RICE UNIVERSITY

A LONG-SPAN CABLE NETWORK STRUCTURE:
An investigation of the relationship between space - structure - form in Architecture

by

Dimitrios Mikos

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ABSTRACT

A LONG-SPAN CABLE NETWORK STRUCTURE:
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space - structure - form in Architecture

Dimitrios Mikos

This study is based on an investigation into the relationship 
between space, structure and form in architecture. It is divided 
basically into three stages.

In the first stage, I attempt to review and to clarify general 
arrestural and structural ideas from the point of view of the 
composition of three basically different functions each of which would 
require, by itself, a structure of bridging long span. This stage of 
my research includes "problem No. 1" and "problem No. 2".

In the second stage, architectural and structural problems are 
discussed which spring from the specific functions of a Natatorium, 
an Auditorium or a Gymnasium of the given scale. This stage includes 
"problem No. 3" of my research.

The third, or last stage, includes a survey of various long-span 
possibilities, and the selection and development of a prototypical 
example that most directly, simply, and clearly houses the various 
functions. This resulting long-span cable network structure serves 
as a demonstration of the relationship between space, structure, and 
form.
A LONG-SPAN CABLE NETWORK STRUCTURE:

An investigation of the relationship between space - structure - form in Architecture.
DATA:

A NATATORIUM for 500 - 1000 people

an AUDITORIUM for 2500 - 3000 people

and a GYMNASIUM

for Rice University

on the Rice Campus.
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INTRODUCTION

In this introduction I try to give my views on how an architect should approach an architectural subject; views which strongly influence all the progress of my work. Also in this part I present the problems and give some explanations about the use of "data" in our specific case.

Embarking on the study of a given architectural subject, I think that an architect has to review and to clarify his own architectural ideas and beliefs. Also, if it is possible, he has to find out and to classify the general problems which he foresees that he may encounter during the progress of his research.

I think the clearing and classification of architectural ideas and problems from the beginning constitutes the main guide of the architect. Simultaneously, it keeps him away from dangerous and basic wrong steps on his responsible and multilateral work.
Architecture is not simply a toy between "I like it" or "I don't like it". If that were the case anyone could practice architecture or be an architect. I believe that architecture is the "choice" between possibilities; that is "I prefer it to that one for these reasons". This preference springs from (or is the result of) a deep recognition and understanding of the various architectural values, problems or data.

In accordance with these ideas I will proceed to a completely general and theoretical facing of problems, which as I think are the common problems of every composer or structural architect or more generally of every architect.

In our given case, the dominant and fundamental problems from which the rest of the problems arise are:
Problem No. 1
"The composition of three basically different main functions".

Problem No. 2
"The special factor of three basically different large, clear, uninterrupted span functions requiring long span structure".

Problem No. 3
"Special functional or structural problems or more general problems which arise from the "data".

Finally, I will present as a demonstration the practical results of all the above in the form of a working structure.
Before proceeding in the development of my subject I believe that it is expedient that I clarify something very significant, the point of view from which the entire study has been confronted.

Perhaps the simplicity - some might call it the "imperfection" - of the data already has created the first question in the mind of the reader. Probably he expected a very complicated and massive program for a work of this scale. Instead he finds only several basic "data". So as to put aside every question of this type from the very beginning I am obligated to explain that this research was developed as one part of the general investigation into the relationship among "Space, Structure and Form". In this line of research special emphasis has been given to "structure" as an element of materialization of the given space. This structure basically also gives the "final form". The "data" have not been given as a total of information and facts which will guide us in the finding of "a space". Instead they are given as information and
fact which will guide us in the finding of a "given space". This "given space", in turn, will constitute the "datum" on which the research of the structure is based. This constitutes the main subject of our study.

The result of the above is the fact that "functionally" the subject has been faced theoretically and from the point of view of selecting a "diagrammatic architectural solution" I might say. This "diagrammatic solution" constituted the basis of the further research of the structure. That is the "data" constituted elements of determination of a "diagrammatic functional space" which in turn constituted the "datum" of the study of "structural space".
Problem No. 1.

In "problem No. 1" is faced the problem of the composition of two or more main functions completely different from each other. The purpose of this chapter is to find all the possible directions of composition and to investigate the general advantages and disadvantages which appear in each of them. For a better understanding and approach to the problem we introduce two terms: the term "functional space" and the term "structural space".

The term "composition" is a very common term to many arts and sciences. Melodies, sonatas, symphonies (musical compositions); Poems, essays, novels (compositions of ideas); Glossology (linguistic compositions); Buildings, gardens, cities (architectural compositions) and many others use it. Basically, the term composition always contains the meaning of creation of a comprehensible unity.

We could characterize as a "composition" the combination of elements of the same quality in order to obtain the appropriate total which will serve a pre-determined need or a pre-determined
number of needs, spiritual or material, intangible or tangible, psychological or physical.

In architecture, the term "composition" is a frequently used one. Architectural compositions may be subdivided into two characteristic categories:

- functional compositions ($\mathcal{F}$)
- functional + structural compositions ($\mathcal{D}$)

Functional compositions ($\mathcal{F}$) we shall call those compositions in which not all the composite parts connect together structurally. Only functional reasons dominate and give the final total shape to compositions of this type.

Functional + structural compositions ($\mathcal{D}$) we shall call those compositions in which all the composite parts do connect together structurally.

In architectural compositions relationships of the following form are possible:
\[ (1) \quad \gamma_a = \delta_1 + \delta_2 + \delta_3 + \ldots + \delta_n \quad \text{when} \quad n \gg 2 \]

It is never possible for relationships like (2) or (3) to exist.

\[ (2) \quad \gamma_a = \delta_1 \]

\[ (3) \quad \delta_n = \gamma_1 + \gamma_2 + \gamma_3 + \ldots + \gamma_n \]

The first one, that is (2), is not valid because it is impossible for all the parts of a composition both to connect together structurally and not to connect together. Either the first happens or the second.

Because of the fact that the second relationship, that is (3), is not valid we can understand graphically as follows:

A functional composition is always a composition of figure 1.

A functional + structural composition is always a composition of figure 2.

The graphic expression of relationship (3) is presented in the figure 3. But fundamentally its shape is as the shape of figure 3.
Consequently a relationship of a form such as (3) basically cannot exist.

Commonly it is possible to find relationships as follows:

\[(4) \quad J_a = J_1 + J_2 + J_3 + \ldots + J_v \quad \text{when} \quad v > 2\]

\[(5) \quad \delta_a = \delta_{a_1} + \delta_{a_2} + \delta_{a_3} + \ldots + \delta_{a_v} \quad \text{when} \quad v > 2\]

that is, we can have functional or functional + structural compositions as a total correspondingly of other functional or functional + structural compositions. We must emphasize that relationship (5) in some cases may be valid and in other cases may not.

An interesting point is the research of scale to the previous relationships (1), (4), and (5).

Relationship (1) is to be found in architectural compositions which start on the scale of little groups of buildings and end in works of urbanism scale. From compositions of small units for
camping, where each unit serves no functions beyond those of sleeping and elementary protection against hard weather conditions to big compositions, urbanism groups, it is possible to meet this relationship (1).

An enlargement of relationship (1) is the relationship (4).

In contrast relationship (5) is a diminution of (1). It starts from the scale of the most elementary architectural work in order to end at the scale of composition of small building groups.

An interesting problem of architectural compositions is the making clear of the reasons imposed by them each time, and the finding and classification of advantages which you must expect from them or the functions to be served through them.

Such a classification of the reasons which impose the composition accommodates the architect in his final component work.
Generally these reasons can be divided into two main categories:

Economic reasons.

Special functional reasons.

In the first category belong reasons such as the common service of common use space such as parking places, entrances, probable reduction of expense of materials, reduction of cost because of consumption of quantity of material.

In the second category belong reasons which are imposed by the nature of the functions of the building.

Every material creation of man presupposes the serving of some function and, in order to be expressed, requires a structure.

The organization and composition of the functions to be served by a certain material creation give the opportunity to its
composer to develop an intelligible shape for it. Let us call this intelligible shape "functional shape". The structure or structures through which the creation will materialize give another shape which is directly dependent on the material used and on the manner in which it is used in the structure (structural system); This is the "structural shape".

In a correct creation the "structural shape" must completely cover or must be identical with the "functional shape" and must never cover only a part of it (figure 4). That is, the structural system or the structural systems and the material or materials which will be used for service of functions must completely serve all the functions without overlooking or ignoring any of them (covering of "functional shape").

Let us give an example for better comprehension of the above. Let us take a very common article such as a spoon. The making of a spoon presupposes:
- The transport of a small quantity of material, either solid or liquid.
- A comparatively light weight for easy carrying.
- A form which will facilitate stable and easy holding.
- A form which will permit an easy approach to and contact with the mouth.
- A form and a material which will permit the transfer without the strong consequences of the thermal difference of the carried materials.

All of these functions give to the creator the possibility of formation of the "functional shape". The "structural shape" must have at least the possibilities of service of the "functional
shape" if not more. If it does not include the possibilities of serving of the previous properties it must be rejected; otherwise the "functional shape" cannot exist. For example, if the spoon is so heavy because of the material used that it cannot be carried easily, or if it is so flat that a certain amount of material cannot be transported, it ceases to be a spoon.

Specifically when we are discussing the above in architecture we can identify the term "functional shape" with the term "functional space" and the term "structural shape" with the term "structural space".

"functional shape" ≡ "functional space"
"structural shape" ≡ "structural space".

"Functional space" is derived from two different categories of functions:
the biological functions
the symbolic functions.

Biological functions (or tangible functions or mechanical functions) we will call the total of all the functions which serve the materialistic needs and demands of man.

Symbolic functions (or intangible functions or spiritual functions or mystical functions) we will call the total of all the functions which serve the psychic and spiritual needs of man.

"Structural space" is derived from two elements; from the material or materials used and from the manner or manners in which it is used in the structure (structural system or structural systems).

Corresponding to the term "functional space" we could have the term of:
"biological space"

and "symbolic space".

We can express all the above as follows (relationship (6)):

\[
\begin{align*}
\text{biological space} & \rightarrow \text{functional space} \\
\text{symbolic space} & \rightarrow \text{architectural work} \\
\text{structural system} & \rightarrow \text{structural space} \\
\text{the material used} & \rightarrow \text{structural space}
\end{align*}
\]

The biological and symbolic spaces enter into the formation of "functional space" with variable changeable percentages. These percentages depend on the kind of architectural work, on the degree of civilization, on the spirituality and the sensitivity of the creators.

Also with the passage of time and continuous repetition, in many cases "symbolic space" degenerates into a "biological space"
and it gets away from its symbolism, retaining only some exterior sign or name which reminds one of its origin.

A strong example of the above is the Greek word "Εστία". In its original meaning "Εστία" means fire (outdoors or in a cave). Men would congregate around it to warm themselves, to talk, to eat, to become friends and to sleep. With the passage of time and with the progress of civilization, man started to build shelters. At this stage, according to the research of ruins, they put this fire (or "Εστία") at the center of the house as a symbol but also to serve as a function. Finally with progress through the years this fire changed locations, was eventually replaced and, therefore, lost its importance even as a symbolic function. But, by then, the space where it was originally located took its name. Today "Εστία" is the name for residence and also the term for family home.
Let us section a pyramid and apply all the previous, simultaneously making clear the terms. (figure 5).

We can notice that biological reasons (and especially anthropometric reasons), determined the minimum dimensions of the main spaces and corridors. Symbolic reasons determined the kind, the number and the connections of spaces. Also symbolic reasons and in addition reasons of safety (biologic reasons) determined the space $\beta$ (a space which would remove and isolate the dead body from the living). Structural reasons gave the final form and in part the dimensions of the architectural work. "Symbolic" permanence.

Previously (page 21) we clarified the meaning of the terms "biological functions" and "symbolic functions" in a manner directly dependent on the kind of needs as is actually the case. Starting off from these same needs let us try to find relations and expressions of the previous ideas which will help us in the further development of our subject.
From relationship (6) and from the classifications of "biological functions" and "symbolic functions" we can conclude that the final form of a "material work" is the result of the balance of needs (\(N\) - which gives the possibility of formation of "functional space") and structure (\(S\) - which gives the possibility of formation of "structural space"), (figure 6); that is:

\[ |N| + |S| = \text{final form} \]  

(7)

and \(\bar{N} + \bar{S} = 0\)

The needs of man, according to the previous, can be classified into two categories:

\(\alpha.\) materialistic or tangible human needs (\(\eta\))

\(\beta.\) psychic and spiritual or intangible human needs (\(\rho\))

\[ |n| + |p| = |N| \]

(8)

\[ \bar{n} + \bar{p} = \bar{N} \]
An architectural work as a "material work" is subject to the above rules, as is any work of sculpture or painting. In sculpture or in a painting:

\[ |n| = 0 \]

thus

\[ |p| = |N| \quad \bar{p} = N \]

that is, they serve psychic and spiritual human needs and only that.

As man places at the entrance of his cavern a heap of stones, he takes the first step in architecture: he tries to form space which will serve his tangible needs. A little later he serves these same needs with the cottage knitted with branches and wood, and also with the underground dwelling. Tangible needs and only tangible needs are served by the architecture of the Eskimo in using blocks of snow. In the previous we can notice that:
(11) \[ |p| = 0 \]

thus

(12) \[ |n| = |N| \quad \bar{n} = \bar{N} \]

In the primitive architecture the following relationship is clearly valid:

(13) \[ \text{purpose} \rightarrow \text{means} \rightarrow \text{result}. \]

\[
\begin{align*}
\text{purpose} &= \text{the service of materialistic needs of the human being} \\
\text{means} &= \text{the structure} \\
\text{result} &= \text{the form}
\end{align*}
\]

Great intervals of time intervene.

The same or different needs - but always needs.

The same or newer materials.

Anyway newer structures.

Man continues to search for methods which will best serve his physical needs but simultaneously does not overlook his psychic
The column until yesterday was useful in order to receive a vertical load. Now man starts to work on it, to engage it to cut grooves in it. It remains a column, it is still useful to hold the roof which will form for man the space in which he will live, but simultaneously it satisfies a psychic and spiritual need. The first relationship ...

purpose → means → result

..... remains, but with a certain change;

purposes = primarily the serving of materialistic needs, but without ignoring the psychic and spiritual needs as long as the latter do not conflict with the former.

means = the structure.

result = the form.
The architect must have as his guide the purpose: the space which he visualized, or better still, the space which he visualized after a logical study of needs which are to be served by the space ("functional space"). With this purpose as his base he will search to find the means which suits this purpose best ("structural space").

\[
\begin{align*}
\text{purpose} & \rightarrow \text{means} \rightarrow \text{result} \\
\text{space} & \rightarrow \text{structure} \rightarrow \text{form} \\
"\text{functional space}\" & \rightarrow \"\text{structural space}\" \rightarrow \text{final form}
\end{align*}
\]

Let us make the arrangement of these three terms with the presupposition that: space = organized space. We will have the following chart:
Let us proceed to our main problem, the combination of two or more functional spaces, either different from each other or not. At first let us examine the theoretical possible combinations.

<table>
<thead>
<tr>
<th>architecture</th>
<th>purpose → means → result</th>
<th>SPACE</th>
<th>STRUCTURE</th>
<th>FORM</th>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>technological demonstration but not architecture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sculpture</td>
<td></td>
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</table>

consequently:
Let us call the different "functional spaces" $f_i$, the corresponding "structural spaces" $S_i$ and the structural systems which correspond to each "structural space" $\mathcal{F}_i$. We will have:

\[
\begin{array}{cccc}
  f_1 & f_2 & f_3 & f_v \\
  \downarrow & \downarrow & \downarrow & \downarrow \\
  S_1 & S_2 & S_3 & S_v \\
  \uparrow & \uparrow & \uparrow & \uparrow \\
  \mathcal{F}_1 & \mathcal{F}_2 & \mathcal{F}_3 & \mathcal{F}_v
\end{array}
\]

(15)

Basically we discern three cases

- case $A$: $f_1 \equiv f_2 \equiv f_3 \equiv \ldots \equiv f_v$
- case $B$: $f_1 \equiv f_2 \neq f_3 \equiv \ldots \neq f_v$
- case $\Gamma$: $f_1 \neq f_2 \neq f_3 \neq \ldots \neq f_v$

(16)

Reasons of logical consequence impose to compositions of spaces which belong to the first two cases, that is case $A$ and case $B$, the relationships:
\[ S_1 = S_2 = S_3 = \ldots = S_v \quad \text{(case A)} \]
\[ S_2 = S_2 \neq S_3 = \ldots \neq S_v \quad \text{(case B)} \]

It is natural in compositions of similar "functional spaces" \( f_i \), to have similar "structural spaces" \( S_i \). Results of the previous relationships (17) are the relationships (18).

\[ \mathcal{I} = \mathcal{I}_2 = \mathcal{I}_3 = \ldots = \mathcal{I}_v \quad \text{(case A)} \]
\[ \mathcal{I}_1 = \mathcal{I}_2 \neq \mathcal{I}_3 = \ldots \neq \mathcal{I}_v \quad \text{(case B)} \]

The third case, that is case \( \Gamma \), has as a logical result the relationship (19)
\[ S_1 \neq S_2 \neq S_3 \neq \ldots \neq S_v \quad \text{(19)} \]

What though is the relationship of \( \mathcal{I}_i \) in this case? We can distinguish three cases:
\[ \mathcal{I}_1 \neq \mathcal{I}_2 \neq \mathcal{I}_3 \neq \ldots \neq \mathcal{I}_v \quad \text{(case \( \Gamma_a \))} \]
\[ \mathcal{I}_1 \neq \mathcal{I}_2 = \mathcal{I}_3 \neq \ldots \neq \mathcal{I}_v \quad \text{(case \( \Gamma_b \))} \]
\[ \mathcal{I}_1 = \mathcal{I}_2 = \mathcal{I}_3 = \ldots = \mathcal{I}_v \quad \text{(case \( \Gamma_v \))} \]
In essence, it is possible to amalgamate cases $\Gamma_a$ & $\Gamma_B$ into one. We can present all the previous cases as follows:

\[ \begin{align*}
\Gamma_a \quad & \quad \downarrow + \downarrow + \downarrow + \cdots \downarrow \quad \rightarrow \quad \text{Figure 7} \ (\Gamma_a, \Gamma_B) \\
\Gamma_B \quad & \quad \downarrow + \downarrow + \downarrow + \cdots \downarrow \quad \rightarrow \quad \text{Figure 7} \ (\Gamma_a, \Gamma_B)
\end{align*} \]

when
\[ \begin{align*}
& \mathcal{J}_1 \neq \mathcal{J}_2 \neq \mathcal{J}_3 \neq \cdots \neq \mathcal{J}_v \\
& \mathcal{J}_1 \neq \mathcal{J}_2 = \mathcal{J}_3 \neq \cdots \neq \mathcal{J}_v
\end{align*} \]

and

\[ \begin{align*}
\Gamma_y \quad & \quad \downarrow + \downarrow + \downarrow + \cdots \downarrow \quad \rightarrow \quad \text{Figure 8} \ (\Gamma_y^x) \\
\Gamma_y \quad & \quad \downarrow + \downarrow + \downarrow + \cdots \downarrow \quad \rightarrow \quad \text{Figure 8} \ (\Gamma_y^x)
\end{align*} \]

when
\[ \begin{align*}
& \mathcal{J}_1 = \mathcal{J}_2 = \mathcal{J}_3 = \cdots = \mathcal{J}_v
\end{align*} \]
In the first two cases, that is cases $\gamma_a$ and $\gamma_\beta$, the following disadvantages and advantages appear:

- Difficulty in the combination and connection of different structural systems and consequently difficulty in the connection of functional spaces. (Usually disadvantages of functional + structural compositions).
- An abundance of structural problems, all different.
- Final form usually complicated.
- On the contrary with all the above disadvantages the cases $\gamma_a$ and $\gamma_\beta$ permit the finding of ideal structural space $S_i$ for each functional space $f_i$, an advantage which sometimes in case $\gamma_i$ falls short.

The third case (cases $\gamma_{\gamma I}$, $\gamma_{\gamma II}$) presents the following general advantages and disadvantages:

- Limitation of structural problems to a minimum (because of the repetition of the same structural system).
- Easy structural connections of functional spaces.
- Incomparably clearer form in comparison with the previous two cases.
- In contrast, a disadvantage is that at certain times the tendency of repetition of the same "structural systems" leads to not finding the ideal "structural space" for each "functional space".

Comparing the two sub-cases of $\gamma$ we notice that:

- $\gamma_2$ presents a much clearer final form than $\gamma_1$.
- On the contrary, the form $\gamma_1$ is more easily adaptable to functional needs.
- And, in addition, it expresses strongly and characteristically the function of spaces.

Characteristic of the above is the absence of scale, or better, the generality of scale. Theoretically one faces the same previous
problem whether he composes "structural spaces" on the scale of a small residence or he composes on the scale of larger groups of buildings. That is, I mean that you have to face the same quality of problem, whether trying to connect a wooden balcony to a small brick house or trying to connect a metal skeleton to a concrete shell structure.

Generalizing the problem even more we can say that qualitatively the same series of problems is faced by any composer (or builder) even of the smallest object which is supposed to serve human need.

Summary:

After a short discussion of the term "composition" we proceed to the research of architectural compositions. We divide them into two categories: "functional compositions" and "functional + structural compositions", and we express some equations regarding the relation of these two categories. At this point we introduce the
terms "functional space" and "structural space" as component elements of an architectural work. We explain these terms and then proceed to the research of combinations of "functional spaces" with the corresponding "structural spaces" through an algebraic approach. Finally we mention both the advantages and disadvantages of each of the general directions of composition which we had reached.
Problem No. 2.

In "problem No. 2" we try to find the general categories of structures presenting the possibility of being bridged over a long span. The finding of these categories of structures determines the field in which we must investigate the appropriate structure for the covering of our functions which, as is well known, are functions which require long span structures.

Prof. H. Seymour Howard, Jr., in his book "Structure, an Architect's Approach" defines the structure (in the place of architecture) as follows: "Given a space or series of spaces, delimited by given elements (such as columns, walls, and floors of given materials), the parts which receive the forces acting on these elements and absorb or carry those forces down to some level within the earth are called the structure".
Generalizing the concept of structure beyond the narrow limits of architecture we could call "structure" the total of the bearing or main parts of a composition or generally of a creation, and the metrical relationship or simply the relationship among them.

Every structure \( A \) is possibly a total of secondary structures, that is, there may be relationships of the following form (23).

\[
A = a_1 + a_2 + \ldots + a_n
\]

where

\[
(23) \quad a_i = \beta_1 + \beta_2 + \ldots + \beta_{\mu}
\]

where

\[
\beta_i = \gamma_1 + \gamma_2 + \ldots + \gamma_\mu
\]

\[
\ldots
\]

\[
\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
Every material creation contains within itself a structure and its form partially is the result of this structure. Human creations as well as the creations of nature are subject to this rule. Previously we had mentioned that the architectural structure is always the result of structural system and material. Structural system we will call the geometric relationship of bearing members of an architectural composition.

We can distinguish structural systems into two groups:

"closed structural systems" and
"open structural systems".

We will call "closed structural systems", those structural systems which, when they reach a certain predetermined form, cannot grow more. Most shell structural systems bridging large spans are
"closed systems" (figure 9).

We will call "open structural systems" those structural systems which present the possibilities of growth even in their latent form. Common structural systems of this category are structural units that are repeated. (figure 10).

The research of "open structural systems" and especially the manner of their growing is very interesting.

We distinguish two basic ways of growth:

the additional growth and

the biological growth.

Additionally grown structures we will call those structures in which growth occurs by the addition of new structural elements. Examples of such growth are the common rectangular structures of metallic skeleton.
We will call those structures biologically grown structures in which growth occurs by the expansion or generally by the rearrangement of the same original structural elements. Examples are the way that animals or plants grow.

In order for us to proceed to a separation of structures let us see first how this classification is faced by the various researchers.

Curt Siegel in his book "Structure and Form in Modern Architecture" researching special structural problems classifies them into two fundamental categories:

Skeleton construction.

Space structure.

In the first category he has placed structures with rectangular, metallic or concrete skeleton. In the second category he created four sub-categories in which were included all the rest of the structures:
a. Space frames. (These are composed of a large number of members which members are stressed axially only (in tension or compression) and which are braced against each other in a three-dimensional system.)

β. Folded plates. (These are plates the strength of which derives from the stiffness of the folds and in which the elementary slabs are stressed in tension, compression and shear in their own plane and in bending in a direction at the right angle to this plane.)

γ. Shells. (These are thin, curved surfaces in which, in the ideal case, the stresses are limited to normal stresses and shear, bending being excluded.)

δ. Suspended roofs. (These are formed of cables, steel nets, fabric or thin sheet. They are stressed exclusively in tension.)

Mario Salvadori in his book "Structure in Architecture" classifies the existing structures in the following categories according to the kind of stresses which each of them can sustain and according
to the way of carrying of loads:

a. Tension and Compression Structures.
(cables - trusses - Funicular Arches - cable roofs - space frames).

b. Beams.
(cantilevered beams - simply supported beams - fixed beams -
continuous beams).

γ. Frames and Arches.
(simple frame - multiple frames - gabled frames).

ζ. Grids, plates and folded plates.
(load transfer in two directions - Rectangular beam Grids - skew
grids - plates - ribbed plates - folded plates).

ε. Membranes.

ζ'. Thin shells.

An interesting classification of structures, based on completely
different criteria than those of the previous researchers, is pre-
presented by Prof. H. Seymour Howard, Jr. He classifies structures in
four categories:

a. Minimal structures (Structures which use the least amount of material).

β. Adequate structures (Structures in which material is not used efficiently, much of it being utilized below its maximum load bearing capacity).

γ. Formal or Sculptural structures (Structures whose elements are exaggerated or whose forms reflect a non-efficient use of material just for sake of emotional impact).

δ. Pretentious Structures (Structures for structures' sake).

The diagrammatic classification of structures which Frei Otto presented in October 1962 at the World Conference on Shell Structures is worthy of note and has a character all its own. Each structure is presented in relation to the quantity of material which is expended, the kind of stress which it receives, and the texture of structural material. The final form of the diagram is somewhat
Some of the most characteristic classifications of structures have been mentioned thus far. One notices that each researcher classifies structures according to his own ideas and in a manner which will make easy the development of the rest of his subject. I think that the form of our problem and the consequence of general spirit of this research impose a classification according to the manner in which each of these structures is sustained. In accordance with this principle we discern the following structural categories:

1. Structures which receive simple tension only.
   Cables - membranes - cable roofs.

2. Structures which receive simple compression only.
   Funicular arches.

3. Structures which receive simple tension or simple compression only.
   Space frames - trusses.
4. Structures whose elementary surface receives simple stresses (tension or compression) or shear, bending being excluded. Shells.

5. Structures whose elementary surface is able to resist tension or compression and shear on its own plane and bending in a direction at right angle to this plane. Folded plates.

6. Structures which can receive different, simple or complicated stress, according to their form, according to the point of the bearer, about which we are talking, according to the manner of subsistence and according to the position of the bearer in relation to the vertical direction. Plates, frames, arches, etc.

The first five categories contain structures with possibilities of bridging large or generally substantial spans. The last category contains the common small-structures and generally does not have the
possibilities bridging significant spans.

Before I proceed to our next problem, I think that it is very useful to create the following chart in which is presented the relationship between structures and the corresponding stresses of structures bridging large spans (that is the first five categories).

<table>
<thead>
<tr>
<th>Kind of stress category of structure</th>
<th>simple tension</th>
<th>simple compression</th>
<th>shear in the surface of the structure itself</th>
<th>shear perpendicular to the line or the surface of the structure itself</th>
<th>bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. categ.</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2. categ.</td>
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<tr>
<td>3. categ.</td>
<td>+</td>
<td>+</td>
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<tr>
<td>4. categ.</td>
<td>+</td>
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</tr>
<tr>
<td>5. categ.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
We note that generally all of these structures bridging large spans basically receive a limited number of categories of stresses.

This is mainly the result of the choice of appropriate form and is aided significantly by the material chosen.

Finally we must emphasize that when we say a category of structures receives a certain type of stress only it is not supposed that various other types of stresses do not develop secondarily or locally at certain points of the structure. Generally, the role of these stresses in the total structural function is secondary and it is possible to ignore or to get around them.

Summary:

At the beginning of this chapter we define the terms "structure" and "structural system". We then proceed to the study of classification of structures as it is faced by various important and contemporary researchers such as Curt Siegel, Mario Salvadori,
H. Seymour Howard, Jr., and Frei Otto. Based on the data of previous researchers we classify long span structures according to the manner in which each of these structures is sustained.
Problem No. 3.

In "problem No. 3" we face the various special functional and structural problems which arise from the three main functions of natatorium, auditorium and gymnasium. In this chapter we choose the solutions (to the various problems) which we prefer to pursue and justify our choice of these solutions. Certain of these problems (especially the general and theoretical ones), have already been presented in the previous two chapters; others of a more specific nature are presented here.

1. NATATORIUM
   AUDITORIUM
   GYMNASIUM.

The above three functions concentrate two clearly different categories of people:

the acting people (actors, swimmers, or athletes)
the attending people (spectators).
In the first two functions, that is the natatorium and auditorium, basically there is a relation between two categories of people such as in figure 12.

The last function, that is the gymnasium, primarily contains acting people. Rarely it contains a very limited number of people for games only.

All the above leads us to a shape such as figure 13.

2. **NATATORIUM**
**AUDITORIUM**
**GYMNASIUM**.

If we symbolize:

- =action.
- =optical radius of the spectator.
- =useful space.

the above three functions can be presented as follows:
Figure 14

floorplan

cross-section

Figure 15

graphic form of cross-section
NATATORIUM

Figure 14. We notice that the nature of function's serving gives us a clearly "linear" action. Following such an action requires the "optical radius of the spectator" to be perpendicular or nearly perpendicular to this "linear" action. The result of this is that we must have a floorplan shape as in figure 14 and we should avoid placing the spectator into area c of the arena.

AUDITORIUM

We notice that in the case of the auditorium the form of action basically is of two different kinds. We can have "action of point" (figure 15) or "action of plane" (figure 16). In the first case (action of point) there is a clear separation between "acting people" and "attending people". In the second case (action of plane) the separation is totally obscure and the basic principle of composition is the abolition of separation between "acting people" and "attending people". At first the architect and, later, the director and actor
try to change the neutral attending people to secondary acting people.

GYMNASIUM.

Acting people only (figure 17).

3. NATATORIUM

AUDITORIUM

GYMNASIUM.

Let us try to find the minimum dimensions which we must have for each of the above functions.

NATATORIUM

According to the standards and our previous thoughts about the relation between "acting people" and "attending people" we must have for a 50 meter swimming pool with seating for 500-1000 people a space of 205'.135'.50' (spring board requires minimum 42' above water's level in order to meet the international standards). (figure 18).
To these dimensions you must add a significant space for several secondary functions such as showers, dressing rooms, rest rooms, locker rooms, rooms for special mechanical needs, etc., etc., etc.

From different examples which I have studied, I notice that this area of secondary functions is approximately equal to the main space (swimming pool + seating).

AUDITORIUM.

TIME-SAVER STANDARDS (page 268)

"Maximum seating distance. Even in theaters of 1200 to 1500 capacity the last seat is preferably not over 75 to 100 ft. from the stage and much less in smaller houses. When balconies are used the front of the balcony is preferably within 50 ft. of the stage".
ARCHITECTURAL GRAPHIC STANDARDS.
(theaters - live show - page 420).

**PROSCENIUM WIDTH**

- W:
  - 30'-40' for Drama
  - 40'-50' for Musical
  - 60'-80' for Opera

**PROVIDE**

- Foyer: 1 sq.ft. per seat
- Lobby: 1½-2 sq.ft.
- Lounge: 6-8 sq.ft.

Good seeing & hearing area

In practice, last row often goes clear across but nobody likes these seats
The auditorium about which we are talking is for 2,500 - 3,000 people. Having in mind the previous data in order to determine the magnitude of \( W \) (figure 19) we must solve the following equations.

\[
2,500.6 = 100.W_{\eta\eta} \quad W_{\eta\eta} = 150'
\]
\[
3,000.8 = 100.W_{\eta\max} \quad W_{\eta\max} = 240'
\]

In both cases we have a significant value of \( W \) (150' - 240').

The above suggests to me the thought that it is difficult to keep the value of \( W \) as a straight line. Perhaps we have to curve it around the "acting area". As an "acting area" I am thinking of three different smaller functions:

- the backstage
- the stage
- the place for the musicians.

Around these three functions I will place the "attending people" (figure 20 - figure 21).
GYMNASIUM.

From the study of different games and sports we notice the largest length which we must have is for football games and rugby:

' minimum length for football game or rugby 420' (with the free space behind the goals in the first one).

The largest width which we must have is for running track (if we want to keep the radius of curving within the rules):

' minimum width for a running track 260'.

The minimum given height which we have is for tennis courts 38'-40' but I think that for some throws such as javelin etc. perhaps we need more height as a minimum:

' minimum height at the very least over 40' (recommended about 50').

But it is also good to have another limitation if possible, the complete lap of the running track to be a simple fraction of a mile, that is 1/4, 1/5, 1/6 etc. Keeping the radius of curving the same (106' the radius of inside line of track) and changing the liner part
between two semicircles (figure 22) that is \( \alpha \), we must take the following values of \( \alpha \) for different lengths of a complete lap.

\[
\begin{align*}
\alpha_4 &= 323.85' \quad \text{for } 1/4 \text{ mile} \\
\alpha_5 &= 191.85' \quad \text{for } 1/5 \text{ mile} \\
\alpha_6 &= 103.85' \quad \text{for } 1/6 \text{ mile}
\end{align*}
\]

Correspondingly we will have different \( \beta \) in each case, that is

\[
\begin{align*}
\beta_4 &= 583.85' \quad \text{for } 1/4 \text{ mile} \\
\beta_5 &= 451.85' \quad \text{for } 1/5 \text{ mile} \\
\beta_6 &= 363.85' \quad \text{for } 1/6 \text{ mile}
\end{align*}
\]

I choose the \( \beta_5 \) because we must have a length more than 420' (for rugby and football games) but as near as we can to this certain number.

All the above give us the dimensions of this particular gymnasium which are 452'.260'.over 40' (recommended 50'). (figure 23).

Additionally we must provide some areas for equipment storage, shower rooms, locker rooms, rest rooms, etc., etc., etc. as we mentioned before.
Starting from the idea that the above three functions must constitute not only a functional composition but a functional + structural composition we can distinguish two fundamental directions of composing:

I. The three functions in a continuous air-conditioned space (figure 24 a,b).

II. The three functions in three different air-conditioned spaces under the same roof (figure 25 a,b).

All the above and also the classification of compositions which we made at the beginning of our research lead us to the finding of two other subcases in each of the above directions:

a. A structure distinctly outlining each function (figure 24a, 25a).

b. A structure more independent of each of these functions (figure 24b, 25b).
5. **NATATORIUM AUDITORIUM GYMNASIUM.**

It is preferable from the point of view of span - for structural reasons only - in the general composition, for the same area \((E)\) the maximum value of fraction \(\frac{\alpha}{\beta}\). (figure 26).

6. **NATATORIUM AUDITORIUM GYMNASIUM.**

Researching the needs for the height of each function we notice that these needs are not the same for each of them. Generally the above three functions have in common the requirement of spaces of significant height, but simultaneously the required heights are different for each function. Besides this, many times a special function of another more general one requires a particular height different from that of the general function. (example: the spring board space of the Natatorium).
We can present the needs of our composition for height as a diagrammatic cross-section of the form of figure 27. This is not a realistic reflection of the activities; it is just a fictitious cross-section for purposes of demonstration.

Trying to achieve the perpendicular organization of our composition we notice that basically there are three directions of organizing these needs. Each direction has as a result a completely different exterior and interior form.

Direction a:

Keeping the roof as a single (unique) and simple geometrical shape (curve or plane) thus servicing the needs for height by changing the levels of the floor - extreme case. (figure 28).

Direction β:

Keeping the floor unique (and because of its nature plane) thus servicing the needs for height by changing the levels of the roof - extreme case. (figure 29).
Direction $y$:

An intermediate solution by which both the level of the floor and the level of the roof can change according to the needs. (figure 30).

In our own case direction a was chosen and applied in order to organize the functions perpendicularly, that is, it has organized a "functional space" of the form of figure 31. We arrived at this decision after special research. Results of this research were that altimetric differences did exist but because of the significant dimensions of the work these differences in relation to the length and width of the work were trivial (42' minimum for natatorium, 40' minimum for gymnasium, 30' minimum for auditorium). Thus even if we tried to give a completely plastic form covering, closely collaborated with the interior functions and the requirements of height, again we would have arrived at a basically unique form, but with certain insignificant "facts" on it. The "structural space" which will be selected must correspond to the form of that "functional
space". More specifically in this case the correspondence or not of two spaces (that is, "functional space" and "structural space") must come from the structure and the form of the covering.

7. \textbf{NATATORIUM} \\
\textbf{AUDITORIUM} \\
\textbf{GYMNASium}.

The next fundamental problem which appeared was the basic category of the structures in which we would have to investigate the appropriate structural system. Already the Gymnasium presents the serious requirement of a surface of minimum 260' x 460' dimensions without any intermediate support. This in combination with the requirement of a single structural system for the entire project directs our research to structures bridging not simply "a large space" but "a very large space". The cable structures appeared to be the most efficient structural systems for this special case. (figure 32).

Having done all of this preliminary work and having investigated
PRESTRESSING PREVENTS FLUTTER OF CABLE ROOF

by Seymour Howard, A.I.A., Associate Professor, Pratt Institute
Municipal Auditorium, City of Utica, New York; Gehron & Seltzer, Architects; Frank Dello Ceso, Associate Architect; Lev Zetlin, Structural Engineer; Fred S. Dubin Associates, Mechanical and Electrical Engineer; General Sovereign Construction Co., Ltd., Builder

Steel has remarkable strength in tension so when roof spans must stretch beyond several hundred feet, steel cables surpass other systems in structural efficiency. The thing that has bothered engineers until very recently, however, is flutter. Cables—in contrast to other roof systems—have no inherent rigidity to dynamic loads. So one way or another they have to be stabilized against vibrations or noises caused by wind and other external forces—truck traffic, for example.

two sets of cables, stretched apart by means of spreaders, and thus prestressed by forces of 135,000 lb or more per cable.

Upper cables always have a different tension than the lower cables—first because the prestressing force is applied against cables of different sizes, and second, because any applied load will increase the tension in one set of cables and reduce it in the other. Thus the two sets of cables always have different natural frequencies. No matter what frequency the

("New Structures" by Robert E. Fischer).

Figure 32

THEORY OF CABLE ROOF CONSTRUCTION

(This portion of the booklet is also derived from material prepared by Mr. Gensert.)

A cable-roof structure employs an interesting principle: "Over wide areas the most economical steel span is a cable." Utilizing normal allowable working stresses and a 10 per cent sag for a suspended cable, a 36-in. wide-flange beam can carry its own weight for about 220 ft, while a steel cable can carry its own weight for approximately 3.3 miles.

A loose description of a cable-roof structure could be, "Any roof structure which employs the steel cable as a load-bearing, structural element." This would vary widely from a building where a cable is the principal structural roof member, such as in the

("Cable roof structures" Bethlehem Steel - February 1968

5 structural metal roofs)
Figure 33

Figure 34

Figure 35
the basic directions between which we will have to move, we finally tried to find the certain structural system or the certain structural systems which would have to be applied for the covering of this space. In the figures 33 - 41 appear several of the different possibilities showing out of this research. Some of these solutions in a more analytic research presented certain significant structural or functional problems. Some others did not give us the "expected" correct space according to our personal opinion. Others were not pursued because after a comparative research it was proven that another better solution existed.

Finally we chose the structural system of figure 42 in order to cover the given space. This system was chosen as the more pure structural system and simultaneously as the structural system whose "structural space" was closer to the given "functional space".

In order for someone to understand the criteria with which we proceeded to the final choice I will mention certain of my basic
ideas and certain general principles of cable structures.

The main problem of this kind of structure is the achievement of stability. There are four ways through which stability can be given to a cable structure:

I. By the loading of cables with sufficient dead loads to overcome uplift.

II. By the forming of a single double - curve form of deck (consequently the stiffness of the total surface of roof's deck being very significant).

III. By the creation of a grid of cables.

IV. By the use of a double set of cables with both cables in tension (figure 43).

In my opinion the achievement of stability in a cable structure by the first method is a "weakness" of the structural system. Most cable structures which exist today are based on this principle, i.e. "the superloading of cables with dead loads for one reason only: 

Figure 43
to give stability to the structure".

This superloading appears in two ways: either by the use of a
deck, not necessarily of very significant weight (usually concrete),
or with the attempt to give a functional use to that superloading,
as is the case for example at "Madison Square Garden" (figure 44).
As an idea I find this excessive and "naive".

Let us research the chosen structural system somewhat more
analytically. To begin with let us face it from the point of form
and the geometrical manner of formation.

In order to determine the form we will turn to the geometrical
determinations which Colin Faber gives in his book "Candela/The
Shell Builder".

The total form of covering is an "anticlastic" or "hyperbolic"
surface (that is a surface whose main curvatures run in opposite
directions - figure 45b). It is formed by a principal parabola ABC
that moves parallel to itself along an inverse principal parabola
B.O.F. (figure 46). Therefore the total shape is a "Hyperbolic paraboloid". As a result it has two systems of parabolic generators. Each system is composed of "identical" parabolas situated in parallel planes.

At this point we must mention that the final form of the pre-stress cable network of primary and secondary cables. is approximately but not exactly a Hyperbolic paraboloid.

All these properties are very useful for the understanding of form. Additionally, a very important principle is that every plane which cuts the Hyperbolic paraboloid and which is not parallel to the axis $O\Delta$ (figure 46) gives a section which is hyperbola. That is a conclusion of Colin Faber's book: ".... Plane sections parallel to the bisecting planes of the director dihedral angle $\alpha O\gamma$ are parabolic. They are named principal parabolas and are respectively curved upward (GOC) (figure 47) and downward (AOE); hence the surface is anticlastic or inversely doubly-curved. All other plane sections and their projections on the plane $xy$ are hyperbolas or their
degeneration in two straight lines, except those parallel to the axis which are parabolas, and of course, those parallel to the director planes which give the straight generators ......." (figure 47).

Let us proceed to a brief description of the structural system of the chosen solution. We could separate the entire structural system into two basic categories:

a. the system of cables

and

b. the system of supports.

Let us discuss them:

a. The first system includes cables of two directions, perpendicular to each other and of opposite curvatures. The ends of the cables of one direction terminate at the tops of supports (fixed points). The cables of this direction have the form of figure 48a. The developed forces are indicated in the same figure. Each one of $F_i$ (that is $F_1,F_2,......$) is a total of dead load and pressure by the cable of opposite direction. We will call the cables of figure 48a
The ends of cables of the other direction terminate on the ground (fixed points). The cables of this direction have the form of figure 48b. These are the "secondary cables". The "secondary cables" are for prestressing and restraining the primary cables.

This precisely is the difference and the similarity of this way of approaching stability as opposed to the way of approaching it by the use of significant dead load. In that case we have vertical forces on the primary cables which result from the weight of materials. Here, in this chosen case, we have vertical forces which result from the pressures of secondary cables (and partially from the weight of necessary materials). Complete freedom is offered by this structural system for the structural engineer to develop on the primary cables any force he needs in order to achieve complete stability without having to add new material but simply by changing the stress of secondary cables. And he can make it without changing the architectural idea and form, adding onto the final "structural form" of
cable structure secondary functions (as cooling towers etc.).

Absolute independence of the architectural idea from the calculations of the engineer!

b. Another general problem which was faced was the subject of supports. The fact that in order for the cable structures to function properly they must have a fraction \( \frac{s_{\text{ag}}}{s_{\text{pan}}} \) between 1/8 and 1/15 has as a direct consequence a serious problem, the requirement of supports of great height. If this problem is combined with the special problem of the appearance of horizontal \( H \) (necessary forces in cable structures) which are shown in figure 48a tremendous moments are created at the base of supports \( (M = H \cdot h, \ h = \text{height of support}) \). Exactly this gave us the idea of making the top of each support a "fixed point" utilizing the same principal of cables (figure 49). Parts AB, AC, AD of this figure are cables (consequently we have tension). Part AZ is a bar. In order to balance point A (the top of the support) a force \( F_z \) (counter-action to the forces of the cables) is exerted by the support. Simultaneously the
The area (solid curve) and square root of the area (dashed curve) of the strongest column as a function of distance along the column. These curves are based upon equations (21) and (22). The vertical coordinate is \( \eta = AL/V \) or \( \eta^{1/2} = (AL/V)^{1/2} \) and the horizontal coordinate is \( \frac{x}{L} = x/L \). Here \( A(x) \) is the cross sectional area at the distance \( x \) along the column, \( L \) is the length and \( V \) the volume of column.

Figure 50

entire support sustains a significant buckling load. A result of this is that there exists the danger of deformation in the middle of its length.

In the final choice of the form of part AZ we were guided by the study of Joseph B. Keller (figure 50). Below I cite the abstract of that article:

"The problem of determining that shape of column which has the largest critical buckling load is solved, assuming that the length and volume are given and that each cross section in convex. The strongest column has an equilateral triangle as cross section, and it is tapered along its length, being thickest in the middle and thinnest at its ends. Its buckling load is 61.2% larger than that of a circular cylinder. For columns all of whose cross sections are similar and of prescribed shape - not necessarily convex - the best tapering is found to increase the buckling load by one third over that of a uniform column. This result, which was independently obtained by H. F. WEINBERGER, is originally due to CLAUSEN (1851). For a
uniform column, triangularizing is shown to increase the buckling load by 20.9% over that of a circular cylinder. The results lead to isoperimetric inequalities for the buckling loads of arbitrary columns". Joseph B. Keller in this part speaks about columns with solid cross-section. But hollow cross-section is even more efficient as a column than a solid cross-section. For this reason we chose the triangular hollow cross-section on the final form for the shape of our columns.

As we studied the model we realized that probably from an esthetic point of view the most correct solution to the whole problem would be a space without surrounding glass walls. I believe though that for practical reasons we also must have a common air-conditioned space.

The achievement of the above (no surrounding glass walls plus air-conditioned space) presents complex mechanical problems, the solution of which would require additional time and study.
Because of lack of adequate time to pursue this idea, the architectural solution has been left in its present form, with glass walls and supporting mullions.

Summary:

This chapter is divided into seven parts each of which presents a certain subject or a certain category of subjects, as follows:
1. Acting and attending people in relation to each of our functions -
2. Diagrammatic presentation of action in each of these three functions - 3. Determination of the dimensions of these functions - 4. Possibilities and choice of the general form of our composition - 5. Proportions of the space - 6. Research of space through vertical sections - 7. Choice of structural system and the study of different specific problems of the system chosen.
Practical results.
Elevations
Plan and section - typical intersection main roof cables

Diagrams - secondary cable system for typical interior roof panel
Vertical sections - edge of roof
Horizontal sections - corner and edge of roof
CONCLUSIONS
CONCLUSIONS

The following conclusions have been drawn in regard to the basic relationship between space, structure and form.

1. Space, as needed, is the beginning and end of Architecture.

2. Structure, once chosen to enclose the needed space, imparts limitations according to its characteristic working forces.

3. Form cannot be predetermined and is derived from the crystallization of the space organizing structure.

Architecture is the choice between these possibilities within determined limitations. The basis of the choice lies finally in the architectural values of the individual architect.