

A STUDY IN ARCHITECTURAL SYSTEMS

by

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Signature of Author . . . . . Department of Architecture, June 15, 1965

Certified by . . . . . Thesis Supervisor

Accepted by . . . . .  
Chairman, Departmental Committee on Graduate Students

June 15, 1965

Pietro Belluschi, Dean  
School of Architecture and Planning  
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Dear Dean Belluschi:

In partial fulfillment of the requirements  
for the degree of Master of Architecture, I  
hereby submit this thesis entitled: A Study  
in Architectural Systems.

Respectfully,

Eric H. Theiler

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and

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## INTRODUCTION

Compared to the progress made in other fields of technology and science architecture has developed at a rather slow pace in the past two centuries. Many trends in science have hardly had any impact on architecture and most recent ones like automation or computation have not affected construction methods yet.

However, the enormous problems facing an architect today force him to use all the potentialities of modern technology. In many countries today there is a critical shortage of construction workers and at the same time the demand for constructed floor area is rapidly increasing due to the growing population and the constantly rising standards of living. In addition the buildings get more and more complex. This is reflected by the increasing importance of the mechanical and electrical engineers beside that of the civil engineer within the construction process.

The dynamic of the time we live in urgently requires a re-evaluation of our traditional way of construction. Not only is there a demand for more building space but buildings are becoming so complex that a commercial or

or industrial structure often becomes obsolete within ten or twenty years. The concept of a building has to change radically to allow a maximum transformation within a structural frame of reference.

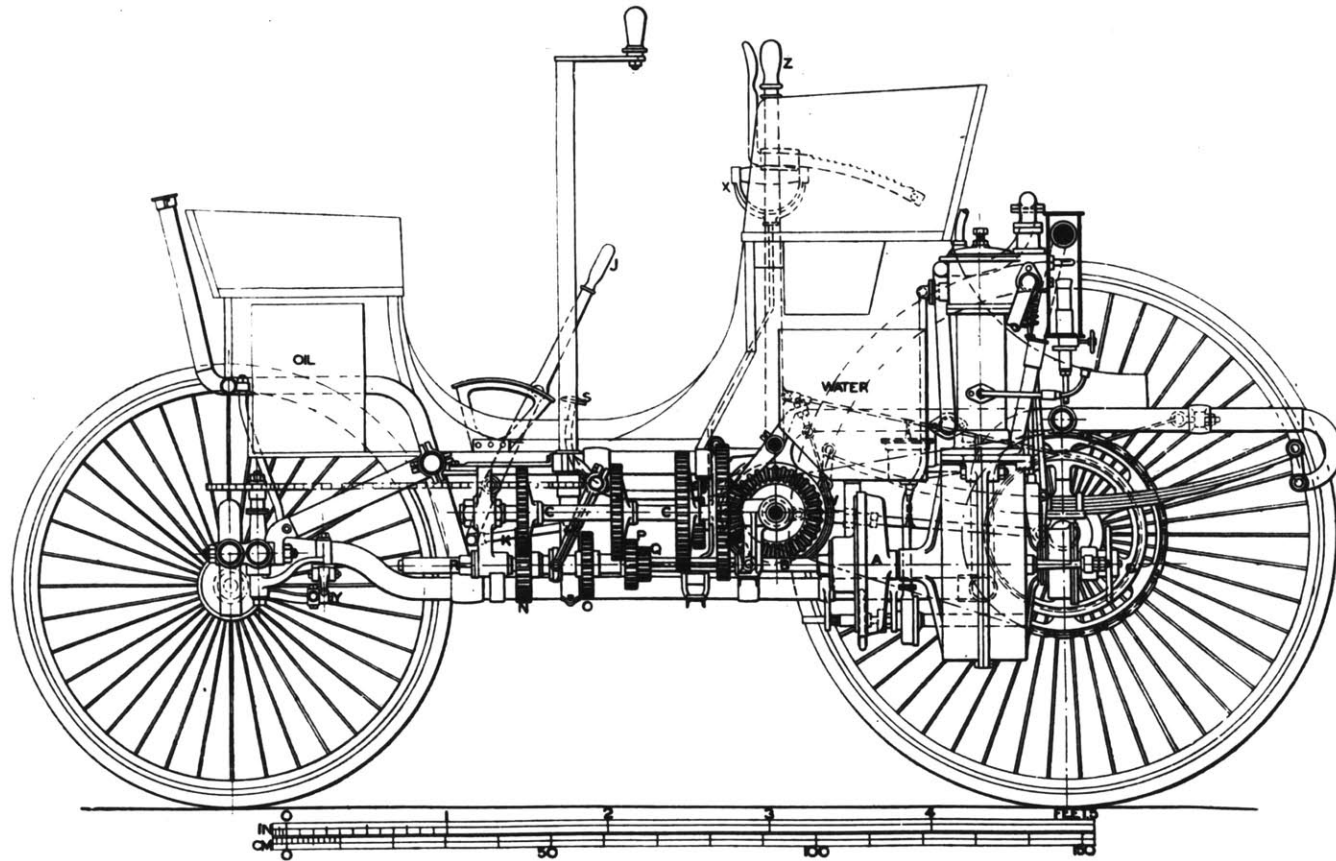
To cope with these tremendous problems the architect has to search for new methods. As Nervi says, "He has not to tackle a structural problem with aesthetic prejudices, but to search for the most suitable solution technically and economically, then following patient and passionate work the detailing and calculation of the various structural elements so as to refine the form and thus meet the static and structural requirements." Nervi believes in the inherent aesthetic force of a good solution, "Never did I find a good building old or new which departed from this principle". Speaking of modern buildings that are conceived purely sculpturally, he says, "Their equilibrium has not been achieved by the spontaneous give and take of action and counteraction, but through complex and artificial structural solutions. That is why I believe that the mark of a good structural organism is the degree to which the qualities and potentialities of steel and reinforced concrete have been exploited while following natural static forms." (1)

With this paper an attempt is being made to demonstrate the potentialities of prefabrication with the principles

in mind mentioned by Nervi, and applying it to a given problem. Later on why this particular construction method has been chosen will be explained.

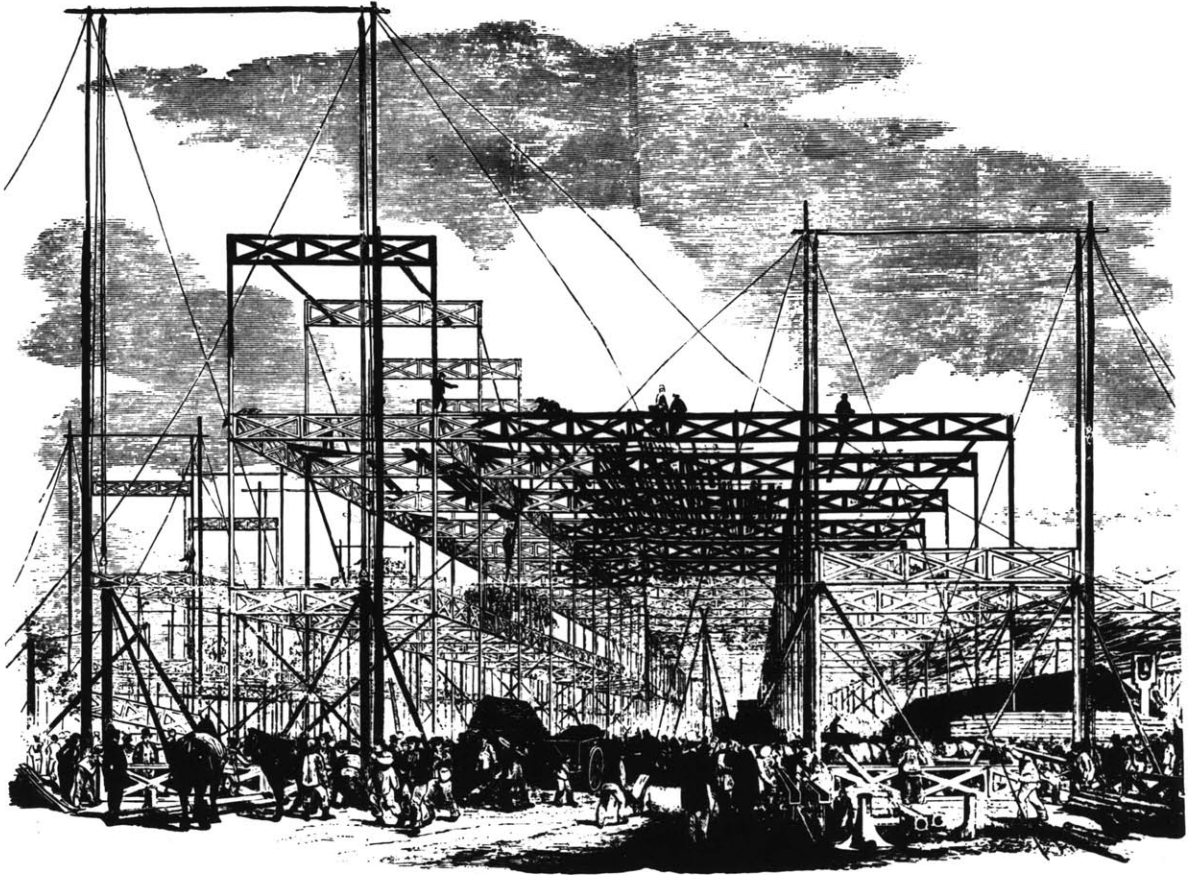
The idea of using prefabrication for structural parts combined with prestressing is not a new one. It goes back as far as 1886 when P.H.Jackson, an engineer in California, obtained patents for tightening steel rods in 'artificial stones' to make floor slabs. But to compete economically many inventions and refinements had to be made, and it was in the Second World War that precast elements were mass produced for the first time (railroad ties and roof beams with a parabolic extrados and a straight soffit spanning up to 100'). Many obstacles had and still have to be overcome for it to be used on a commercial basis. The building industry is reluctant to make the big investments required for the replacing of existing facilities and machines, being doubtful if the prefabricated parts will be used in a sufficient number to guarantee economic success. The first breakthroughs combining prefabrication with a high degree of artistic responsibility were made in Europe by Nervi, Maillart and Perret. In this country one of the first structures using a prefabricated slab system comparable to the one proposed in this paper is the complex of Medical Towers by Louis Kahn. Of importance in this context is

also the success of structural mass produced components like the Lin-Tees in the last decade produced now by over fifty manufacturers in the United States and Canada, paving the way for solutions like the one suggested here.

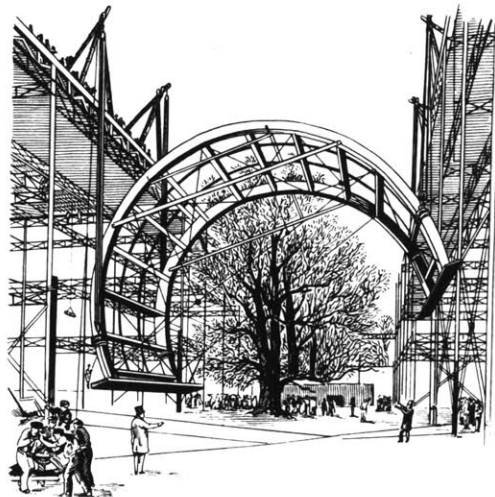


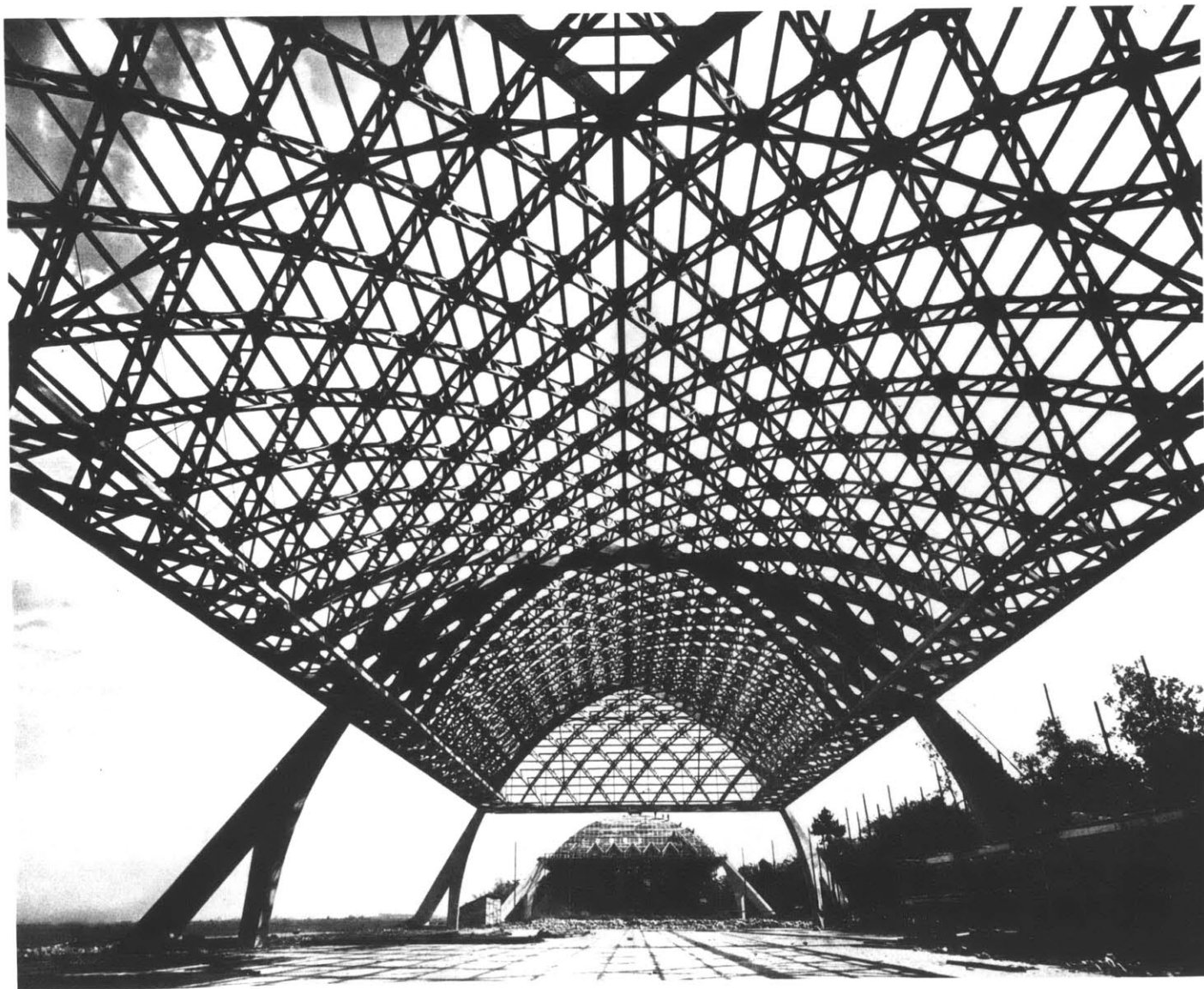
Peugeot - Daimler Motor Carriage 1896



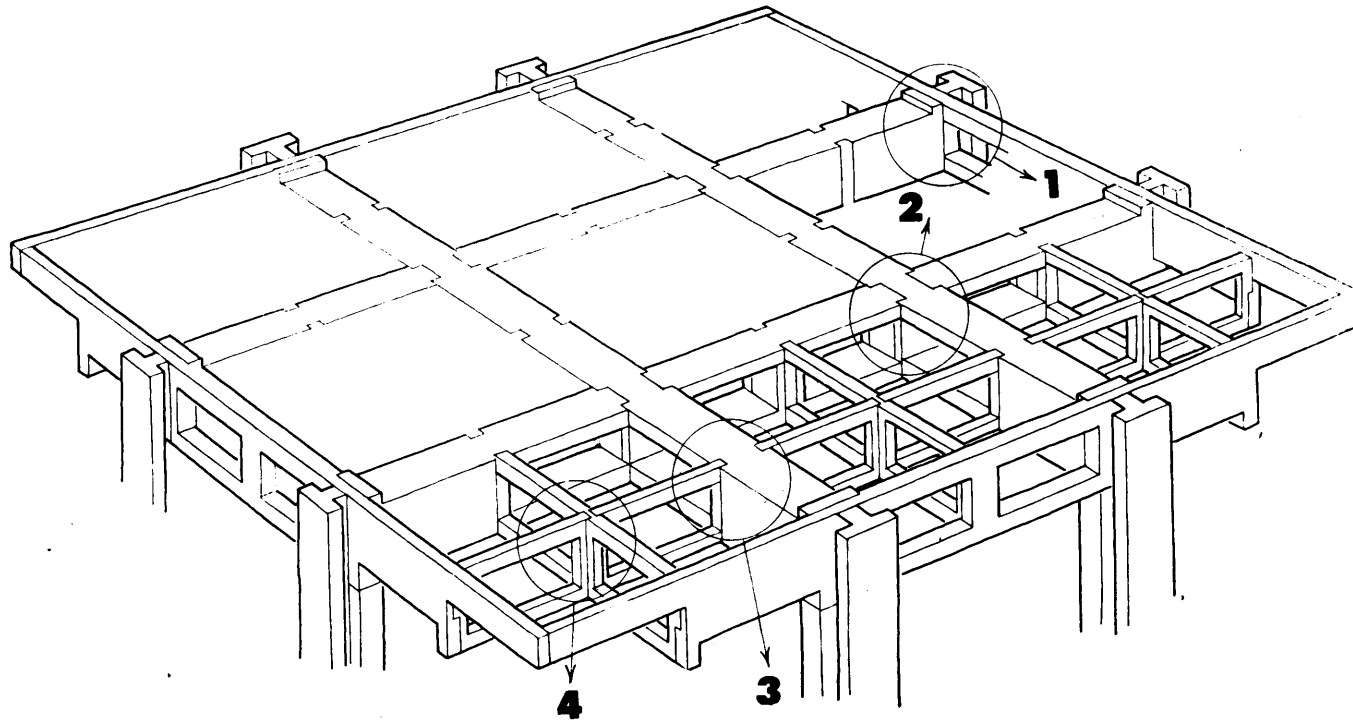


Raising of the prefabricated  
structural members  
Crystal Palace, London 1850

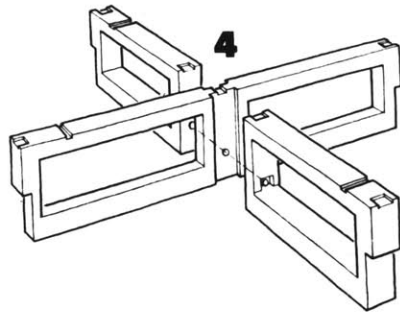
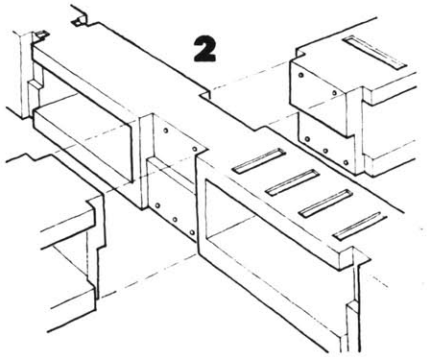
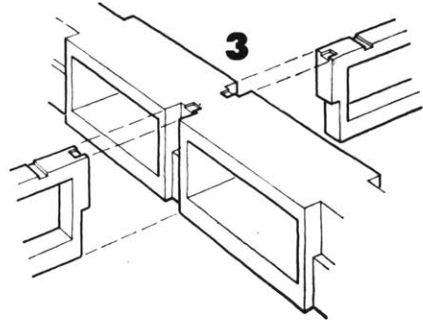
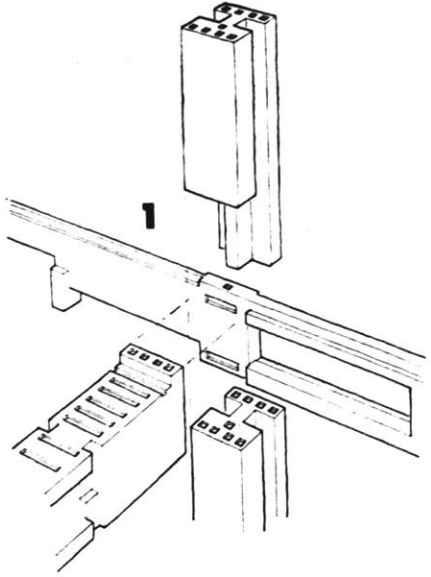




Hangar near Orbetello, Italy by Pier Luigi Nervi 1939



Structural Slab System      Medical Towers      by Louis Kahn 1961



## DESIGN PREMISES

The particular problem investigated in this thesis is defined as the design of a prototype building of a permanent nature to house research activities in the fields of science and technology. It is conceived as an integrated system of space, structure and services used for the development of scientific and technological ideas, furthering the exploration of space.

The design has to be based on:

1. maximum continuity of its divisible space.
2. modular division of the space. Planning module is 5'-0" based on minimum widths of corridors and rooms and on illumination requirements.
3. modular supply of services.
4. a total gross floor area of approximately 600,000 square feet in a first phase.
5. minimum area per floor 30,000 square feet.
6. a cohesive system for expansion of area as well as services has to be developed to allow the maximum number of possibilities for future growth of the building complex.
7. constant ceiling height on each level although floor to floor heights can vary.
8. demountability of some of its structural parts.

9. mandatory accessibility of all utilities.

The building design is approached as a total system of life, circulation, growth, change within itself (flexibility), spaces, structure, services etc.

As a first step a distinction has been made between systems of permanent and temporary natures.

Systems of permanent nature:

- a. air volume handled by the mechanical equipment for certain areas of the building remains generally constant.
- b. basic area lighting
- c. basic electrical installation
- d. communication (telephone, TV, pneumatic tubes)
- e. sanitary system
- f. vertical circulation i.e. elevators, stairs
- g. solar control

Systems of temporary nature:

- a. additional mechanical requirements for certain areas (e.g. laboratories with fume hoods)
- b. acoustical needs differing according to use of space
- c. partitions
- d. main horizontal circulation
- e. laboratory services such as gas, drainage, oxygen, vacuum

For the design of this building a system has to be found incorporating the structural skeleton, services and space requirements of normal and foreseeable conditions.

It has been the aim to clarify the different systems involved; the structural, mechanical, circulation, electrical, acoustical systems etc. Not all of the systems can work at its maximum efficiency since they influence each other, and impose limitations on each other-e.g. the modular system of partitioning demands a flat underside to the exposed structural floor slab, which does not vary with the different stresses acting on it. A hierarchy of systems has to be established in accordance with the particular needs and requirements minimizing the concessions of one system as related to the others.

## DESIGN SOLUTION

The building presented in this thesis is the result of an attempt to solve by rational and logical means, some of the problems facing architects today. It is hoped that it will provide a means and a direction in which to proceed towards an integrated structural and mechanical system that provides a maximum of flexibility of the building itself in terms of space, circulation and utilities, as well as the possibilities for future growth according to its particular needs. The building must allow for future changes of space and the introduction of new mechanical, electrical or circulation devices in order to reduce obsolescence in the future, a problem that is still largely unsolved in buildings of today.

Finally it is hoped that the design solution presented has an architectural expression that has meaning for today's society.



## STRUCTURE

A column spacing of 40' on center for the lower floors, and 80' for the top floor for special purposes requiring unusually large spans has been chosen. This suiting best the purposes of office display, laboratories and parking underneath. The structural system investigated is a two way system of an umbrella type using a basic factory cast linear channel like unit 35'-8" long and 5'-8" wide pierced with openings for ducts of a weight of 16 tons allowing easy shipping by standard methods. In a sequence of photographs at the end of this thesis a method is suggested of casting this unit in different parts and assembling it in the factory. The floor slab is completed with a prefabricated flat infill unit 4'-2" wide and 8" thick that is to be seated between the channel-elements taking in the tolerances, covered with precast plates and leaving open between them slots for posttensioning cables for the negative moments. The joints between the precast elements are filled with mortar and can then be posttensioned. The forces in the joints are of a magnitude that welding can be omitted. For the 80' span slab the same elements are used. The joints between the channel elements in the longitudinal direction correspond with the zero point in the moment diagram, i.e. the stresses in the critical joints are at a minimum.

The resulting floor system is a two way orthogonal grid with a network of perforations in the vertical members. The effective depth is 4' 3" including the 2" topping slab that has a secondary structural role as shear connection. Groups of units are posttensioned in a direction at right angles to the pretensioning at 5' centers, resulting in a continuous slab over spans of 40 feet (or 80 feet on the top floor) with cantilevers of 20 feet each way.

The cantilever of 20 feet is not the best structural condition for a continuous slab as related to the column spacing, as this would lie somewhere near one third of the span, but it allows a disposable office space between the column and the window line of 14' 2" as an optimum dimension. It also has advantages for the growth of the building as is explained later. The negative moments are dominant in this structure which is advantageous for posttensioning because the cables can easier be controlled in the open slots on top of the slab.

The actual spans have been reduced by introducing diagonal members of the height of the slab projecting from the column points to the opposite corner of the modular slab unit. They act in compression and provide a direct support for that corner. Thus the structural behavior of the element is a continuous beam supported on points alternating 15 feet and

25 feet apart. Not only are the stresses in this way reduced but it also minimizes the additional reinforcements for transportation and erection as is necessary for members acting primarily in the negative moment zone.

The columns have the size of a 5' x 5' module with massing of concrete at the four column points; they consist of four identical precast elements joined by welding. The columns are hollow to allow the passage of mechanical services, fume hood exhausts and the roof drains.

Cores which have their own slab system are spaced in a regular pattern throughout the building, in such a manner that the maximum distance from the building perimeter to the core does not exceed 150 feet (Requirement of Building Code). Within the cores are the main air risers, plumbing and laboratory services, electrical, telephone and janitors closets, toilets, public phones and vending machines. Stairs are included in all cores, elevators in each alternating one in a checkboard manner and of the remaining three, two incorporate toilets and the third a freight elevator.

## MATERIALS

Precast concrete was selected in lieu of poured in place because of the following advantages:

1. erection speed is greatly increased.
2. economy in moulding especially for complicated shapes which best facilitate the passage of mechanical equipment.
3. economy in scaffolding on the site by using elements of considerable length.
4. production of precast parts in factory is on a 24 hour basis and independent of weather conditions (frost)
5. factory control of materials, placement of reinforcement, steamcuring, use of higher quality cement assures higher quality and better surface control.
6. quantity of concrete and mortar used on the site is greatly reduced resulting in a cleaner and dryer building process.

There are also disadvantages inherent in this method but for the problem presented here they are of minor importance: The precast units have to be handled repeatedly and transported to the site with all of its structural implications. Also the connections between the precast parts have to be

carefully executed since they must provide perfect continuity in the finished structure as in a monolithic cast-in-situ structure.(2)

## METHOD OF ERECTION

The erection sequence is in very general terms:

1. footings, basement, retaining walls.
2. cores erected independently of floors, e.g. with slip form system.
3. placement of columns of one floor height.
4. temporary supports across units.
5. placement of channel elements to serve as a working platform for the placement of the smaller infill units.
6. filling of all compression and tension joints between precast elements with mortar and for the top slab in addition welding of these joints because of the higher stresses.
7. posttensioning, first in the top chord of the beam, then in the bottom member. If the sequence was reversed, cracks might occur in the bottom member due to tension.
8. pouring of topping slab and grouting of post-tensioning cables.
9. repetition of procedure.

The footings determine the constant height of the building.

For future growth the foundations are calculated on a basis that allows them to carry only one additional floor on the

roof of the present building. This avoids very expensive overdimensioning of foundations for future vertical growth that might or might not occur.

The cores with their independent slab system are cast with slip forms and thus could be completed within a week, being ready immediately for installations (plumbing, mechanical risers, elevator work) and to carry the cranes eventually. The resulting saving in construction time is considerable - for the 16 story Pierre Laclede Building in St. Louis, Missouri have been saved by this method three months construction time (3).

Posttensioning can be performed with any of the proprietary methods, and adequate room is left for jacks and wedge plates. They determine the shape of the duct opening as can be seen in the detail section. The cables may be run in open slots which are later grouted by the topping slab or through cast in annular passages as indicated in the drawings.

The lift slab method has been investigated as a possibility for erection. But due to the required height of 2' 8" for the openings in the slab for ducts, plumbing and other services the total structural slab height results in 4' 3", which makes it relatively stiff and subject to high stresses during lifting (4).

MECHANICAL SYSTEM

There are two basic mechanical equipment rooms together with the air handling equipment rooms for the area served in the basement connecting each three cores in a row. From this level are directly served the two lower office and laboratory floors and the basement floors. Additional small air handling equipment rooms, one per each core, are located on the terrace level and serve the floor above. The mechanical ducts for the lower floors run in the columns and serve each a mushroom like area of 1600 square feet. This has determined the inner constant area of the column cross section as follows:

Supply air: 1 sq.ft. duct/1000 sq.ft. of area served

Return air: 1 sq.ft. duct/1000 sq.ft. of area served

(both low velocity)

Supply duct:  $4 \cdot 1.6 \text{ sq.ft.} = 6.4 \text{ sq.ft.}$

Return duct:  $4 \cdot 1.6 \text{ sq.ft.} = \underline{6.4 \text{ sq.ft.}}$

12.8 sq.ft.

Inner free column area:  $4'4" \times 4'4" = 18.8 \text{ sq.ft.}$

There is enough space left to carry fume hood exhausts in the columns to fans on the roof. These could not be carried up in the duct space of the cores since most of these hoods must be exhausted individually and can not be carried horizontally.



Lighting fixtures and air diffusers are incorporated in a sheet metal construction which is hung between the ribs of the precast structural system. The fluorescent tubes used are four feet long with four in every second bay arranged in a linear manner. Air is returned through the lighting diffuser units removing the lamp heat immediately and keeping the lamp environment at a temperature of maximum lamp efficiency producing 25% more light (5). Acoustical control is provided where necessary in the same unit, completely closing the module to the neighbouring ones. Daylight is provided by means of glazing around the perimeter. Both the top floor which is the largest one and the floor underneath the terrace level allow, in addition, skylighting of a large percentage of the floor area.

Partition positions are determined by the five foot structural module. Details were developed that allow for both negative and positive deflection of the structure without damage to the partition.

### FUTURE GROWTH

The future expansion of the building has determined in many respects the solution presented. The lower floors with 40 foot spans have been designed with the structural and mechanical systems worked out in a way that allows growth of parts of the area supplied by a core; whereas the top floor with its 80 foot column spacing is expected to grow only in large sections, involving always the construction of a new core.

On the lower floors the cantilever at the perimeter is half the span, thus allowing the addition of a new unit with the same size cantilever all around. The two cantilevers will be connected with a hinge, but not transformed into a continuous slab which would require introducing posttensioning cables in the existing structure and disturbance of the working personnel.

Since the mechanical installations are primarily of a permanent nature, requiring only certain readjustments for some areas, they are distributed regularly over the whole floor area. Therefore the modular 5' x 5' columns are used for vertical feeder ducts supplying a mushroom like area of 40 feet by 40 feet on the lower floors. Future expansion does not affect the neighbouring area for each new 40' x 40' area added is supplied again from the column supporting it.

The perineter of the building is supplied by induction units (high velocity supply) along the windows allowing adjustment of the room temperature to the special conditions prevailing there due to sun, wind, and heat loss through the windows.

The plumbing requirements and the laboratory services, however, are of a more temporary nature. Every change and reorganization demands a change of the plumbing. And so does expansion. Most of the areas requiring these services do not need daylight and are in the inner part of the building in the vicinity of the cores that determines the supply of these services from the cores. Additional space is left in the vertical shafts to install new services as might easily occur with the developments of the technique and the enlargement of the scope of activities.

Because the top floor expands only in large sections involving the construction of one or more cores, the areas are supplied by ducts directly from the core which is immediately above the mechanical room on the terrace floor. For plumbing and laboratory services the same conditions prevail as for the lower floors and the same system is used.

Finally the demand for growth of the building is reflected in the irregular shape with the unifying rhythm of the free-standing columns allowing future expansion wherever required without violating the visual order of the building.

NOTES

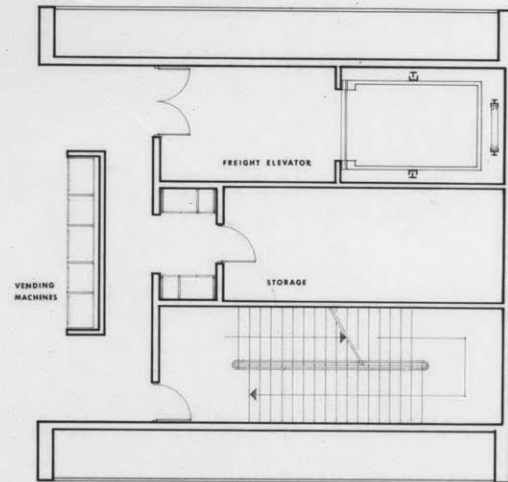
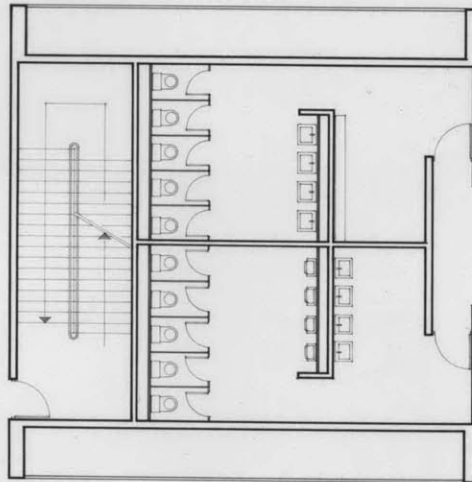
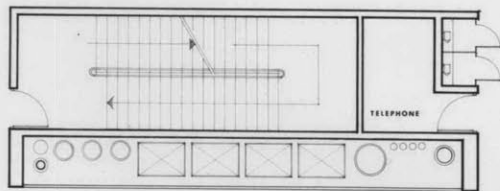
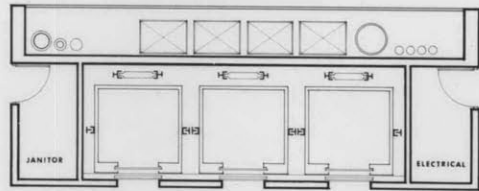
- (1) Pier Luigi Nervi: Preface to "The Works of Pier Luigi Nervi" F. A. Praeger, New York, 1957.
- (2) Kurt Billig: "Structural Precast Concrete" and F. Leonhardt: "Spannbeton für die Praxis" W. Ernst und Sohn, Berlin 1955.
- (3) S.Y.Greenleaf: Progressive Architecture, October 1963.
- (4) T.Y.Lin: "Design of Prestressed Concrete Structures" 2nd edition, John Wiley and Sons, New York 1963.
- (5) W.J.McGuinness: Progressive Architecture, July 1963.

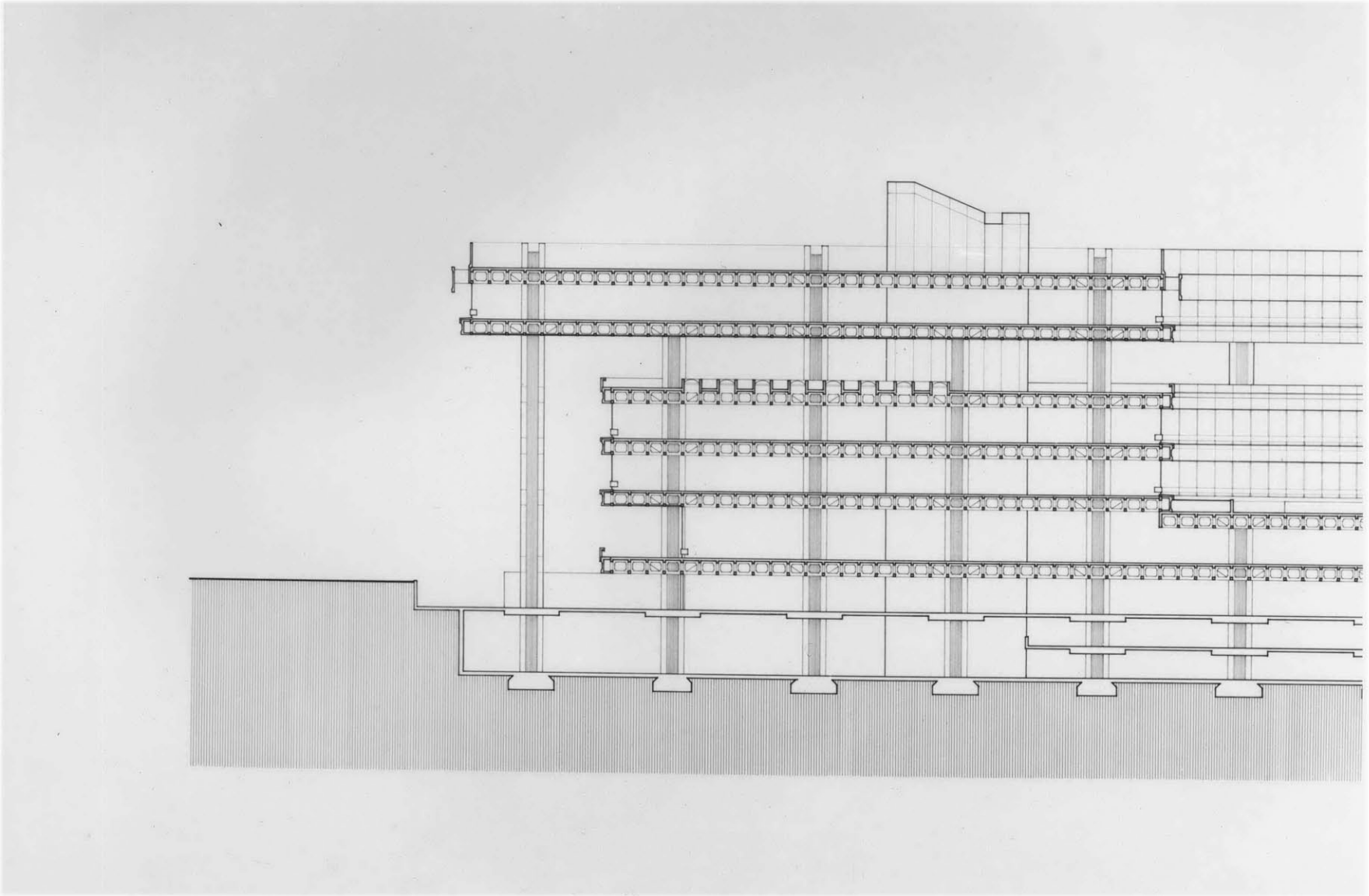
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<p>Six of this type were built during 1939-41 but all were destroyed in the war. Upper part of construction is of prefabricated reinforced concrete components.</p>	
Medical Towers by Louis Kahn	4*-5*
<p>Isometrics of structural floor system</p> <p>In one direction a pretensioned beam is used.</p> <p>By posttensioning in the other direction a two way prestressed floor system is achieved.</p>	

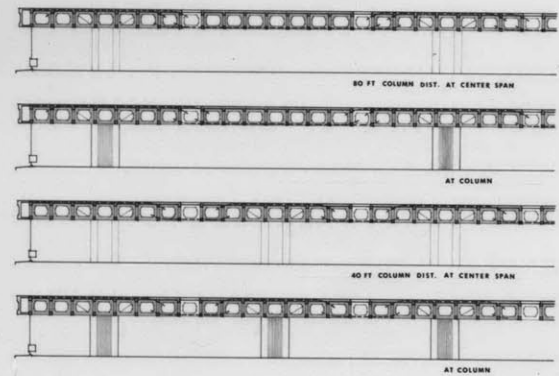
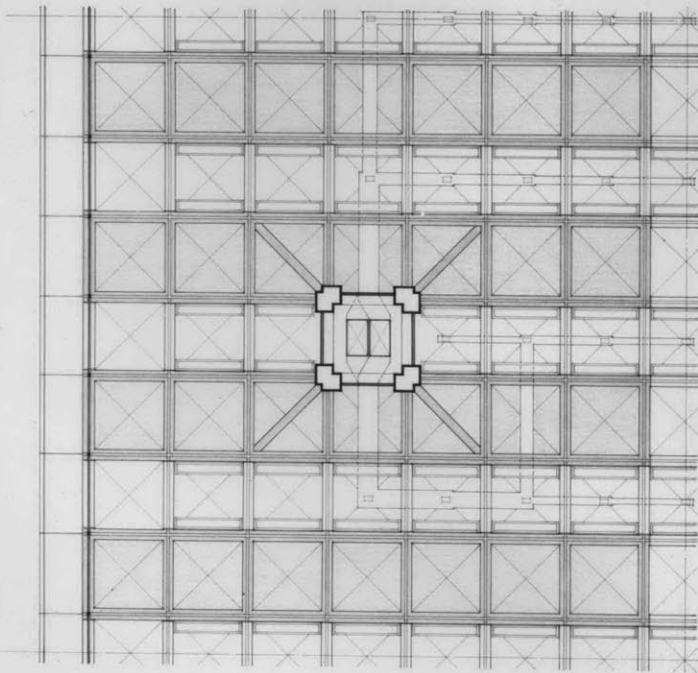
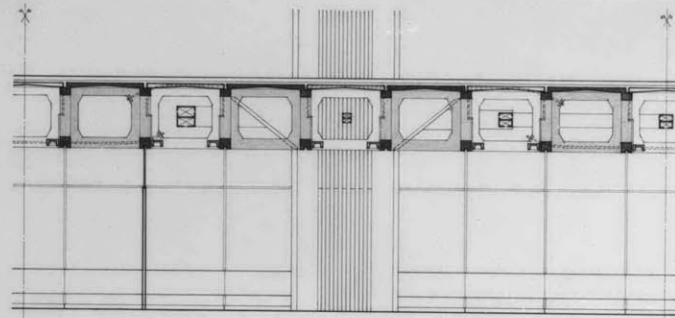
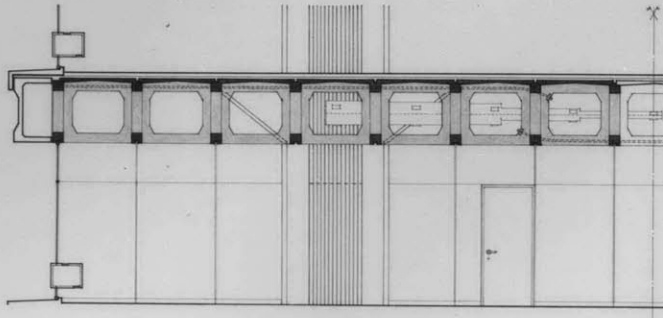
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DISPLAY OF POSTTENSIONING CABLES