can readily adapt to the needs of a modern university.

The physical development of the problem should consider the limitations of the present state of industrialized building in the United States, as well as possible advances in the near future. Therefore, in the light of recent developments an attempt will be made to apply the "component-systems" building design process in this problem.

The specific objectives are:

1. To evolve dimensions that allow flexible variation in function within structural limitations, such that both design and planning flexibility achieved.

2. To achieve coordination of dimension among the systems components and to identify temporary and permanent sub-system components. The sub-system components included are: structure, heating and ventilating, lighting and interior space divisions.

3. Optimization of structure - The governing criteria in determining structural efficiency's material quantity.

4. Transportation of components on highways should be possible without special permits. This means that the size of components have to fall within the dimensional limits set by state governments.

5. The primary material of construction should be reinforced concrete.

Within this framework the development and solution of the problem are presented.

3.0 Problem Development

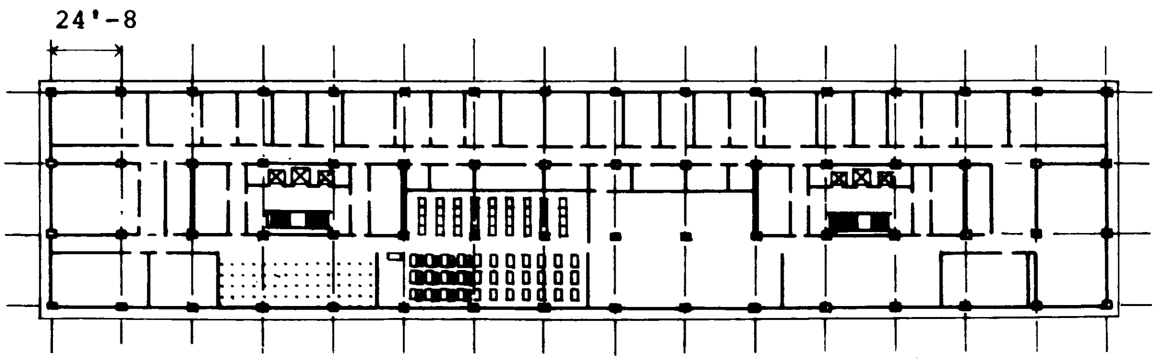
In the actual design process decisions were not made on the basis of any of the available evaluation methods, but on a more or less random interaction of problem requirements and final objectives. To present a clear development of the problem, each design criteria and its ultimate solution are presented separately in the order listed below.

3.1 Dimensions
3.2 Structure
3.3 Fabrication, transportation, and construction
3.4 Vertical Circulation
3.5 Environmental Controls
3.6 Growth

3.1 Dimensions

To establish proper planning dimensions several existing and planned universities were studies. These universities had similar objectives namely, spatial flexibility and growth, dimensional coordination, and the method of construction was based on the "component system" concept (Appendix - A). Additionally, these studies were supplemented with basic space requirements and areas of American universities (Appendix - B).

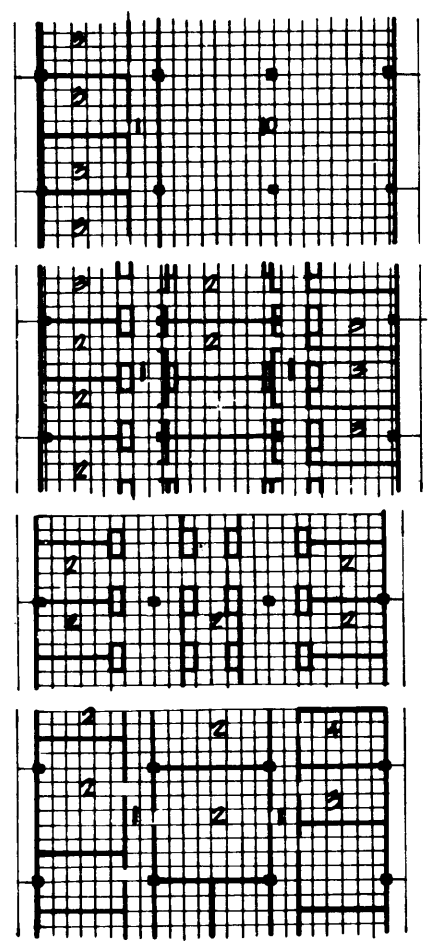
It can be seen in a typical floor plan of the University of Bochum (Fig. 1) that the short bays (23' x 23') create difficulty in providing proper dimensions for some functions. For instance, due to this column spacing the dimensions of a typical classroom are 23 feet and 54 feet



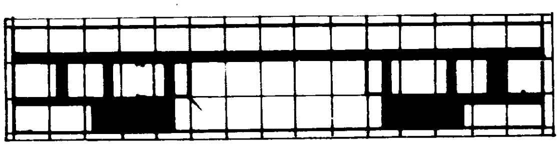
TYPICAL BUILDING PLAN

BUILDING USE VARIATIONS

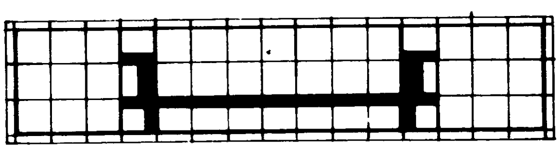
1. corridor
2. Laboratories
3. Offices
4. Conference Rooms
5. Classroom



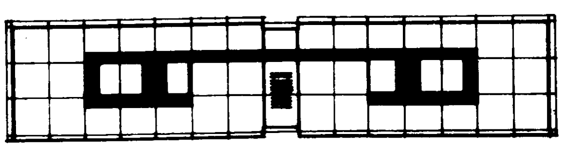
Social Sciences



Biological Sciences



Natural sciences



Physical Sciences & Engineering

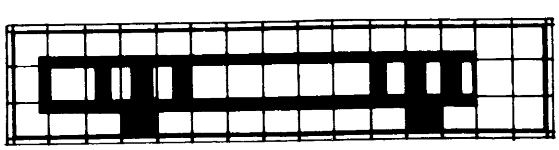
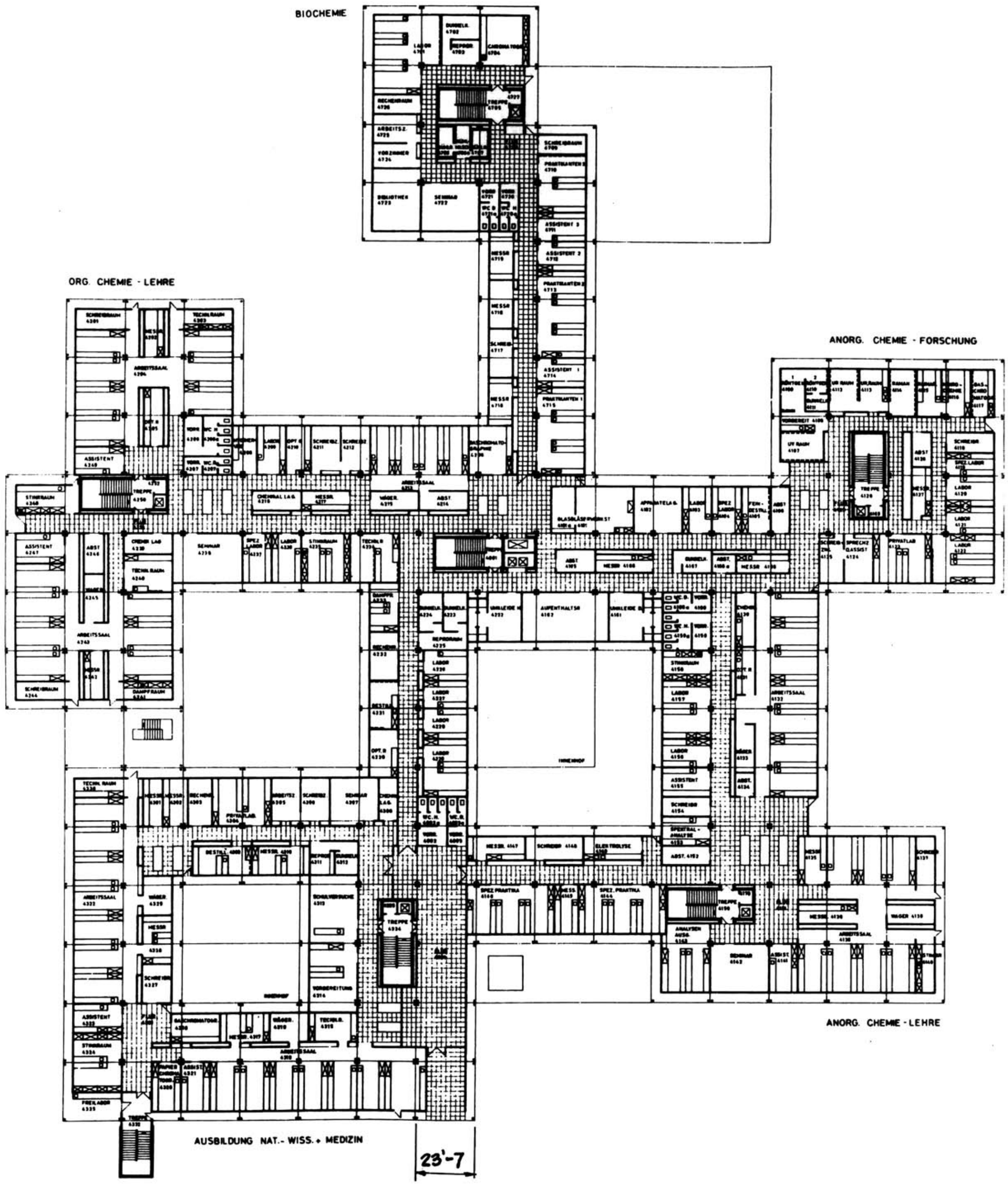


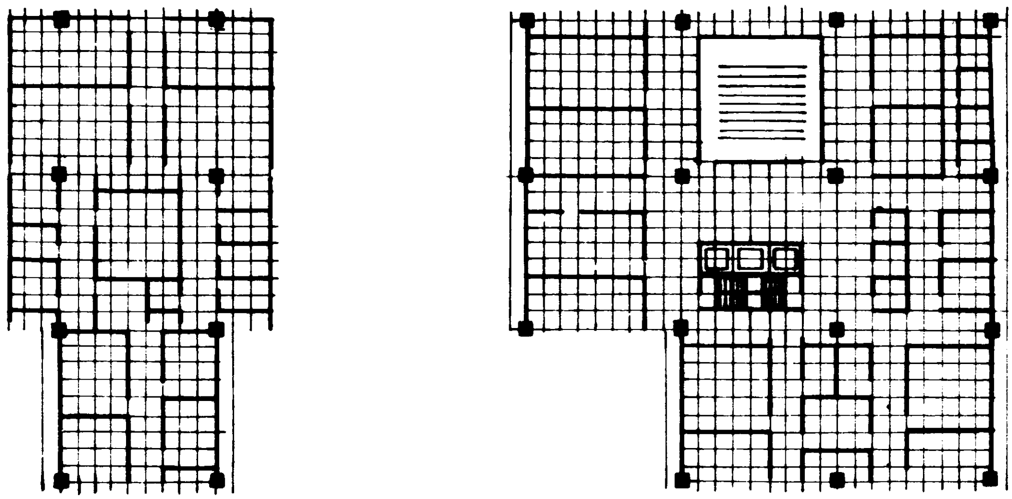
Fig. 1 - University of Bochum

SOURCE: Karl Steiner, Probleme der Hochschulerweiterung, Zurich, 1966.

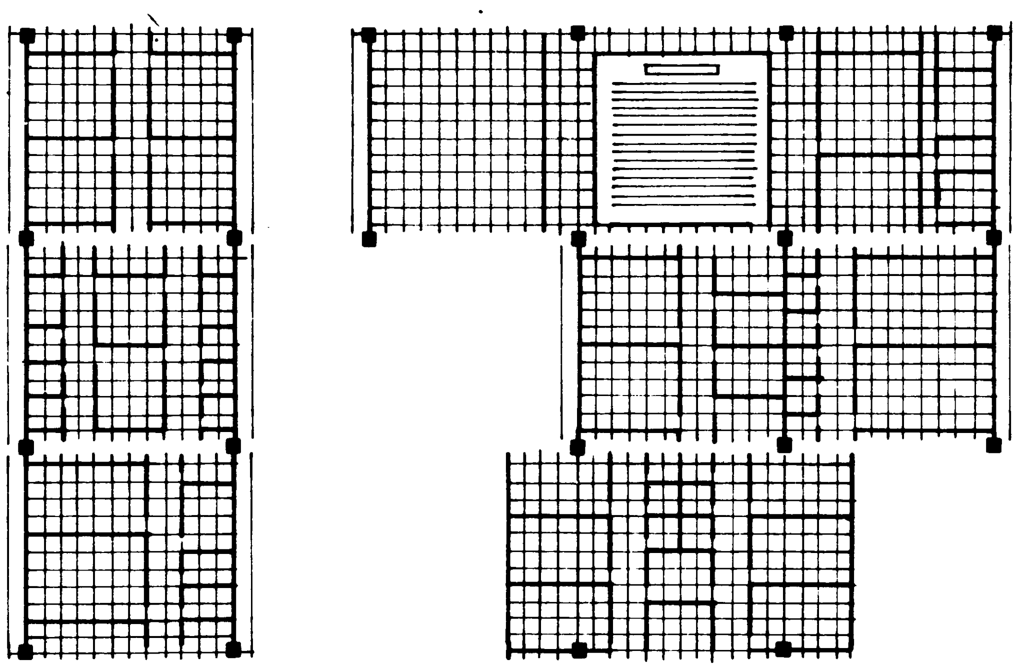


UNIVERSITY OF MARBURG - Typical Plan of Chemistry Building

SOURCE: Karl Steiner, Probleme der Hochschulerweiterung, Zurich, 1966.



45 ft. Bay



60 ft. Bay

Fig.2 - Bay Studies

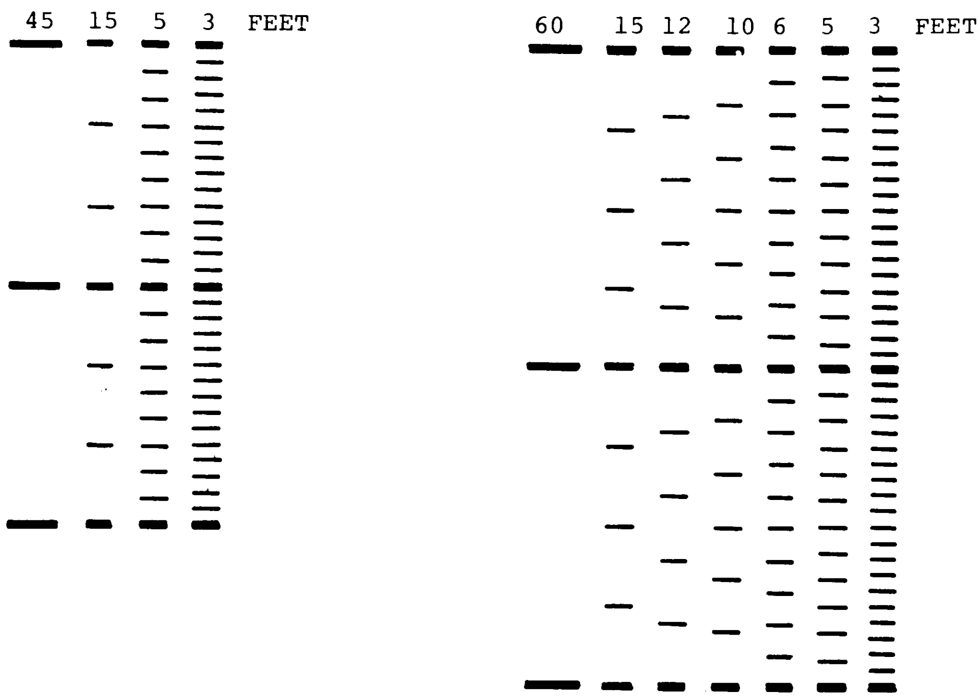


Fig.3 - MODULAR DIVISIONS OF 45 & 60 FT. BAYS

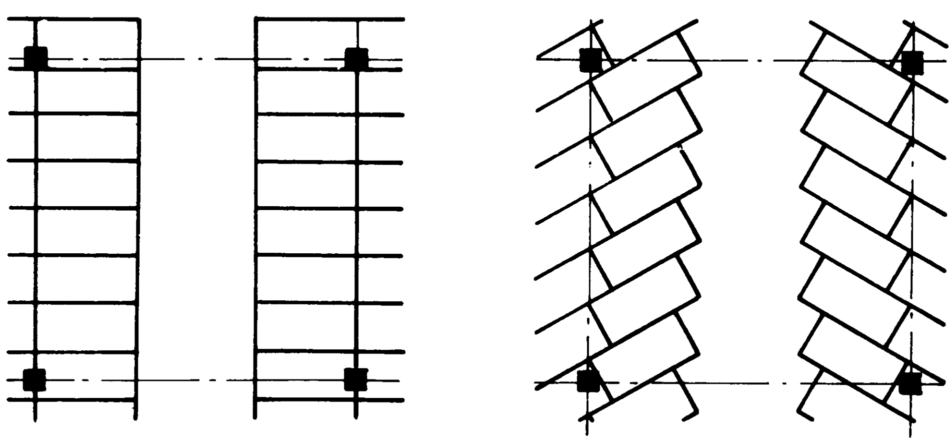


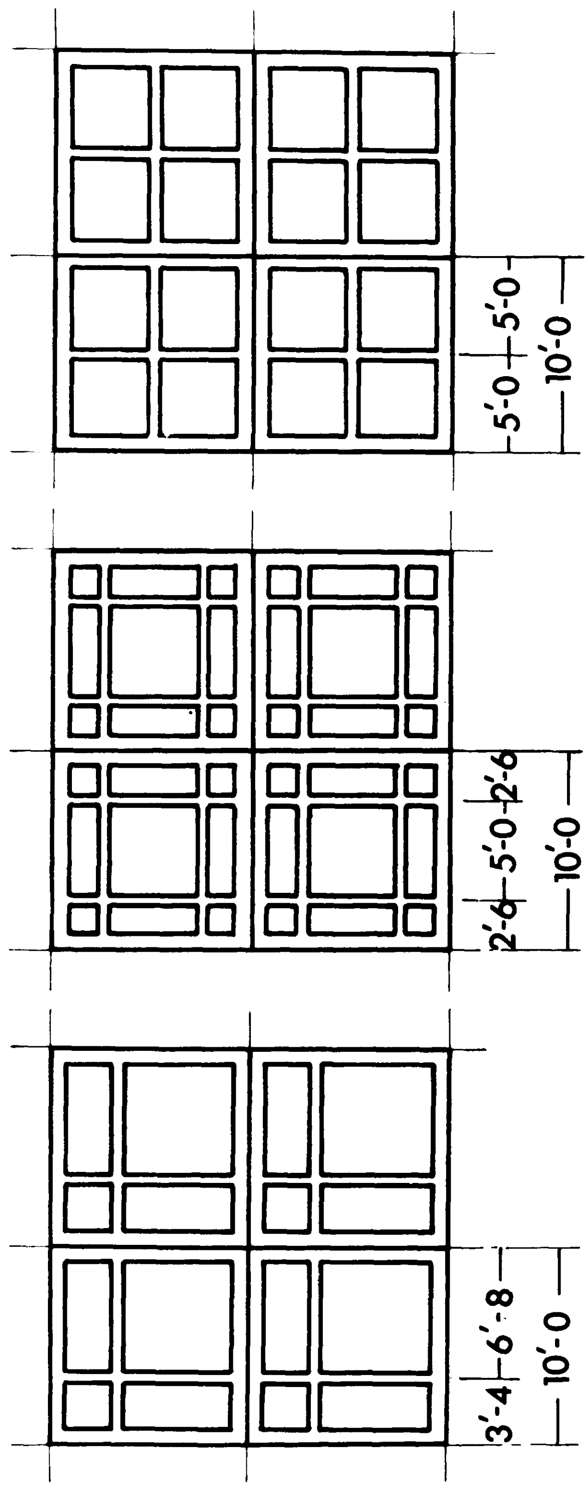
Fig.4 - PARKING ARRANGEMENTS IN 60 FT. BAYS

as opposed to the more ideal classroom for this area of 35 feet by 35 feet. Furthermore, it restricts the number of possible relationships between functions, such as classroom to the laboratory, to office, to seminar rooms. The problem of incorporating larger spaces such as lecture halls at these universities was solved by physically separating these functions into lower connecting buildings that employed a longer spanning structural system.

It seemed clear, therefore, that from the point of planning flexibility and inclusion of all the facilities in the same system that a larger bay was necessary. At the outset, rectangular bays were not considered due to the program requirement of structural optimization.

Studies in the application of larger bays were conducted. The greatest potential in terms of the above requirements was found to be in bays of 45 and 60 feet (Fig. 2). It is obvious that the greater the column-free space the greater the planning flexibility, given all other factors constant. The structural span is directly proportional to design and planning flexibility. However, the economics of building reduce the span to a practical optimum.

The dimensional advantages of the 60 foot bay were found to be planning flexibility, modular divisions (Fig. 3). An additional requirement was satisfied in that parking can be effectively incorporated in a 60 foot span (Fig. 4).



PLANNING MODULE VARIATIONS WITHIN A 10'-0 STRUCTURAL MODULE

3.2 Structure

The program requirements related to the basic structure were to optimize structural behavior; to maintain bottom plane of floor structure at the same elevation throughout; to provide space within the floor structure for mechanical and utility services.

To achieve these objectives, the basic variations of floor structures behavior were investigated.

These variations can be separated into two categories:

1. One-dimensional resisting structure (Oneway)
2. Two-dimensional resisting structure (Twoway)

In one-way structures, load transfer occurs always only in one direction (Fig. 5). This system is inefficient from a material standpoint in that a concentrated load is carried entirely by the member under load while all other beams remain relatively unstressed.* Furthermore, if an even structural ceiling plane is desired, the girder length should be less than the beam length (Fig. 6). As load per lineal foot on the girder is much greater than the load on the beams, the length of the girder has to be less to achieve similar maximum moments in both members and consequently similar depths. This results in a rectangular bay and implied directions in planning as opposed to the directional anonymity of the square bay. The

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*The slab on top of the beams does in effect distribute some load to adjoining members.

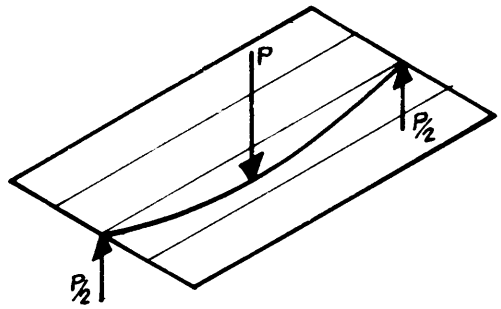

Fig.5 - ONE-WAY LOAD TRANSFER

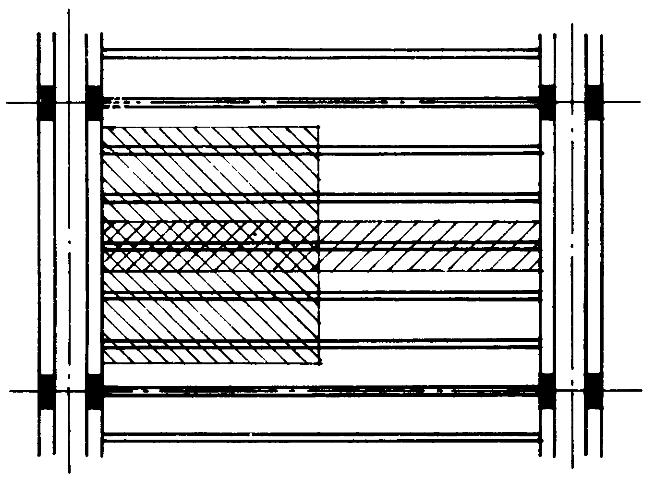

Fig.6 - TRIBUTARY AREAS FOR BEAM & GIRDER

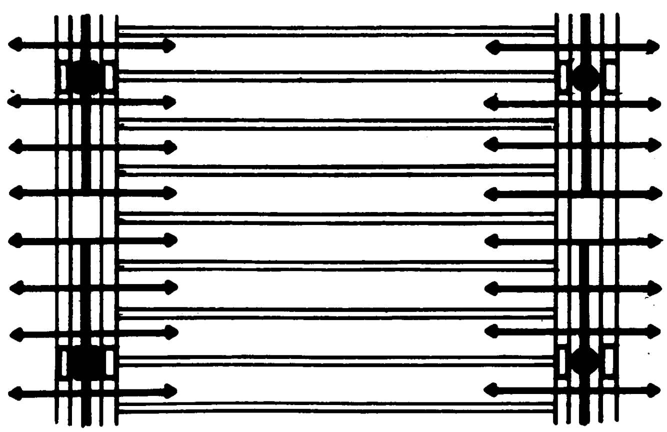

Fig.7 - MECHANICAL DISTRIBUTION

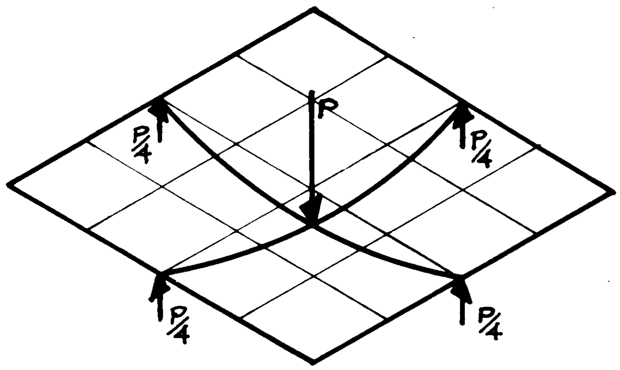

Fig.8 - TWO-WAY LOAD TRANSFER

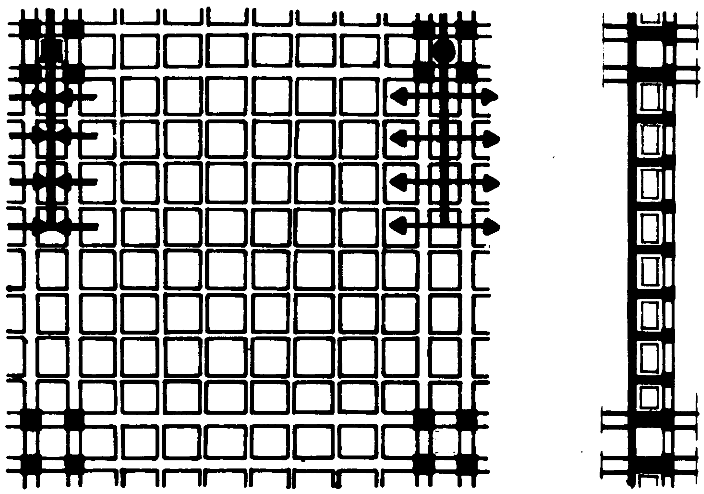

Fig.9 - TWO-WAY BEAM STRUCTURE & MECHANICAL DISTRIBUTION

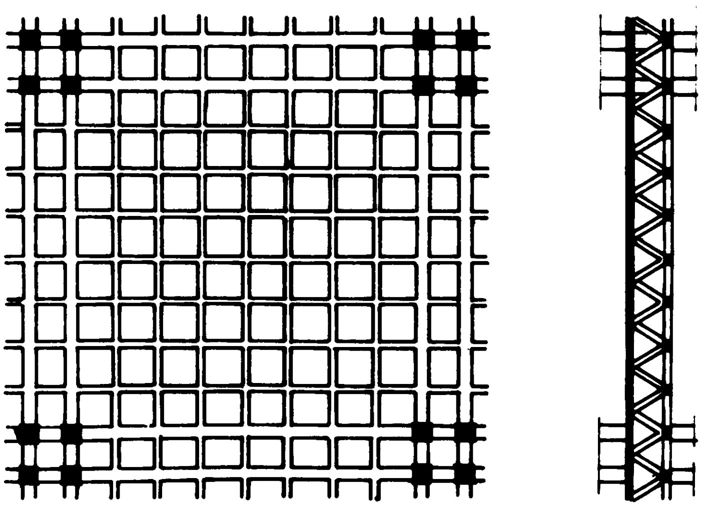

Fig. 10 - TWO-WAY TRUSS STRUCTURE

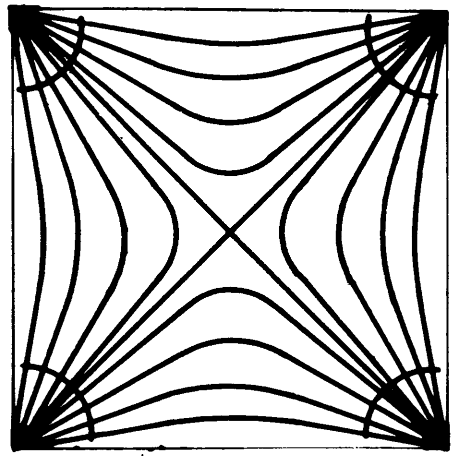

Fig.11 - APPROXIMATE DIRECTIONS OF LOAD TRANSFER IN POINT-SUPPORTED FLAT SLAB

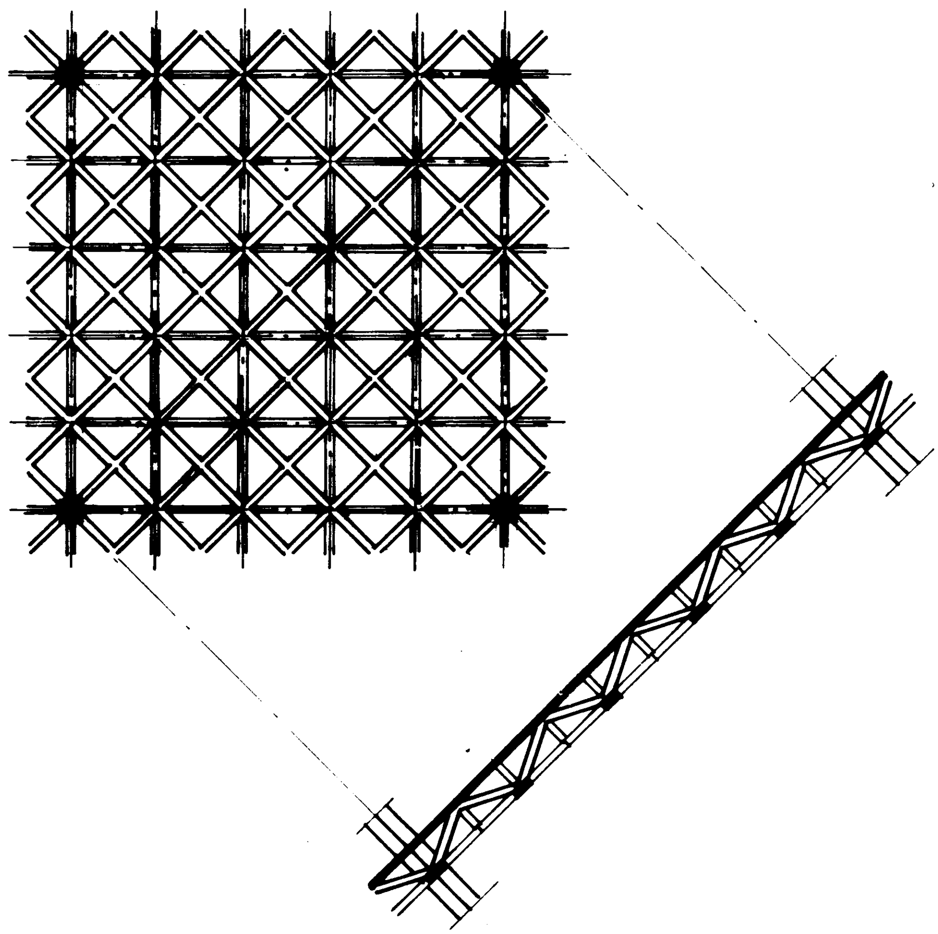

Fig.12 - TRIANGULATED SPACE FRAME

major mechanical branches which run in the direction parallel to the main girders have to penetrate the girders in the critical area near the support to service the bay (Fig. 7).

The main advantage, at the expense of material, of one-way systems is construction. Few joints and handling operations are created due to the large and uncomplicated precast members that are possible, above all, construction can proceed without scaffolding.

In two-way structures each load is channeled in two directions to the support, consequently each member carries only half the load that it would carry in the one-way system (Fig. 8). As the density of the grid of orthoganally intersecting beams is increased, more efficient two-way action results since each beam will carry less load (Fig. 9). Additional efficiency is achieved by substituting trusses for the beams (Fig. 10).

In a point-supported flat slab (a slab is essentially an infinite number of two-way beams) the loads are channeled to the supports through a system of diagonals (Fig. 11). In grids orthogonal to the column lines it is impossible to provide these diagonals. However, if this grid is rotated 45 degrees, direct transmission of the loads to the supports is possible. Furthermore, if the bottom chord is left in the original position and only the web trusses rotated, a triangulated space frame results (Fig. 12). Space frames of this type achieve the most efficient action with minimum material, which satisfies the program requirement of structural optimization.

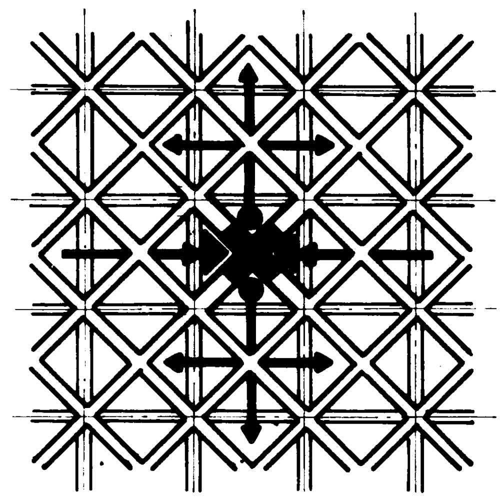

Fig.13 - SINGLE COLUMN SUPPORT AND COLUMN CAPITAL
POSSIBLE MECHANICAL DISTRIBUTION

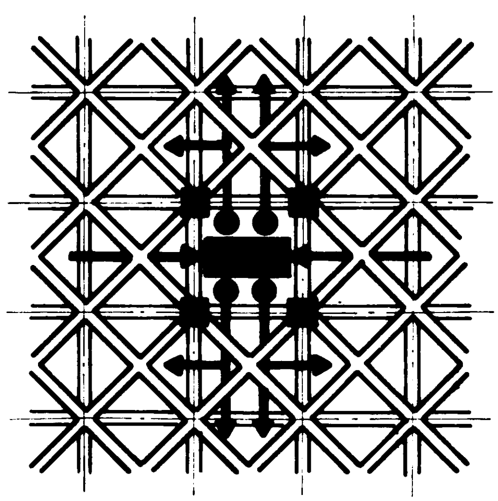

Fig.14 - COLUMN CLUSTER SUPPORT AND MECHANICAL
DISTRIBUTION

The most stressed members in this system are the diagonals directly connected to the supports. Care should be taken not to puncture these areas with circulation openings if structural continuity is desired. Drawing 4 indicates the ideal locations for openings.

For the structural system in Figure 12, various types of supports are possible. In Figure 13 the loads from the principal diagonals are transferred through a column capital to the column. In Fig. 14 supports are provided at each intersection of principal diagonals. The latter not only eliminates an additional member, the column capital, but also more space is provided for mechanical and utility services. In Figure 13 the same space is allocated for supply and return ducts, whereas in Figure 14 the allocated space can be proportioned to provide more area for low velocity return than high velocity supply.

3.3 Fabrication, Transportation and Construction

The following factors have a direct influence on the final cost of a precast structure: the shape of elements, their dimension, allowable tolerances, finishes, number of different elements, weight, and the number of joints.

At an early stage of the design process, decisions have to be made on the dimensions of elements, the number of elements and their weight. This will effect the type, size, and number of cranes needed during construction; the size and composition of the erection gang, since cost is related to the number of elements erected per day by a certain number of workers. It is essential that the labor content of this operations be known to some extent during the design stage.

The number of elements affect the factory or site casting cycle and the number of molds required. The number and dimension of these elements will determine the number and type of vehicles required for transportation--if off-site casting is used. The complexity of molds and type of finish will influence whether or not site casting should be attempted.

Other considerations are that if the components are not a standard product, the fabricator needs enough volume to justify investment in new forms and production lines. Also if off-site casting is used limitations on the size of elements that can be transported over roads have to be observed. Present regulations allow, without special permits, 10, 14, and 60 feet for width, height, and length of an element. These dimensions are extended to 12, 14, and 120 feet if special permits are procured.

If, as in this project, the prefabricated structural elements are precast floor components and off-site casting methods employed, it is necessary that within a certain radius of the site, a precasting firm is available that is capable of producing and erecting the components. According to the Battelle Report[5], the economic area of operation for a central factory depends on several factors; the weight of the component, road and traffic conditions, distance to site, degree to which components are prefabricated. The limit of economic radius of transportation for heavy precast systems is about thirty to forty miles. This distance might be increased in large metropolitan areas and if lighter elements are transported. The less site work involved the greater the distance of economic transportation.

3.4 Circulation

The National Building Code stipulates various frequencies and widths of exit stairs depending upon type and density of occupancy.

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[5]Battelle Memorial Institute, The State of the Art of Prefabrication in the Construction Industry, Research Report to the Building and Construction Trades Department -AFL-CIO.

EXIT STAIR REQUIREMENTS cont.

FOR 2700 sq. feet EFFECTIVE BAY (25% FOR CIRCULATION/BAY)

SQUARE FEET/PERSON	100	80	60	40	20
FEET OF STAIR/BAY	.54	.68	.9	1.35	2.7
NUMBER OF BAYS/4' WIDTH	9.4	5.9	4.5	3.4	1.5

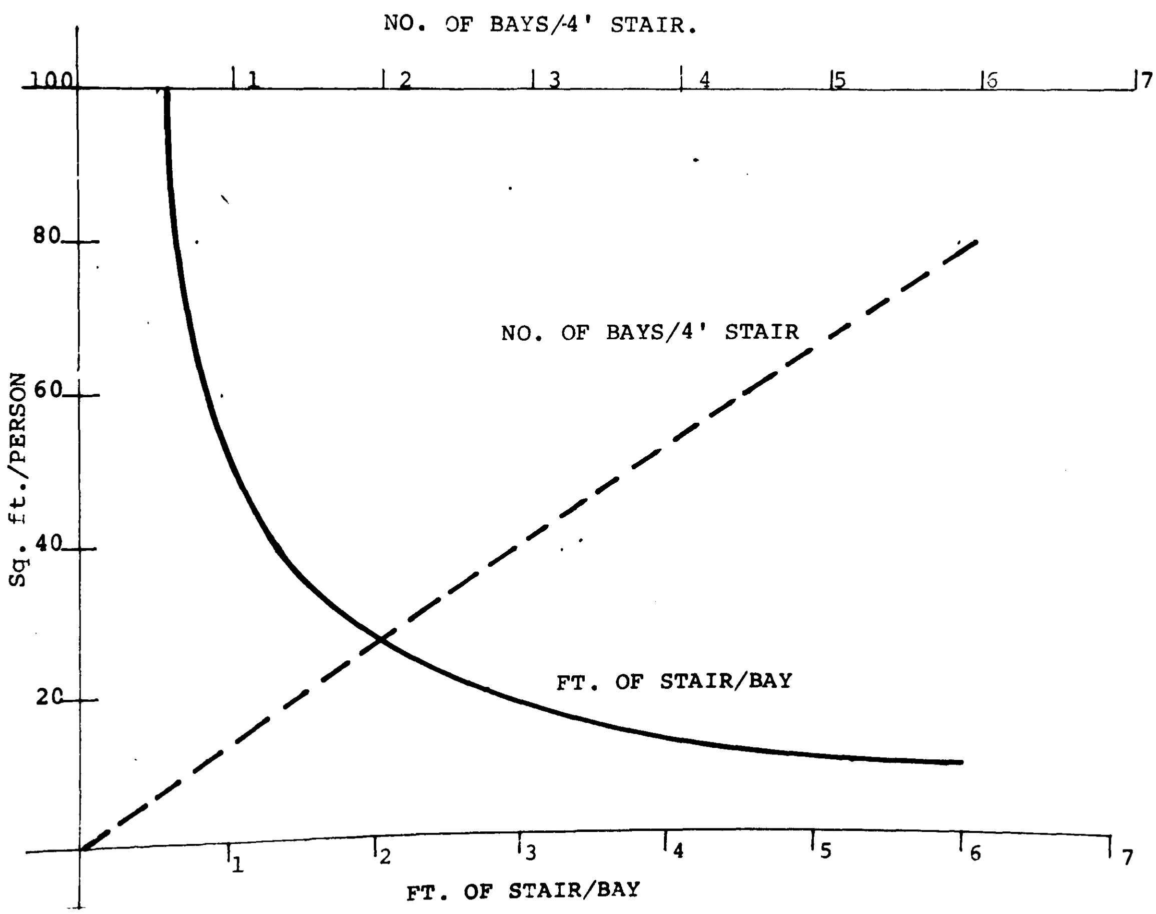

Figure 15

These exit stairs should be located such that the maximum distance from any point in a floor area to an exit doorway, measured along the line of travel, does not exceed,

75 feet	High hazard occupancies
100 feet	Assembly, educational, and institutional
150 feet	Business occupancies

To determine the width of exit stairs for various occupancies the following areas per occupant are established by the Code:

Assembly	40 sq. ft/person
Educational	40 sq. ft/person
Business	100 sq. ft/person

The unit of stairway width used as a measure of exit capacity is 22 inches. The number of occupants per unit exit width for various occupancies are:

Assembly	60 occupants/22in. exit width
Educational	60 " "
High hazard	30 " "

The minimum allowable stair if the total occupancy per floor exceeds 45 persons is 44 inches. The graph in Fig. 15 establishes for a 60 X 60 foot bay the width of stair per bay and the number of bays that can be served by a 44 inch exit stair for different occupancies.

3.5 Enviornmental Controls

For the heating and ventilating of interior zones three all-air systems were investigated.

3.5.1	Single Air Systems
3.5.2	Dual Air Systems
3.5.3	Primary Air Systems

3.5.1 Single Air Systems

A single air supply to the conditioned space performs the heating, cooling, humidifying and dehumidifying functions. The methods of obtaining zone or individual room control are:

a. Zone Reheat: Air is supplied at dew-point and dry-bulb temperatures low enough to balance the expected cooling load in any space, and reheat (usually electric coils) is supplied in the branch duct to each zone as required to match the actual sensible heat load. This provides good control under highly variable conditions.

b. Volume Dampers: Volume dampers can provide control in each room. The air is supplied according to the load. If dampers are used excessively, a reduction in ventilation and dehumidification will result. Also, the range of individual room control is limited by the throttling effects of the volume dampers, and it cannot handle a cooling load in one zone simultaneously with a heating load in another, since this would demand a reversing of the damper action.

c. Volume Dampers and Reheat: Combining volume dampers and reheat reduces the expense of supplying more cooling than actually required, by the damper action. Furthermore, due to the reheat coil the reduction of volume by the damper is reduced such that it does not impair the ventilation and dehumidification capacity.

3.5.2 Dual Air System

These systems provide the choice of heating and cooling as required by different zones, through dual air streams at different conditions (hot and cold) and mixed by proportioning-dampers either in the room or upstream in a plenum. The entire air quantity for absorbing the load is conditioned centrally and distributed by the main fan or fans. To maintain conditions at all times, the cooling conditioner and duct must be sized for the maximum cooling load that exists when no heating is required from the other duct and vice-versa. This means that if there is a wide variation in the cooling and heating requirements among the spaces served, each conditioner and duct will have to be sized to carry possibly 75% or more of the maximum load. This increases the initial cost of the system.

3.5.3 Primary Air Systems

In this system the sensible and latent heat removing functions are separated physically by separate heat exchangers. Temperature is controlled by throttling the source of sensible cooling or heating, which is usually water, while the humidity is maintained within acceptable limits by fixing the dew point of the primary air supply. A coil in each room performs the sensible heating and cooling. Only preconditioned ventilation air at controlled dew point is supplied from the central apparatus through high velocity conduits. This provides great saving in space. The disadvantages of this system are high operating costs and limited flexibility.

From this basic survey it was concluded that the Single Duct Zone Reheat and Volume Control system would provide the best overall efficiency in terms of temperature, air quality, noise, air movement, and radiant effects.

Heating and ventilating ducts can reach the floors from one or more centrally located mechanical rooms by three means.

a. a combination vertical circulation and mechanical core.
b. a separate vertical mechanical core.
c. a combination structural column and mechanical core.

a. If the vertical mechanical runs are combined with vertical circulation cores, one will restrict the other. The maximum duct length is a function of allowable duct friction and available space in floor structure. Therefore, the vertical circulation nodes have to occur at the frequency and pattern demanded by the mechanical services not the pattern determined by function and occupancy.

b. If a separate mechanical core is used the additional vertical element will restrict planning flexibility.

c. From the standpoint of design and planning flexibility and growth, the design requirement is to reduce the number of permanent vertical elements. This is possible if the vertical mechanical and utility runs are incorporated into the structural column. Then each column provides the mechanical services for one bay, which reduces the long runs necessary in the central core concept, and allows flexible location of the vertical circulation nodes.

In addition to heating and ventilating the structural system has to provide for the utilities required by the many functions in a university, such as steam, gas, laboratory waste, fume exhaust, and water lines for laboratories, as well as sprinkler systems, communication and power lines, and lighting provision.

3.6 Growth

The need for providing for expansion in a modern university is apparent. Traditionally this has been accomplished by simply adding a structure as the need arose. To some extent this method was adopted by some of the aforementioned universities. At the University of Bochum the final dimensions of each structure are determined during the design stage. A method of addition to the finished buildings was not incorporated in the design of the system.

The University of Marburg, however, adapted in its system a method of expansion such that additions to existing buildings can be made without altering existing structure. To provide the maximum flexibility within the overall plan, a three-dimensional modular system was developed for the structure of the entire campus. Expansion can occur easily in all directions. The columns are designed to carry varying loads should the decision be made to expand upwards or increase the span of adjoining spaces. The distinct characteristic of this system is that each support was divided into four separate columns. Each bay becomes then an independent structural unit to which can be added other bays without destroying the overall structural behavior. (Drawing 3)

This system of growth is particularly suited to a university designed on the basis of departmental rather than functional organization. Each department can expand by increasing the dimensions of the original building and always maintain total structural character.

4.0 The Proposal

A detailed description of the proposed system is presented. The conclusions that were drawn from the case studies and other investigations were to some extent incorporated in the proposal. However, to satisfy the main program requirement of structural optimization, conflicts arose with other program requirements. An attempt will be made to clarify these conflicts.

4.1 Dimensions

The bay dimensions are 60'X60'. The selected planning module is 5'X5'. Other planning modules can be achieved without altering the 10'-0X10'-0 structural module. Figure shows three module variations and their dimensional combinations.

The floor-to-floor height can vary depending upon function. The structural depth is 3'-6.

The composite column replaces one structural module. Of the total column area the structural column designed to support seven floors is divided into a cluster of four separate columns each 2'-6 2'-6. The additional area of 75 sq. ft. defined by the column cluster is the space provided for vertical mechanical and utility runs.

4.2 Structure

The structural principles applied in the proposal to satisfy the program requirement of structural optimization resulted in a three-

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(Page 35)

dimensionally very complex configuration. A method had to be devised of separating the floor system into units that can be cast as well as transported and a system of joining these units such that they act as a total structure.

This was accomplished by separating the top chord, web, and bottom chord into three separate precast units. Their dimensions were dictated by the allowable sizes that can be transported without special permits, and the largest structural module that is compatible with the desired planning modules. In this case both 10'-0 X 10'-0 and 12'-0 X 12'-0 structural modules were considered, and studies in the application of these modules seemed to indicate that the latter module would be more desireable.* However, due to transport limitations the 12'-0 X 12'-0 structural module was not considered feasible.

The total structure consists of a combination of pre-cast and in-situ concrete. The top chord is formed by 10' X 10' X 4" slabs that rest on the four arms of the pyramidal web member. The apex of the inverted pyramid forms the node of four 10' X 10' bottom chord members. The projected dimensions of all three members are 10' X 10'. The structural depth is 3'-6 for the 60 foot span. Photographs 4 and 5 show the relationship of the three units to each other.

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*The 12'X12' would have reduced the number of structural modules per bay from 36 to 25 and consequently the number of precast units, joints and crane operations prebay. Additionally, stair and elevator openings could have been incorporated more effectively.

The crossectional dimensions of the precast members and their rienforcement were determined by the approximations described in Appendix C. The diagonals of the pyramidal web members are designed for the most stressed condition, which occurs at the support. The same standard elements are used throughout the bay.

To achieve an orthogonal planning grid in the ceiling such that this grid is parallel to the column lines, the bottom chord members are rotated 45 degrees from the direction of the web members.

The design weight of the floor structure was assumed to be 100 lbs/sq.ft. The actual weight, assuming 150 lbs/ cu.ft. concrete, is 145 lbs/sq. ft.

Since the connection of the column to floor slab is critical and very complex, the decision was made to cast the columns in place. (See Drawing 1 for details of these connections). The behavior of the final floor structure is similar to that of a space frame.

The maximum building height of this proposal is seven floors. At this height the limit of space provided for supports and utilities is reached. For higher buildings it becomes more efficient to reduce the spans and channel the mechanical system through the circulation cores.

4.3 Fabrication, Transportation and Construction

The methods and rate of production of the precast units were not investigated beyond proving that in the scale of a model they can be cast (See Photograph 1). Due to the configuration and dimensions of the units' weight rather than number becomes the limiting factor in the number of units that can be transported at a time. The pyramidal web unit would be transported as shown in Photograph 2. This web unit is lifted by attaching cables to the ends of the four arms. The moments created by this lifting process were checked and found to be minimal in terms of its capacity (See Appendix D).

The construction process varies somewhat, depending on the configuration of the building. The construction sequence outlined applies specifically to a building width of one to three bays and unlimited length.

1. Prepare foundation and basement walls.
2. Cast columns up to ceiling level for the number of bays that make up the building width.
3. Erect scaffolding for the number of bays that will comprise the building width.
4. Place bottom chord units.
5. Place web (truss) units as indicated in Photograph 6.
6. Thread post-tensioning in the direction parallel to the width of the building. Although the cables can be threaded through the web unit after it has positioned in place, an easier alternative would be to thread a leader through these units as they are being lifted into place and then with this leader, pull the cable through the structure.

7. Grout the corner joints between the bottom chord unit and the web units.

8. Tension cables to 50% of final strength in the direction parallel to the width of the building.

9. Place top chord slabs; prepare top chord reinforcing; pour topping slab.

10. Complete tensioning of cables.

11. Cast next level of columns.

12. Remove scaffolding except in column lines transversal to width of building. (With post-tensioning completed in the direction of the building width the structure can temporarily span in that direction and all the scaffolding can be removed except in the area of the column lines transversal to that direction)

13. Repeat procedure 2 to 12 until expansion joint or length of building has been reached. (Expansion joints should occur every three bays or 180 feet)

14. Thread cable using previously placed leader in the direction perpendicular to width of building.

15. Tension cable to final strength.

16. Repeat procedure 3 to 14 until final building height is reached.

In this procedure the coupling of cables is prevented at the expense of providing scaffolding for the number of bays that comprise the least dimension of the building (building width). Continuity is achieved over a 3 3 bay area or a total of 9 bays.

An alternate procedure would be to couple the cables at the edges of each bay in one direction. In this case the scaffolding for only one bay would be necessary to construct the building.

The heaviest unit weighs approximately five kips. Using a "Lubherr" traveling crane the distance from center of rotation to hoist line with this weight is 130 ft., which is well within the distances required from the edge of construction to the center of a 180 foot wide structure.

4.4 Circulation

The decision to combine the structural column with the mechanical and utility shafts released the restrictions on the placement of vertical circulation cores.

Openings are prepared in the floor structure during construction to receive stair units and elevators. The minimum fire stair can be placed into a 10'X20' opening in the floor slab, and if located as indicated in Drawing 3, only one cable has to be terminated. The 10'X10' elevator openings are located such that the post-tensioning cables are not terminated. The fire-rated enclosure walls are 6" concrete block or equivalant precast panels which are supported by the floor structure at every level. Into the stairwells self-supporting prefabricated steel stairs are positioned into place (Drawing 3).

Stairs can be placed independent of any central core in a pattern and frequency that occupancy dictates. Drawings 5 and 6 indicate various patterns based on different occupancies.

4.5 Environmental Controls

The heating and ventilating system is based on the Single Duct with Terminal Reheat and Damper Control and designed for 2 cfm capacity (Appendix E). The air is supplied at constant temperature usually 20 degrees lower than the desirable room temperature, at high velocity supply up to the reheat terminals at great saving of space, the problem of maintaining satisfactory sound levels is magnified, and outlets with a low level of noise generation and a high degree of sound attenuation is required. Also special attention must be given to the lining of ducts, the design of fan isolation, and the use of flexible connections.

The velocity of the supply air is reduced by a valve as it enters the floor structure at the column. An adjacent attenuator with a capacity of 2400 cfm reduces the noise level before it enters the floor space. The terminal reheat and volume control units are placed according to the desired control zones, which can range from areas of 100 sq.ft. to areas of a full bay. In the latter the reheat and volume control units are combined with the attenuator

The diffusers can be a part of a specially designed lighting panel through which also the return air would be handled. In interior spaces the problem is usually the removal rather than the delivery of heated air, therefore the lighting panel can be designed such that the heat produced by the lamps can be removed before it enters the space by drawing the return air through the lamps.

Air is returned at low velocity and constant friction in the floor as well as the column.

The acoustical problem is sound isolation between spaces. This is resolved by closing the grid at the ceiling level with either light and diffuser troffers or sound absorbing panels. It is important that sound leaks are prevented between spaces. In large spaces such as mezzanines and lecture halls, the structure is exposed and a cast-in-place absorption panels (tectum) in the bottom surface of the floor slab will provide the necessary acoustic treatment.

4.6 Growth

Each bay is independent in terms of mechanical and utility requirements since these are provided in each column; and if required, an individual bay may be added as indicated in Drawing 3. The resulting discontinuity in the post-tensioning cables allows for a construction (expansion) joint at that point.

As at the University of Marburg, the number of columns in a cluster define the position of the support in the building, such as interior edge or corner. If an addition is required the remaining columns are added to complete the cluster and in this way the problem of connection to existing support is eliminated.

CONCLUSION

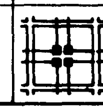
The emphasis in the development of the problem was placed on the structural sub-system. The design and planning potential of the system has so far been based only on the general facilities requirements of a university. It is necessary to verify this potential in the context of a specific building program.

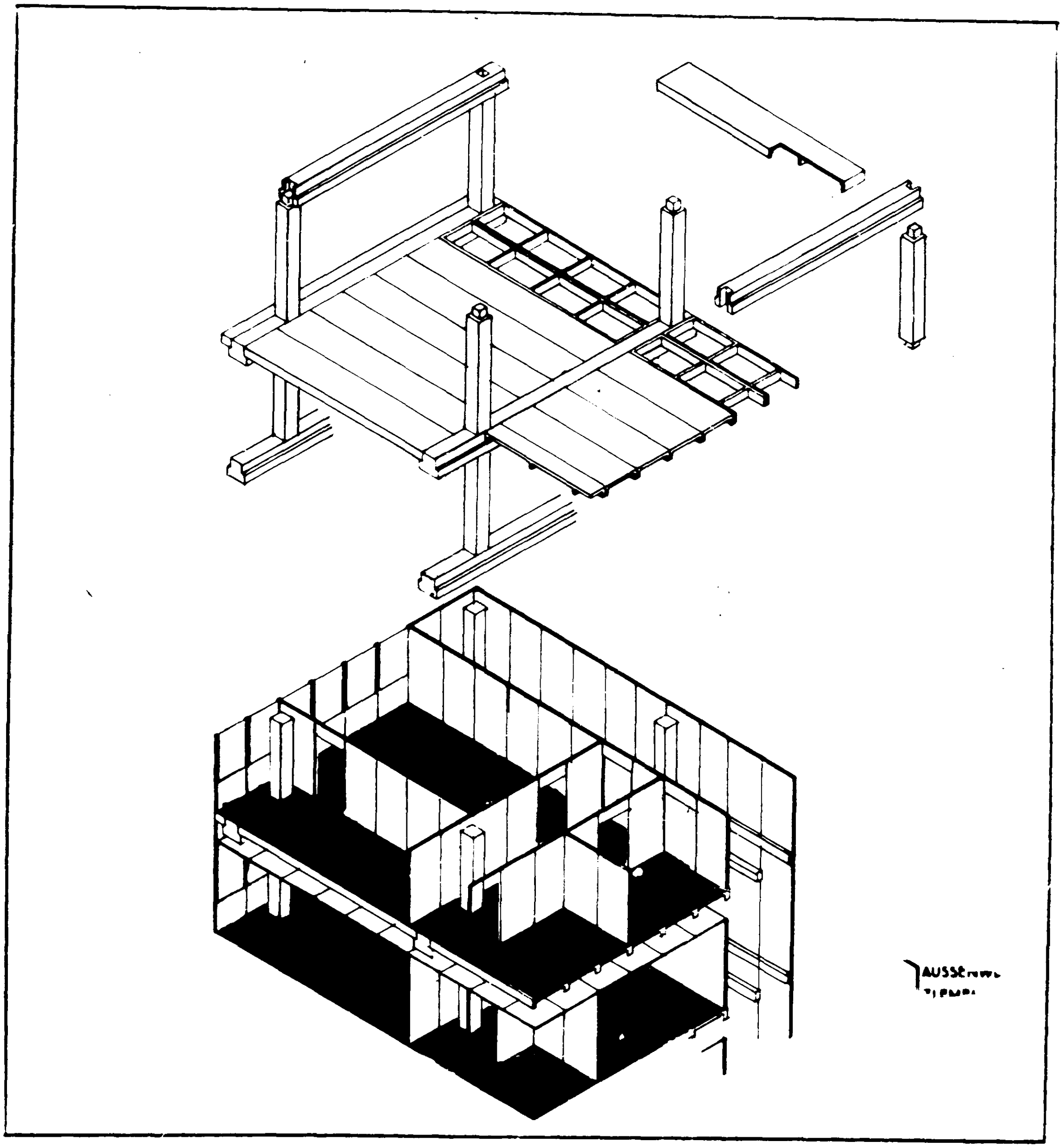
The program requirement of total industrialization and dimensional coordination was realized only in the basic structure. The sub-systems of environmental controls, lighting ceiling, interior space division, vertical skin, and plumbing were either resolved in conventional methods and materials, or not considered in depth due to the time element.

The requirement of structural optimization resulted in the development of a structural floor system that forced the precast members to be small and numerous and consequently an increase in the number of on-site operations such as crane lifts, joints, and post-tensioning. Additionally, extensive scaffolding is necessary. Preliminary estimates indicate that the cost of material saved is offset by the cost of the increased labor content.

In total building industrialization, to be fully effective, the entire building industry must be industrialized; and to reduce the high initial cost, the greatest possible application must be made. At present, only isolated fragments of the building industry are industrialized. Successful industrialization cannot occur without systematization and dimensional coordination of building components, sub-systems and systems. The hurdles that are presently placed in the path of innovative concepts are building codes labor and the marketplace.

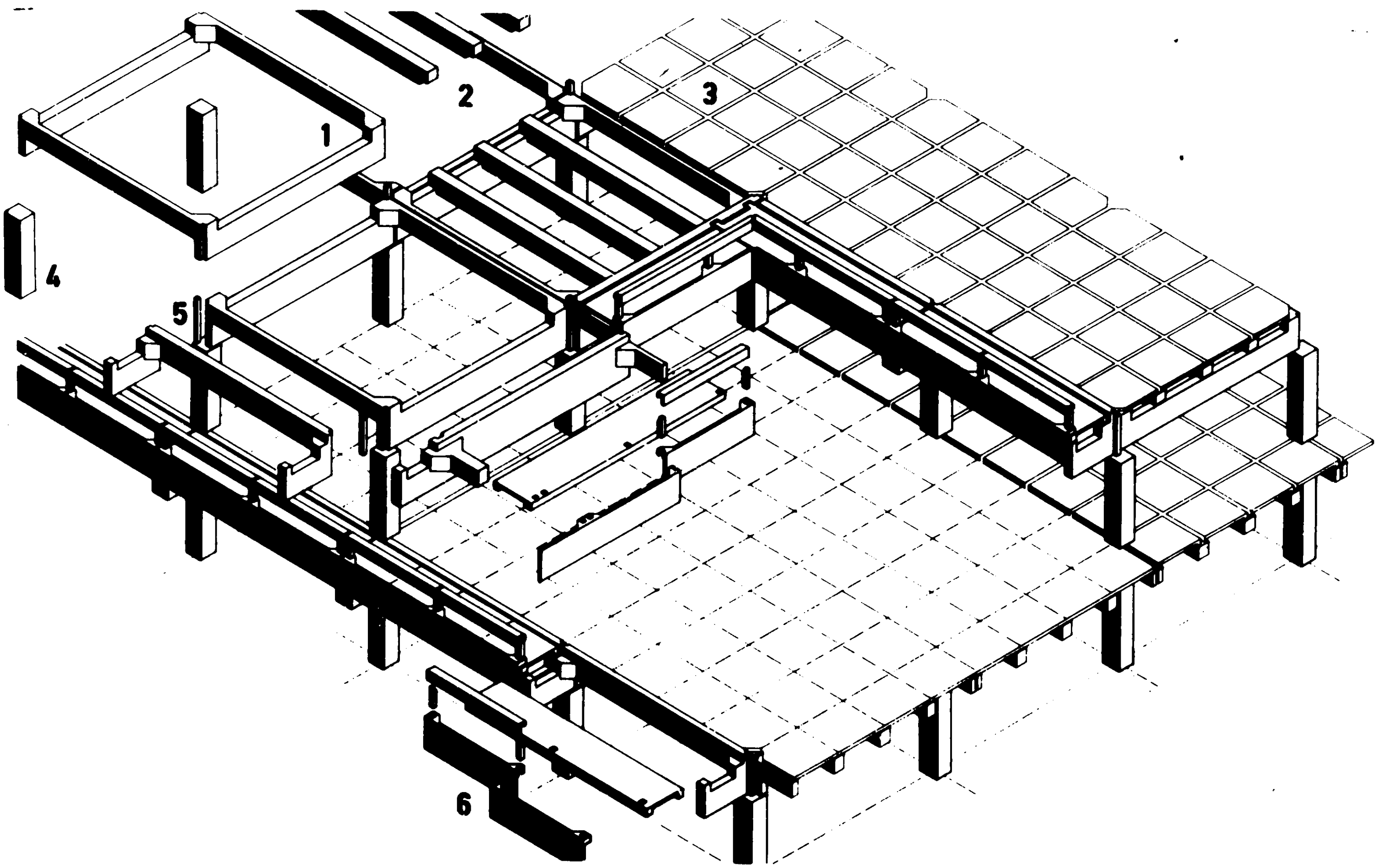
APPENDIX · A
COMPARISON OF EXISTING UNIVERSITY BUILDING SYSTEMS

SCHOOL	STRUC. BAY	STRUCT. MOD.	STRUCT. FLOOR DEPTH	TOTAL FLOOR DEPTH	FLOOR TO CLG. HEIGHT	PLANNING MODULE	BASIC BLDG. WIDTHS	BASIC BLDG. LENGTHS	MAX. NUMBER OF FLOORS	STRUCT. SYSTEM	COLUMN TYPE	COMMENT
UNIVERSITY OF **TÜBINGEN**	24'-8 × 24'-8 (7.5 × 7.5 m)	4'-1 × 4'-1 (1.25 × 1.25 m)	1'-2 (.35 m)	3'-3 (1.0 m)	9'-10 (3.0 m)	4'-1 × 4'-1 (1.25 × 1.25)	77'-8 (23.5 m)	197'-4 (60 m)	8 - 10	ONEWAY PRECAST		COLUMNS ARE NOT PART OF PARTITIONING SYSTEM
UNIVERSITY OF **GÖTTINGEN**	24'-8 × 24'-8 (7.5 × 7.5 m)	4'-1 × 4'-1 (1.25 × 1.25 m)	1'-2 (.35 m)	3'-3 (1.0 m)	9'-10 (3.0 m)	4'-1 × 4'-1 (1.25 × 1.25)	77'-8 (23.5)	153' (62.5) 229' (93.8) 410' (125.0)	5 - 7	ONEWAY PRECAST		TOP FLOOR MECHANICAL SIMILAR TO SYSTEM TÜBINGEN EXCEPT AS NOTED
UNIVERSITY OF **FREIBURG**	28'-8 × 28'-8 (8.75 × 8.75 m)						57'-4 (8.75)		HIGHRISE			SIMILAR TO SYSTEM TÜBINGEN EXCEPT AS NOTED
INSTITUTE OF TECHNOLOGY **STUTTGART**	24'-8 × 24'-8 (7.5 × 7.5 m)						73'-9 (22.5)	73'-9 (22.5)	HIGHRISE			SIMILAR TO SYSTEM TÜBINGEN EXCEPT AS NOTED.
UNIVERSITY OF **BOCHUM**	24'-8 × 24'-8 24'-8 × 49'-2 24'-8 × 73'-9 49'-2 × 49'-2	3'-1 × 3'-1 (93.75 × 93.75)	2'-6 (.75 m)	2'-6 (.75 m)	12'-6 (3.80 m) 9'-4 (2.80 m)	3'-1 × 3'-1 (93.75 × 93.75)	73'-9 (22.5)	368'-9 (112.5)	8	ONEWAY PRECAST		SYSTEM IS APPLIED TO THE FACULTIES OF NATURAL SCIENCES, SOCIAL SCIENCES, MEDICINE, ENGINEERING. USE UNDEFINED - SIZE DEFINED
UNIVERSITY OF **MARBURG**	23'-7 × 23'-7 (7.5 × 7.5 m) 15'-9 × 23'-7 23'-7 × 31'-6	4'-0 × 4'-0 (1.2 × 1.2 m)	2'-6 (.75 m)	2'-6 (.75 m)	12'-4 (3.75 m) 9'-4	2'-0 × 2'-0 (.60 × .60)	NOT DEFINED	NOT DEFINED	8 - 12	TWOWAY PRECAST		NO STANDARD BUILDING SIZES - ONLY STANDARD COMPONENTS. 30 cm M. USE DEFINED - SIZE UNDEFINED



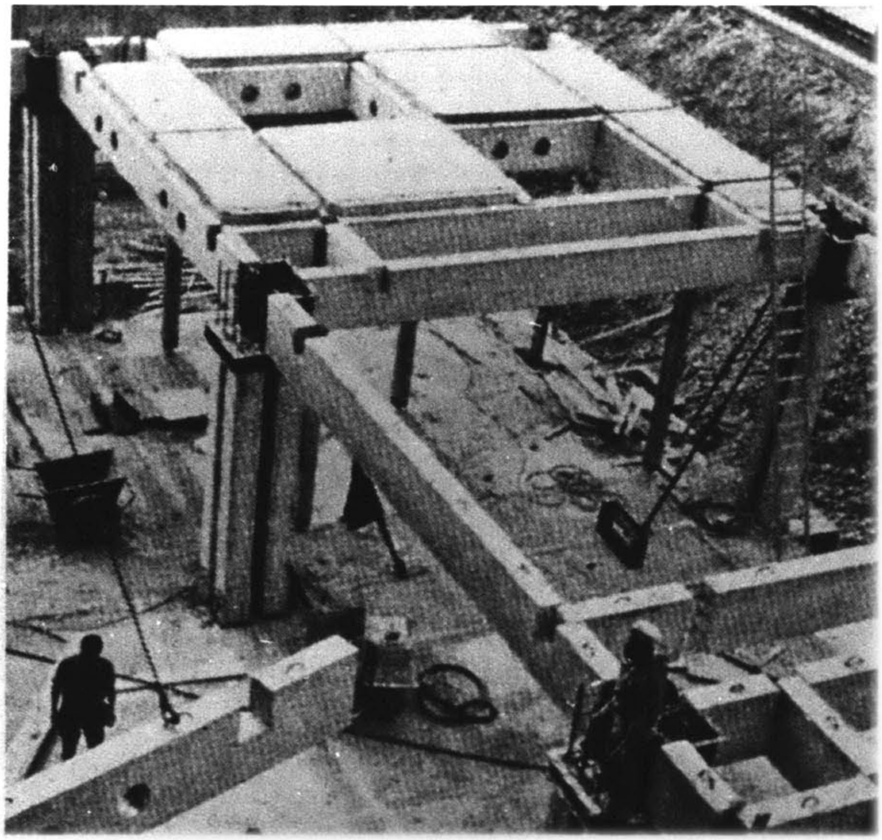
UNIVERSITY OF TUBINGEN (W. GERMANY)

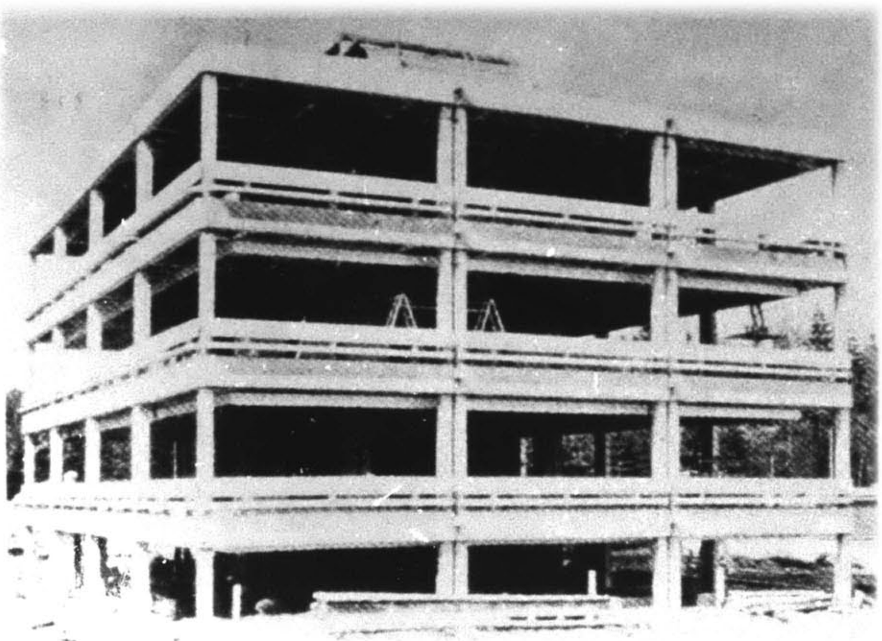
SOURCE: Karl Steiner, Probleme der Hochschulerweiterung, Zurich, 1966.



UNIVERSITY OF BOCHUM (W. GERMANY)

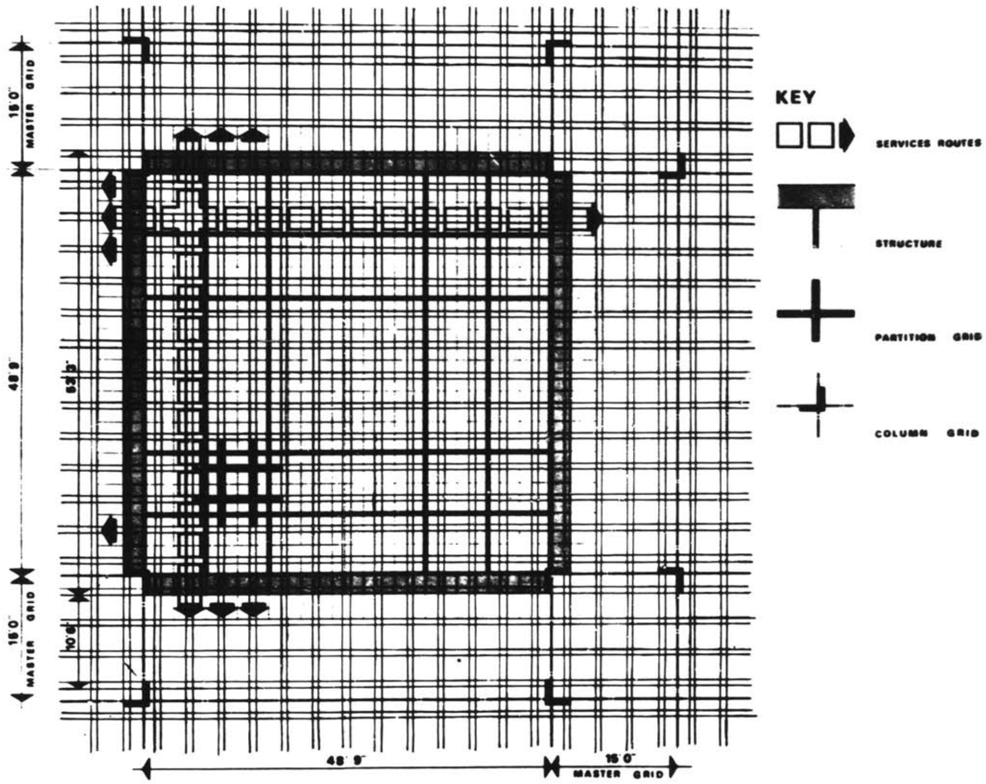
SOURCE; Karl Steiner, Probleme der Hochschulerweiterung, Zurich, 1966.



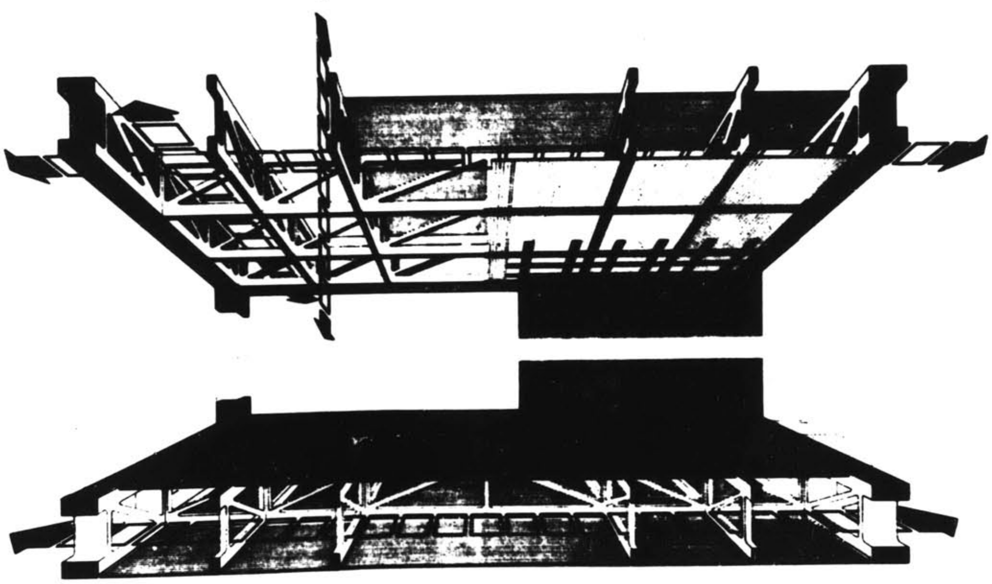


UNIVERSITY OF MARBURG (W. GERMANY)

SOURCE: Karl Steiner, Probleme der Hochschulerweiterung, Zurich, 1966.



Relationship between all grid networks in an academic building



Section through the space unit shown on plan above

UNIVERSITY OF LOUGHBOROUGH, ENGLAND

SOURCE: <u>University Planning and Design</u>, A Symposium edited By Michael Brawne, Architectural Association, London, 1967.

APPENDIX B

AREA REQUIREMENTS FOR VARIOUS UNIVERSITY FUNCTIONS

Science and Technology	Sq.Ft.
Chemistry Laboratory (32 students)	1,200
Balance Room	160
Storage - Preparation Room	400
Faculty Office	80
Biology Laboratory (32 students)	1,200
Plant Room	200
Storage - and Preparation Room	400
Faculty Offices	80
Physics Laboratory (24 students)	960
Instrument Room	200
Storage - Preparation	400
Faculty Offices	80
Electronics Laboratory	960
Storage - Preparation	400
Engineering Laboratory	960
Drawing Laboratory (30 students)	2,800
Reproduction Room	400
Lecture Hall	1,200

Business Education

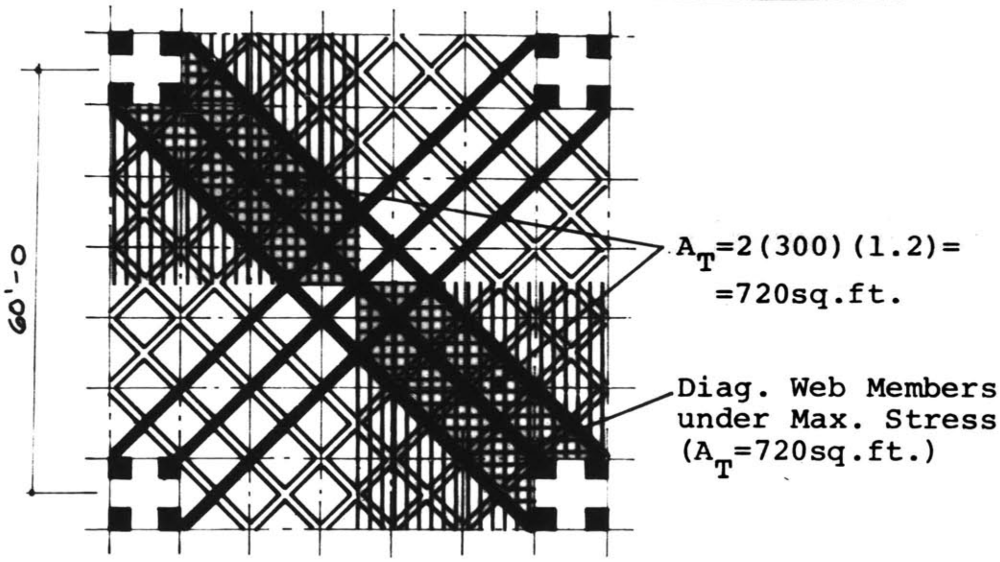
Office Machine Laboratory (20 students)	700
Secretarial Laboratory (40 students)	1,200
Accounting Laboratory (40 students)	900
General Classrooms (40 students)	300
General Classroom (30 students)	800

FINE ARTS -Language Arts - Social Sciences

Lecture Theater & Stage (250 students)	3,000
Art Laboratory	2,000
General Classroom (20 students)	400

APPENDIX C

ANALYSIS TO DETERMINE APPROXIMATE DIMENSIONS AND REINFORCING OF STRUCTURAL MEMBERS



PLAN-SECTION OF BAY THRU WEB

a. Design of Diagonal Web Members

Assuming: f_s= 30 ksi
f_c= 1000 psi
TL= 200 lbs.

$$A_{st} = \frac{A_T}{200}(1.5) = \frac{720(1.5)}{200} = 5.4 \text{ sq.in.}$$

$$A_{cc} = \frac{A_T}{10}(1.5) = \frac{720(1.5)}{10} = 108 \text{ sq.in.}$$

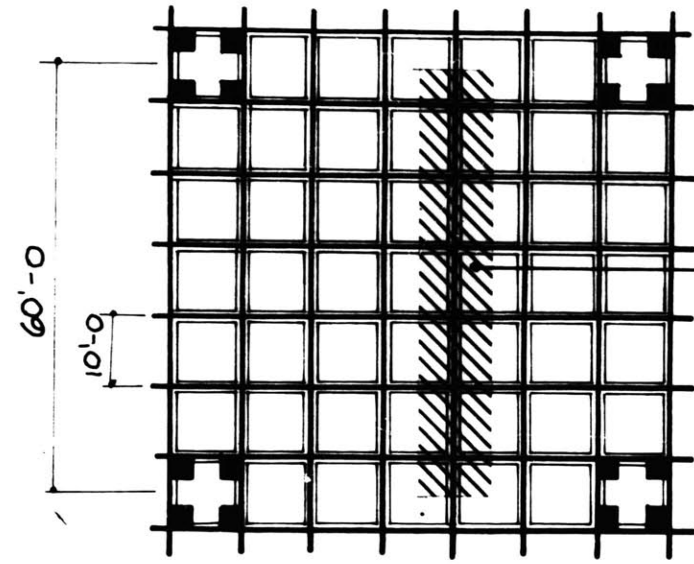
Based on a slope of 1:2 of the diagonal members

Where A_T = Tributary area of member under consideration

A_{st} = Area of steel in tension

A_{cc} = Area of concrete in compression

APPENDIX C cont.



PLAN OF BOTTOM CHORD POST-TENSIONING CABLES

Design of bottom chord compression members and post-tensioning cables

$$A_c = \frac{A_T(L/h)}{5000} = \frac{600(60/3.5)}{5000} = 2 \text{ sq.in.}$$

$$A_{cc} = \frac{A_T(L/h)}{50} = \frac{600(60/3.5)}{50} = 200 \text{ sq.in.}$$

Where A_T = Tributary area of member under consideration.

A_c = Crossectional area of cable

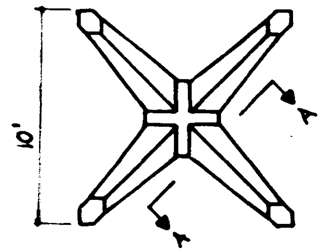
A_{cc} = Crossectional area of concrete in bottom chord compression member.

L = Dimension of bay

h = Height of floor structure

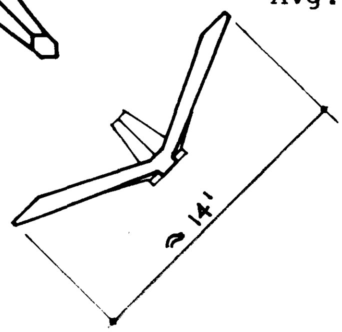
APPENDIX D

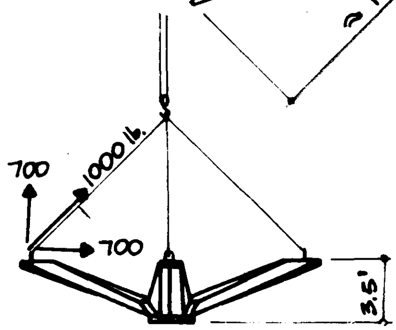
STRESSES CREATED IN WEB UNIT DURING CONSTRUCTION



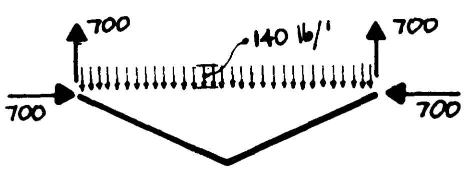
Total weight of unit = 4000 lbs.

Avg. weight per lineal foot=140 lbs.

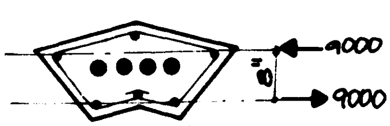




Check moments created by lifting procedure as shown.



$$M_c = \frac{140(14)^2}{8} + 700(3.5) = \underline{6000\ \text{ft.lb.}}$$



SECTION AA

.5 sq.in. of steel is required to resist moments created by handling.

APPENDIX E

DESIGN CRITERIA FOR MECHANICAL SYSTEM

a. Sources of Heat Gain

Lighting:	70 F.C.	3 watts/sq.ft.
	100 F.C.	4.5 watts/sq.ft.
	150 F.C.	6.5 watts/sq.ft.
	200 F.C.	8.6 watts/sq.ft.
Misc. Power:		
	Classroom	.2 watts/sq.ft.
	Office	.5 watts/sq.ft.
	Laboratory	1-4 watts/sq.ft.

People: 300 BTU sensible heat per person

Education	1 person/40sq,ft.
Office or Lab.	1 person/100sq.ft.
Business	1 person/100sq.ft.
Assembly	1 person/30sq.ft.

Fume Hoods: Face opening 4'x2'-6" = 10 sq.ft.

10 sq.ft.x 80 ft. face velocity = 800 CFM

b. Air Supply Calculations

Example 1: Laboratory

Total Heat Gain:

Lighting -	4.5 watts/sq.ft.x3.42 BTU/watt	= 15.4 BTU
Misc.Power	4 watts/sq.ft. x 3.42 BTU/watt	= 13.7 BTU
People	300 BTU/100sq.ft. per person	= 3 BTU
	Total Heat Gain	32.1 Btu

$$\frac{32.1 \text{ BTU/hr/sq.ft.}}{1.08 \times 20° \text{ T}} = 1.5 \text{ CFM/sq.ft.}$$

Example 2: Classroom

Total Heat Gain:

Lighting -	4.5 watts/sq.ft. x3.42 BTU/watt	= 15.4 BTU
Misc.Power	.2 watts/sq.ft.x3.42 BTU/watt	= .7 BTU
People	300 BTU/40 sq.ft. per person	= 7.5 BTU
	Total Heat Gain	23.6 BTU

$$\frac{23.6 \text{ BTU/hr/sq.ft.}}{1.08 \times 20° \text{ T}} = 1.1 \text{ CFM/sq.ft.}$$

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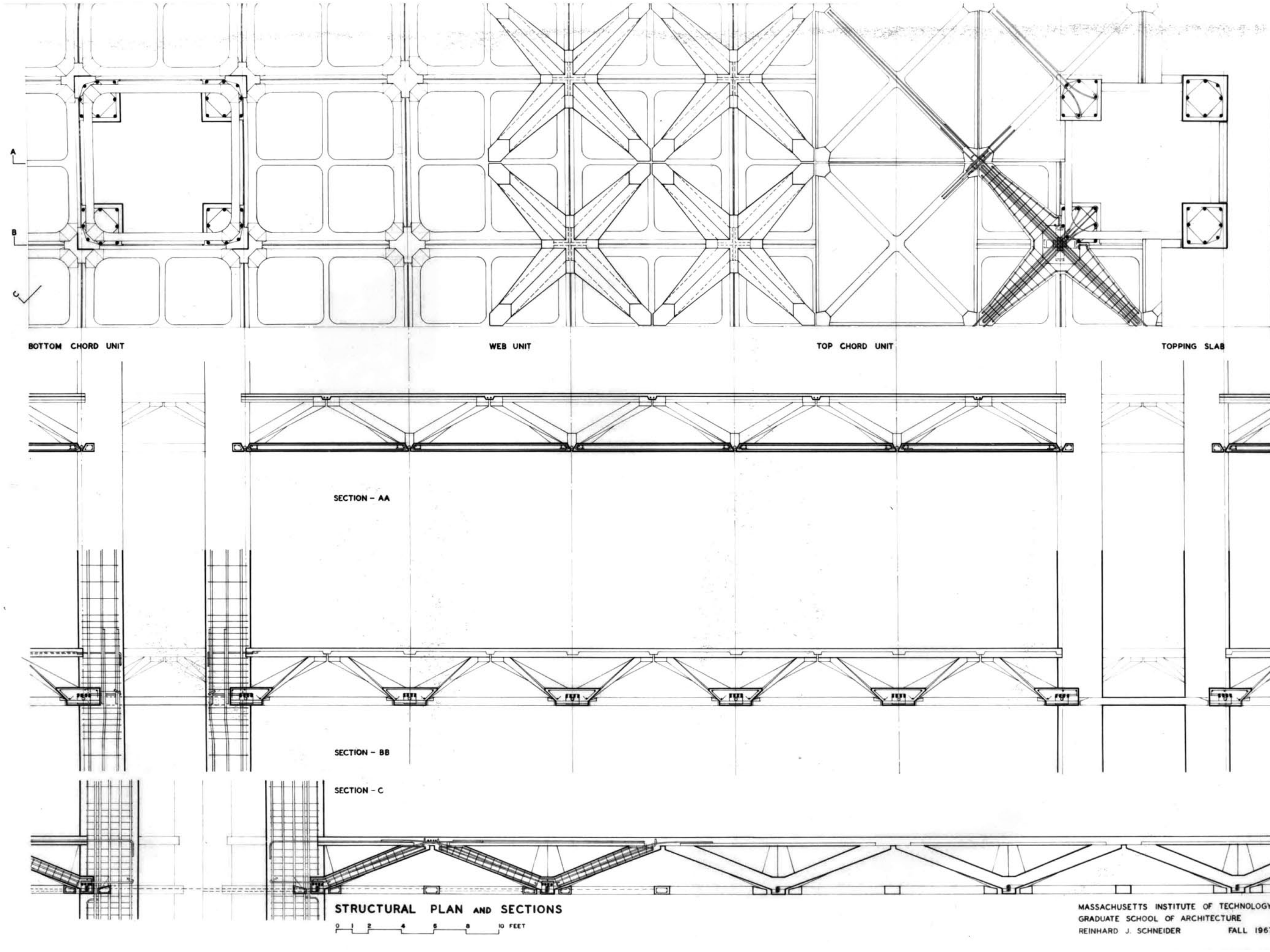
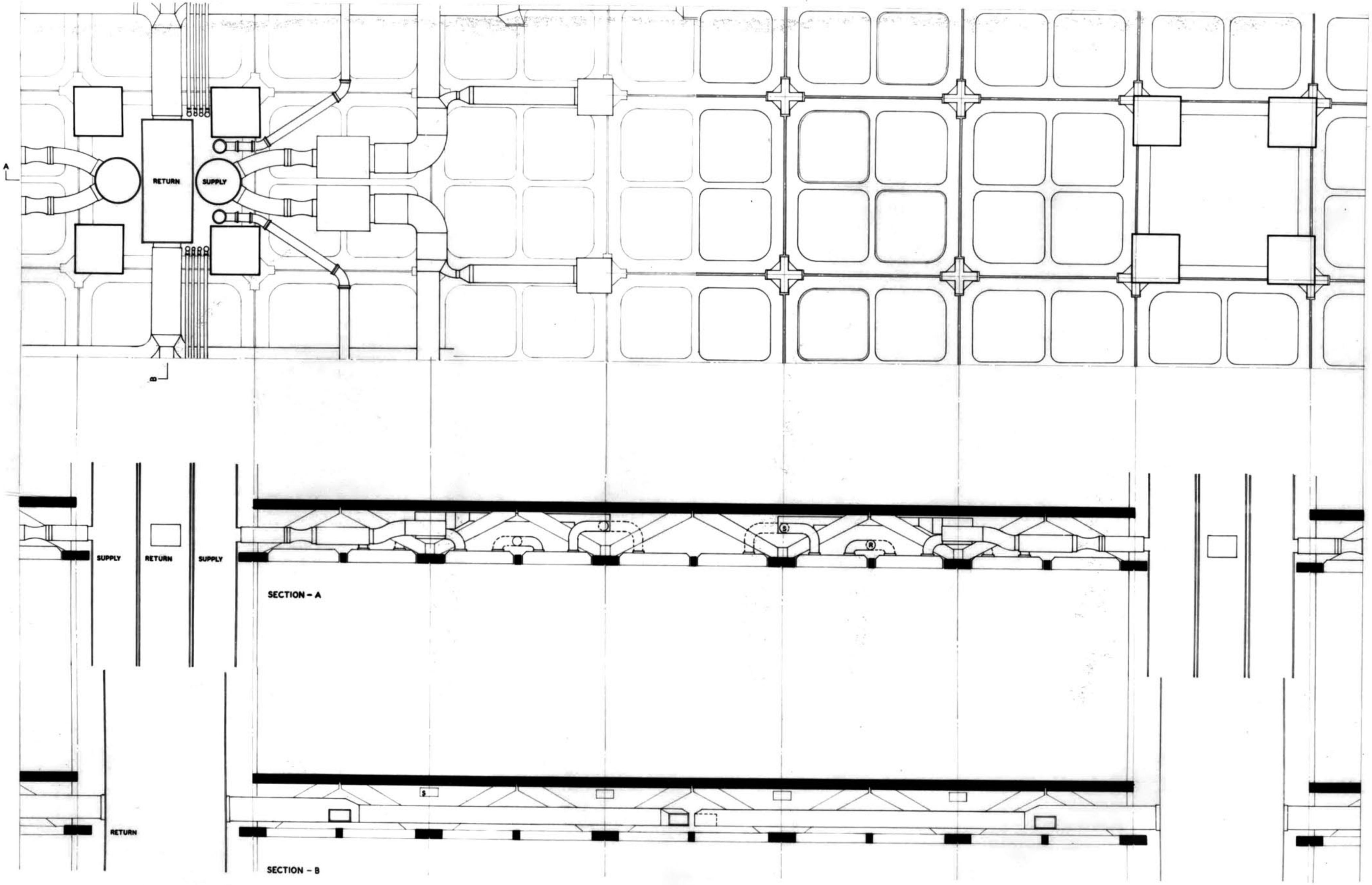


STRUCTURAL PLAN AND SECTIONS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
GRADUATE SCHOOL OF ARCHITECTURE
REINHARD J. SCHNEIDER FALL 1967



MECHANICAL PLAN AND SECTIONS

0 1 2 4 6 8 10 FEET

2

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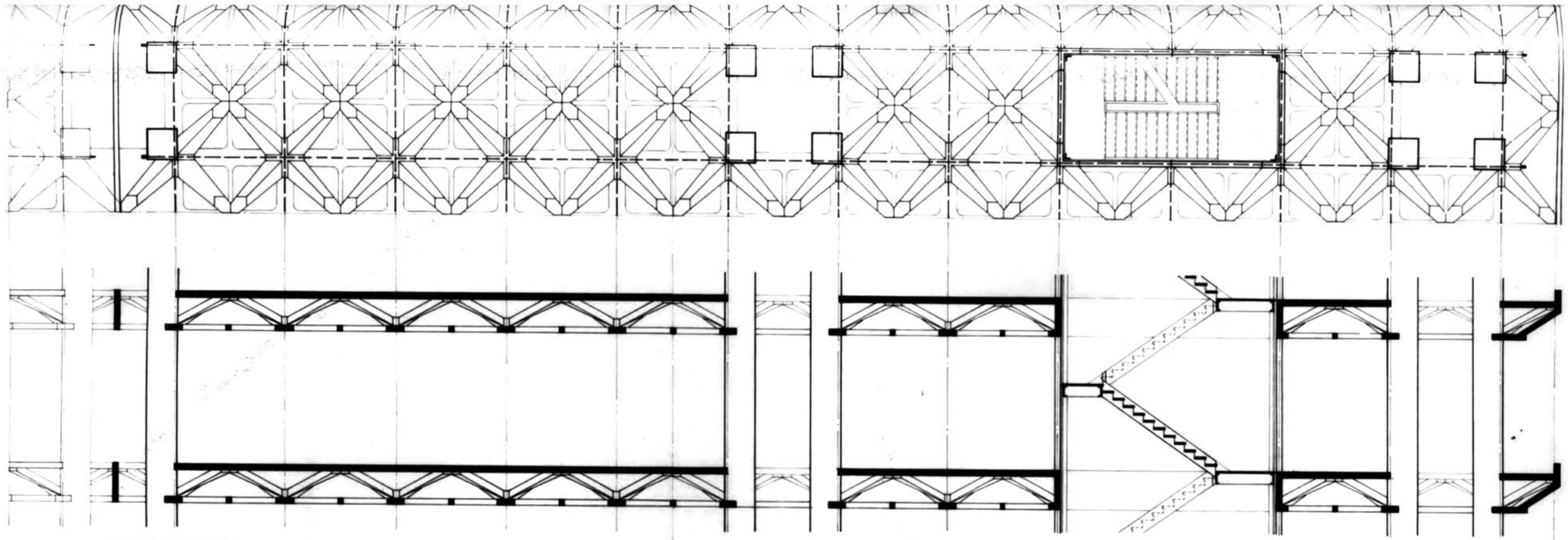
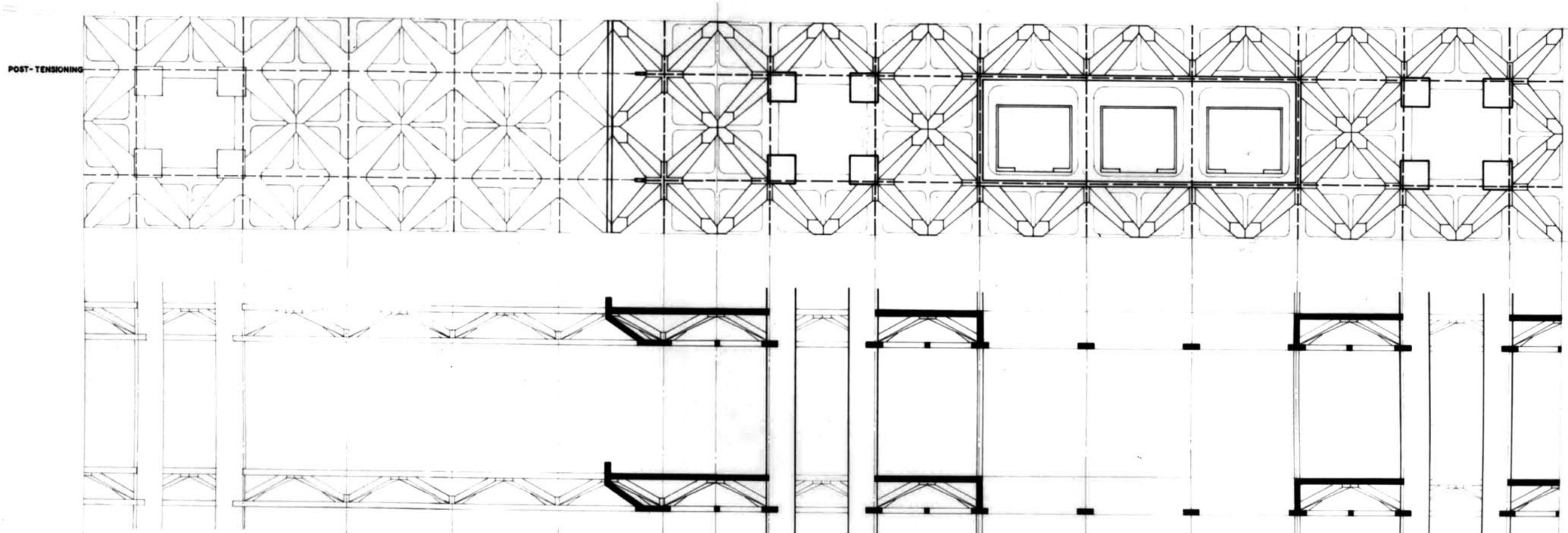


EDGE CONDITION 'A'

EDGE CONDITION 'B'



EDGE AND PENETRATION CONDITIONS

0 1 2 5 10 20 FEET

EDGE CONDITION 'C'

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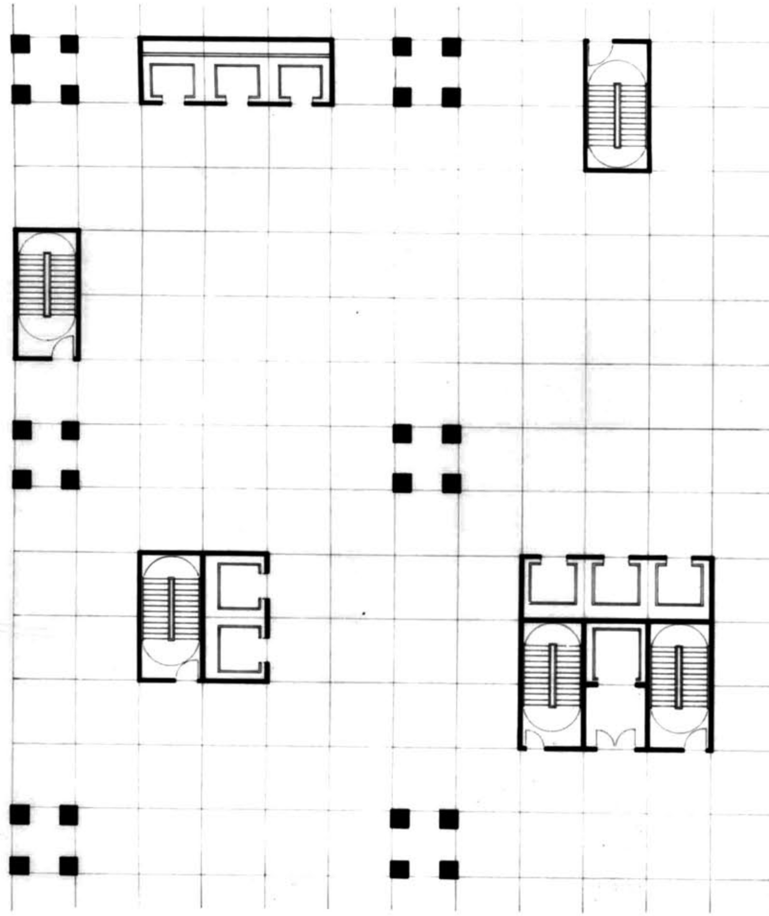
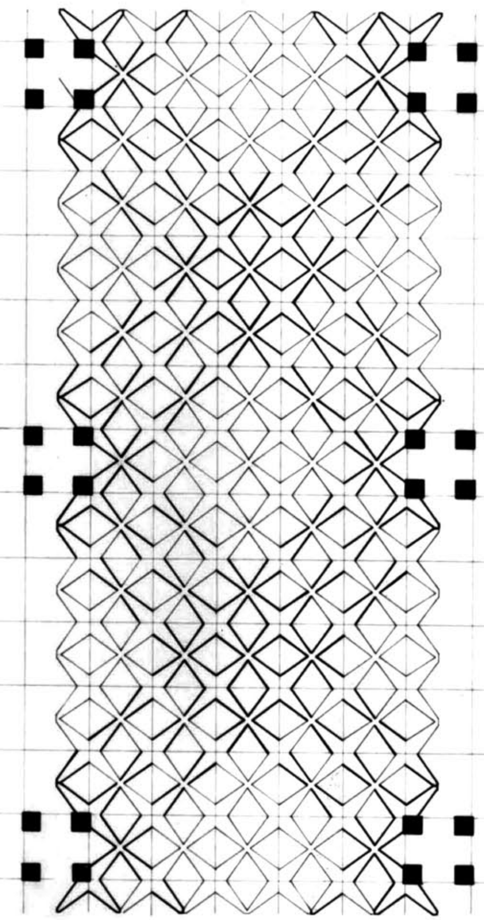
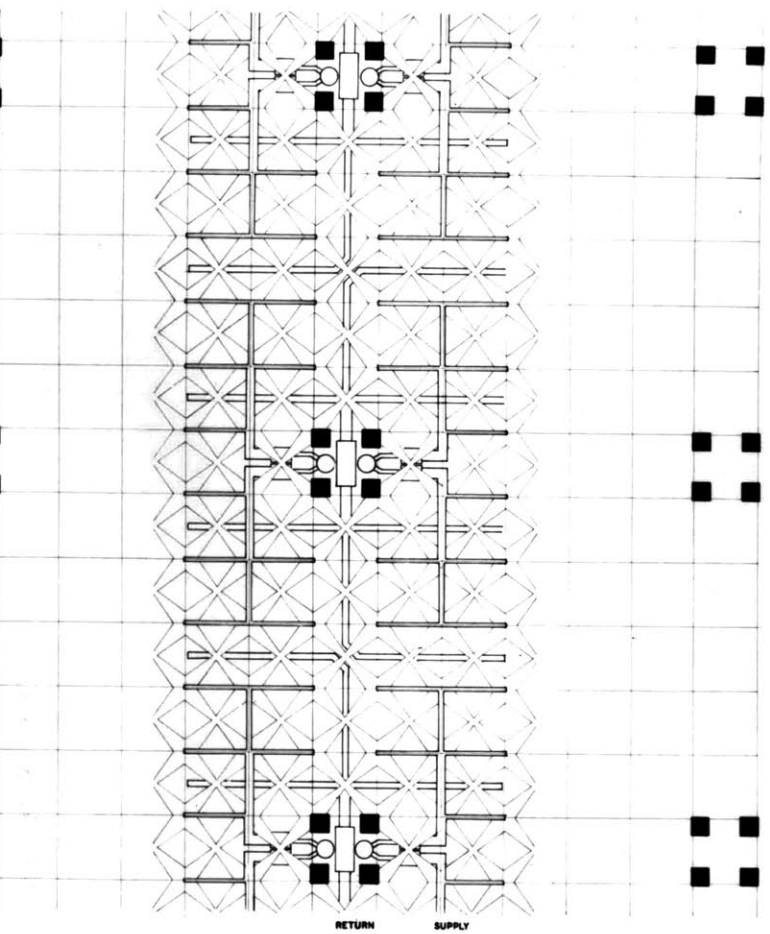


CORE COMPONENTS



PRINCIPAL DIRECTIONS OF LOAD TRANSFER



MECHANICAL DISTRIBUTION

CORE COMPONENTS MECHANICAL DISTRIBUTION

5 10 20 30

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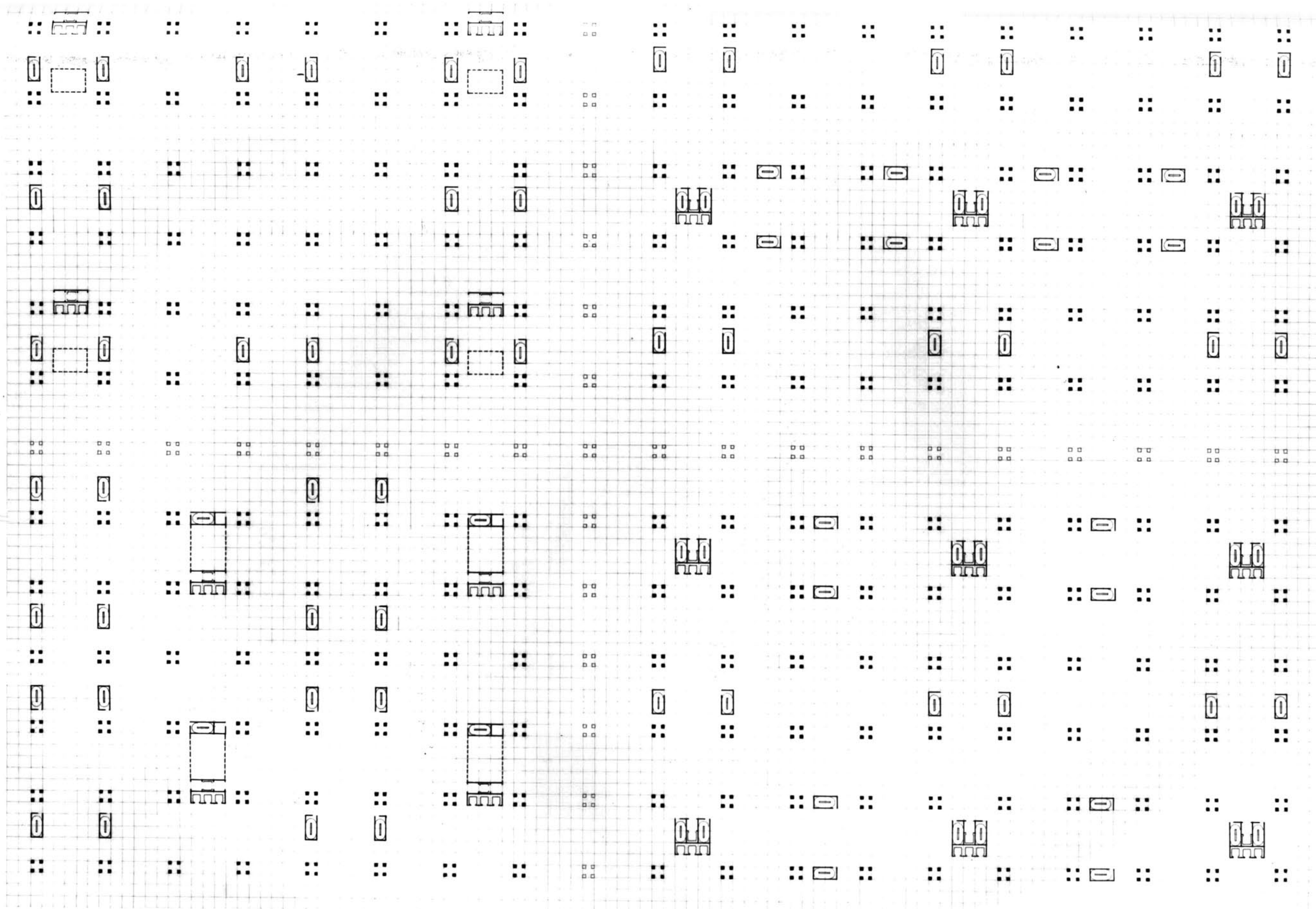
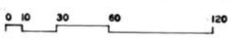


OCCUPANCY VARIATION SCHEMATICS



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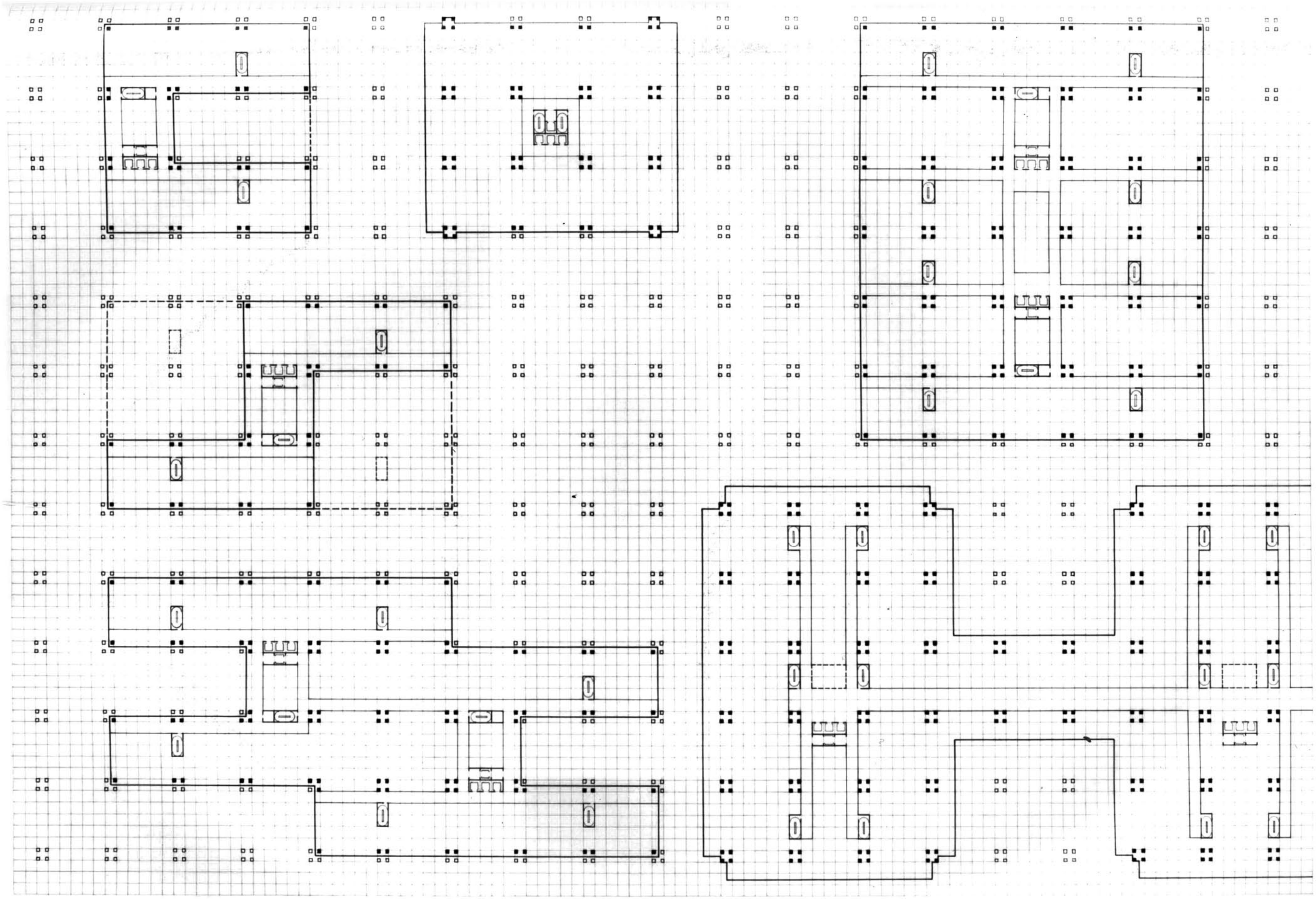

PLAN VARIATIONS

0 10 30 60 120

6

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