A REINFORCED CONCRETE STRUCTURE WITH CABLE SUPPORTED ROOF

by

RICHARD L. MARTIN

B. Arch. University of Southern California, 1957

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER IN ARCHITECTURE

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JULY 1962

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ABSTRACT

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Submitted in partial fulfillment of the requirements for the degree of Master in Architecture in the Department of Architecture on July 27, 1962.

The thesis presents the design and analysis of a reinforced concrete structure requiring a large interior clearspan, wherein the roof is supported by an autoclastic or doubly curved network of cables.

The focus of the investigation is directed at a generalized solution stressing an architectural synthesis which reflects the geometric, structural, and constructive character of the diverse elements. Assumed programatic requirements for the structure are minimized, with emphasis being placed on the creation of a unified architectural system rather than the solving of specific functional requirements.

July 27, 1962

Pietro Belluschi, Dean
School of Architecture and Planning
Massachusetts Institute of Technology
Cambridge, 39, Massachusetts

Dear Dean Belluschi,

In partial fulfillment of the requirements for the degree of

Master in Architecture, I hereby submit this thesis entitled,

"A Reinforced Concrete Structure with Cable Supported Roof".

Respectfully,

Richard L. Martin

ACKNOWLEDGMENTS:

I am grateful to the following persons for their advice and
assistance in the preparation of this thesis:

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I. INTRODUCTION

A. Objectives

1. To design and analyze a reinforced concrete structure requiring a large interior clear span, wherein the roof is supported by an autoclastic or doubly curved network of cables.

2. To formulate the design program for the structure so that the architectural condition created will have a broad application of use.

3. To direct the design toward a solution stressing the resolution of those problems which would prevail in the structure regardless of specific function.

4. To direct the design of the structure toward an architectural entity which reflects its geometric, structural and constructive characteristics.

5. To investigate the structural and physical properties of the materials to be employed, and to determine the technological potential of the building industry with respect to the fabrication and erection of the structure.

6. To establish as much as possible within the generalized program of requirements the pertinent environmental considerations, whether of spatial or functional nature, and to direct the design of the structure so that these needs are satisfied by the inherent or organic qualities of the structure rather than as applications of non-structural nature.

A. Objectives (continued)

    7. To equate the structure's relative economy and efficiency with the resulting architectural quality rather than with considerations which are solely economic.

B. Exposition

    The thesis is generalized to a theoretical condition rather than one approximating a more comprehensive exploration of a complete architectural service. This approach is taken because it is felt that by minimizing the problems encountered in the solving of specific functional requirements, the purpose implied in the general thesis title "The Use of Reinforced Concrete" may best be exploited.

C. Approach

    With respect to each of the following categories, a survey of known applications and techniques will be undertaken so as to best determine what is feasible and in turn facilitate the formulation of a constructive proposal.

    1. The examination of basic dimension considerations with respect to determining a general architectural condition.

    2. The determination of applicable structural and constructive techniques, including a survey of structural and physical properties of materials to be employed.

    3. The determination of required service functions to

be provided with their means of incorporation into the structure.

4. The determination of the roof surface based on span, height, spatial, and structural considerations pertinent to the selected architectural condition.

5. The determination of a unified system of structure for roof system and supporting elements with the geometric determination of slopes and angles.

6. The determination of a sequence of construction.

7. The establishment of basic structure theory and approximate structural analyses.

8. Record findings and design proposal in written and graphic form.

II. RESEARCH

A. History

1. Development of Cable Roof Structures

The use of suspension cables as a primary means of support in roof structures owes its genesis to the suspension bridge which has prevailed in crude forms since the most primitive beginnings of civilization. The modern suspension bridge had its origin with the discovery of steel in the 1880's, and since that time has experienced a continuous development wherein spans reached 4200 feet in the 1930's with the construction of the Golden Gate Bridge in San Francisco. Nothing technically stands in the way of a 10,000 ft. span.

Cable supported roofs are of relatively recent origin, the earliest use being tent structures of various forms, while what was probably the first substantial construction occurred in the locomotive pavilion at the Chicago World's Fair of 1933. Since these beginnings, the utilization of cable roofs in a variety of forms has become more prevalent, but such use remains a basically new and incompletely understood or exploited engineering principle.

The engineering attraction of such a roof is derived from the fact that the most economical means known for spanning large distances is the steel cable. This is due to the physical fact that steel wire or cable in tension is four to six times stronger than steel in any other form. It is this fact which makes possible theoretical bridge spans far in excess of those presently constructed, and creates much of the appeal of cable

supported roof structures. In fact, the chief difficulties
in suspension structures of any type lie not in spanning capa-
city, but rather with the problems of vibrations, flutter and
uplift due to wind or unequal live loading.

Though these problems exist in suspension bridges, they
become even more critical when suspension principles are em-
ployed in roof structures. This occurs because the added
necessities of breadth and weathertight enclosure require
that a greater degree of stability be maintained. This,
coupled with the fact that the large tensile stresses de-
veloped in the cables must ultimately be resisted by some
means has often resulted in excessively large edge beams,
added roof weight, and secondary tie members, all of which
can compromise structural clarity and economy. In effect,
the method of delivering the cable stresses to the ground, and
the means by which the problems of flutter, vibration and up-
lift are controlled become of primary consideration in the de-
sign or study of cable structures.

Of the cable roof structures that have been constructed
or proposed to date, there emerge three distinct types or
categories and a number of other projects or buildings which
are derivations or combinations of the three. The latter are
in some cases noteworthy as structures, but since none is unique
in principle, they tend to be less important in a survey of
suspension roof structures.

Of the basic types, each is distinguished by the geometry
of its respective cable network, but the means in which its

supporting structure performs its function, and to a lesser degree in the manner in which the tendency to flutter or vibrate is resisted.

The three types are:

a. Circular form with cables suspended radially from a central tension ring in midair to an exterior compression ring supported by a wall or columns.

b. A doubly curved saddle made up of two networks of cables of opposite curvature, the thrust of which is resisted by edge beams or arches supported on columns.

c. A singly curved network of cables spanning in one direction and slung between edge beams at each end of the cables.

A more detailed examination of an example or examples of each basic type as well as a partial list of constructed cable supported roof structures follows this section.

Beyond this elementary evaluation and classification of structural type, it should be noted that there exists in project or proposal form a number of diverse application for cables in general structural use. These are of general interest in the area of cable application, but are less pertinent to this thesis. Published applications of this nature, where possible, have been noted in the bibliography.

2. List of Constructed Examples

State Fair Arena
Raleigh, North Carolina
       Matthew Nowicki   designer
       William Henley Deitrick architect
       Fred Severud   engineer

Congress Hall
Berlin, Germany
       Hugh Stubbins   architect
       Fred Severud   engineer

David S. Ingalls Hockey Rink
Yale University
New Haven, Connecticut
       Eero Saarinen   architect
       Fred Severud   engineer

Dulles Airport Terminal
       Maryland
       Eero Saarinen   architect
       Ammann & Whitney   engineer

Utica Auditorium
Utica, New York
       Gehron and Sletzer   architects
       Lev Zetlin   engineer

Pan American Airways Jet Hangar
New York International Airport
Port of New York Authority   architects
Ammann and Whitney   engineer

United States Pavilion
1958 Brussels World's Fair
       Edward D. Stone   architect
                       engineer

Corning Glass Cafeteria

                      architect
       Fred Severud   engineer

Calo Food Market
San Francisco, California
       Frank Wynkoop   architect
       Dudley Wynkoop   engineer

Municipal Stadium
Montivideo, Uraguay
       Mondino, Viera and Miller architects
       Preload Co. Inc.   engineer

French Pavilion
Zagreb, Yugoslavia 1935 Exposition

architect
        Bernard Lafaille   engineer

Health and Physical Education Building
Central Washington College
Ellensburg, Washington
        Ralph H. Burkhard   architect
        Anderson, Birkeland & Anderson, engineers

Exposition Building
Century Twenty One Exposition
Seattle, Washington
        Paul Thiry   architect
                     engineer

Locomotive Pavilion
Chicago World's Fair 1933

architect
engineer

Marie Thumas Pavilion
Brussels Fair 1958
        Baucher, Blondel, & Filippone-architects
        Rene Sarger   engineer

B. Theory

The general forms of equilibrium of suspension cables as well as the formulae for a parabola of equilibrium represent engineering information which falls outside the knowledge of most architects due to its rarity of application. Therefore basic pertinent information is included in this section as a brief survey of the geometric and engineering considerations employed in cable design. Where engineering formulae of more specialized nature are utilized in the analysis, they are explained in the calculations. Formulae utilized in the analysis of concrete structural members are explained where necessary in the calculations.
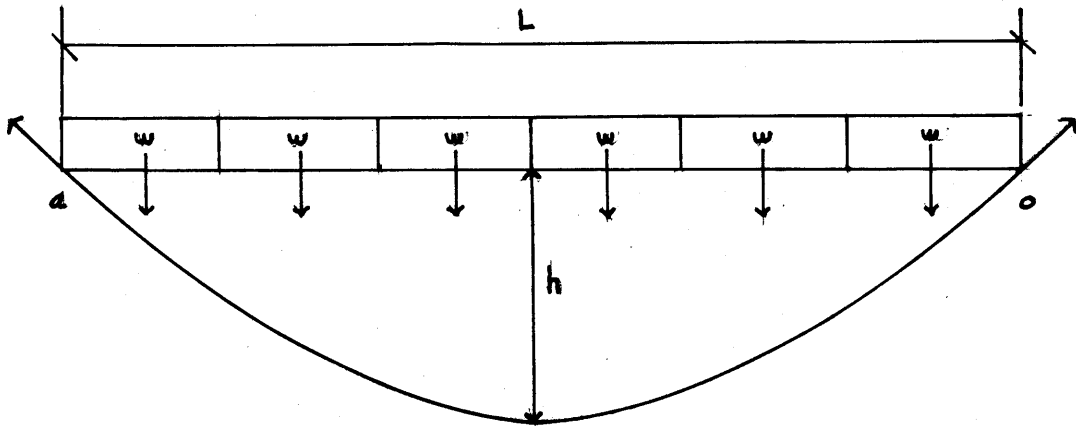
1. General Forms of Equilibrium of Suspension Cables.
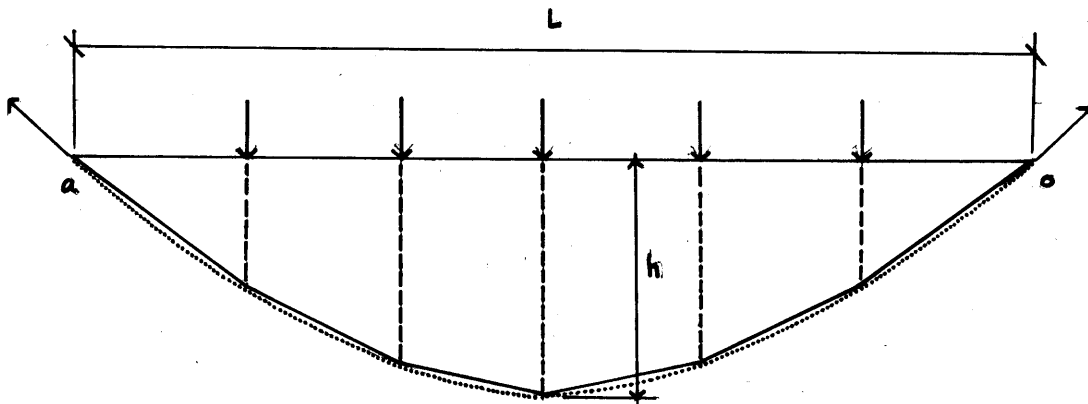
a. <u>Catenary of Equilibrium</u>
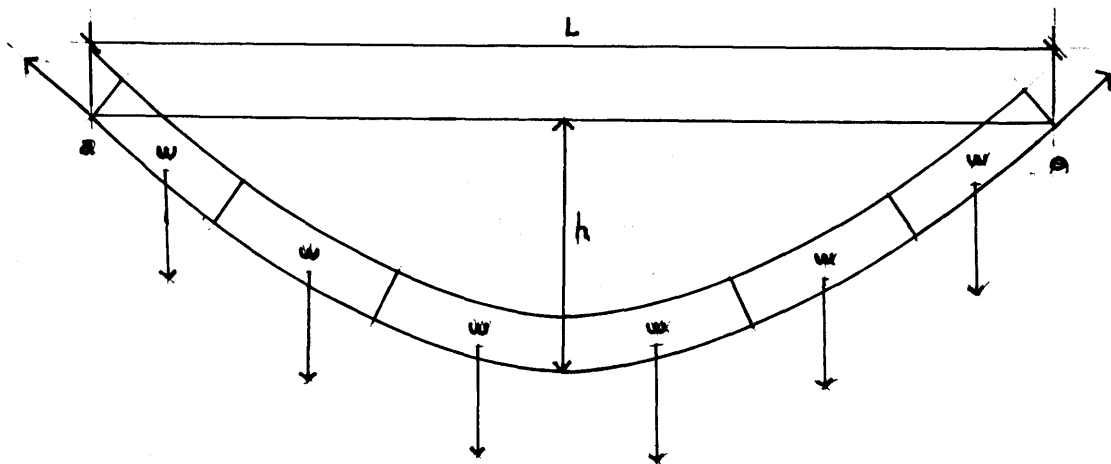
A cable loaded uniformly along its length will take the form of a catenary. This applies also to the case of a cable supporting its own weight only.

b. <u>Parabola of Equilibrium</u>

A cable loaded uniformly along its chord length
will take the form of a parabola.

c. <u>Funicular Polygon of Equilibrium</u>

A cable loaded with a system of concentrated
loads will take the form of a funicular polygon.

2. General Formulae for a Parabola of Equilibrium

a. When a cable supports a load that is uniform
per unit length of the cable itself, such as its own weight,
it takes the form of a catenary. Under closely spaced applied

loads of uniform magnitude the curve through the points of
inflection of a funicular polygon will closely approach that
of a catenary. In either case unless the sag of the cable is
large in proportion to its length, the shape taken may often
be assumed to be parabolic, the analysis being thus greatly
simplified.

Structural calculations for cables included herein will
utilize the cable formulae for a parabola of equilibrium and
the following general formulae will apply:
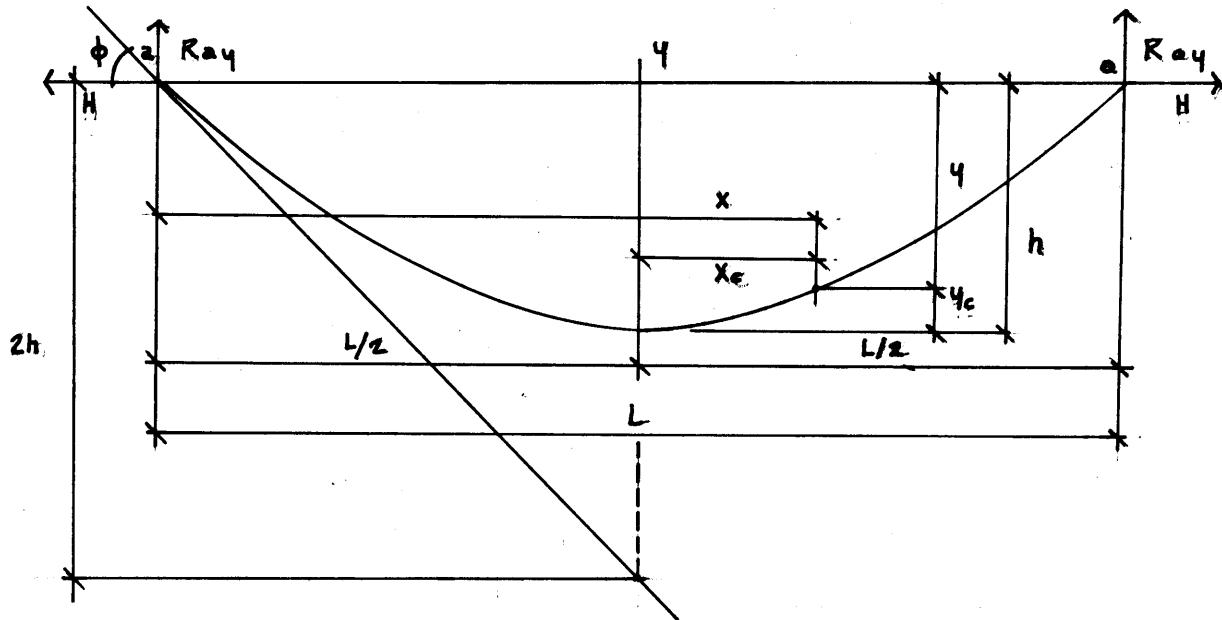
HORIZONTAL COMPONENT OF CABLE STRESS (H)

$$H = \frac{w L^2}{8h}$$ WHERE "w" = UNIT LOAD/FT.

MAXIMUM STRESS IN CABLE (T MAX)

$$T_{MAX} = H(1 + 16\,\theta^2)^{1/2}$$ WHERE $\theta = \frac{h}{L}$

SHAPE OF CABLE

$$y_c = \frac{4h}{L^2} X_c^2$$ ASSUME X_c VALUES AND SOLVE
FOR VARIOUS y_c VALUES.

LENGTH OF CABLE (S_0)

$$S_0 = L \left(1 + \frac{8\Theta^2}{3} - \frac{32\Theta^4}{5} \right) \qquad \text{WHERE } \Theta = \frac{h}{L}$$

AVERAGE CABLE TENSION (T_{AV})

$$T_{AV} = H \frac{1 + \frac{16\Theta^2}{3}}{1 + \frac{8\Theta^2}{3}}$$

CABLE STRETCH

$$\text{ELASTIC STRETCH} = \frac{T_{AV} S_0}{A E} \qquad \text{WHERE:} \quad \begin{array}{l} A = \text{EFFECTIVE CABLE AREA} \\ E = \text{CABLE MODULUS OF ELASTICITY} \end{array}$$

ANGLE OF CABLE REACTION $(\angle\phi)$

$$\text{TAN } \angle\phi = \frac{2h}{L/2}$$

C. Application

The following general uses have been considered in determining possible application and size of structure.

    1. Transportation Terminal

    2. Airplane Hangar

    3. Indoor Sports Enclosure
        a. gymnasium-basketball
        b. swimming pool
        c. tennis court

    4. Exposition Pavilion or Arena

    5. Retail Sales
        a. Supermarket
        b. Junior Department Store
        c. Discount Department Store

D. Economy

No effort has been made to establish the relative economy of the structure due to the complexity of such an analysis. From empirical observation it is possible to sur-

mise that the cost of the structure relative to other more
conventional means of spanning the space enclosed would not
be competitive until spans were great. It is generally conceded
that suspension structures will begin to compete on a cost
basis with other structural methods when spans reach approxi-
mately three hundred feet. It is probable that this figure
can be lowered if economy is of prime importance. This would
be particularly true if full advantage is taken of the rapidity
of erection possible in cable construction.

In the development of this problem it has been assumed
that the resulting structure would be one in which low cost
was not of prime importance, and that quality within some
higherlimit would permit the utilization of the structure em-
ployed in the final solution.

III. DESIGN CRITERIA

A. Building Type

The building is to be a high quality free standing
structure with large interior clearsapce offering a high degree
of flexibility, with the general requirement of a dynamic in-
terior space and strong exterior form. Contemplated uses
would be those of transportation terminal, indoor sports en-
closure, and exposition pavilion or arena.

B. Building Size

From the studies of possible application, with respect
to ground plan size, interior volume enclosed, and exterior
overhang, the following basic dimensional considerations are
established:

1. An enclosed clear space of approximately 30,000 sq. ft.

2. A rectangular plan with dimensions of approximately 150 x 200 ft. at the floor plane.

3. Overhang to be closely tied to the geometric, structural, and spatial characteristics of the system. As such, desirable dimensions are difficult to predetermine. They should, however, reflect in their generosity the interior spatial character and the overall quality of the building.

C. Quality of Space

In light of contemplated uses, spatial considerations would reflect primarily the basic requirement of a large clear space of dynamic character. The end result of these considerations would be a product of the cable network geometry selected, the spatial characteristics of the general structural system, and the articulation of its parts. Other objective considerations such as natural and artificial light, acoustics etc. are discussed under separate sections.

D. Structural Considerations

Beyond the applicable general requirements outlined under building type, certain general considerations apply to the forumlation of the structural system.

1. Structural and modular order offering the following advantages:

a. Similarity of parts
b. Repetition of components
c. Ease of fabrication and erection
d. Mass production of shop fabrication
e. Use of advanced concrete technological levels.

E. Functional Considerations

   1. Lighting

        Since no specific use is advanced for the struc-
ture, the lighting requirements must of necessity remain
general in nature.

              a. Natural Light

                 No specific requirements to be established.

                 The following general conditions to be

                 pursued:

                      1. No natural light to be provided through
                         roof surface.

                      2. Possibility of large glass area to be
                         maintained throughout wall surface.

                      3. Any sun or glare control other than
                         that afforded by structural overhang
                         will not be considered.

              b. Artificial Light

                 No specific requirements for artificial

                 illumination are to be established. The

                 following general conditions will be pur-

                 sued:

                      1. Accommodations for a general illumina-
                         tion system should be incorporated
                         within the structure.

                      2. Such a system should offer a flexibility
                         which would accommodate the lighting
                         required for the contemplated uses of
                         the structure.

   2. Acoustics

        A proper acoustic environment for the general
program requirements will depend upon the following con-
siderations:

a. Reverberation Time

    1. With a fixed volume, required reverberation time can be attained by:

        a. Variation of sound absorptive material at roof surface.

        b. Use of distributed sound amplification system.

b. Background Noise Criteria

    1. For the contemplated uses, an ambient background noise level of between 30 and 40 decibels is indicated. This would be provided by the air handling system.

c. Sound Distribution

    1. For the contemplated uses, and in light of the relatively large volume of the space, a distributed system of sound amplification would be indicated. Such a system would incorporate a high degree of absorption on ceiling and if possible on walls, with the amplification source directed downward upon the inhabitants of the building.

    2. In the event that the space were to serve a function requiring presence - i.e. performance of some sort - it would be necessary to employ a more elaborate system incorporating time delay for proper acoustic conditions.

d. Sound Absorption

Primary sound absorption will be necessary in varying degrees at ceiling level depending upon use. Major source of noise at floor level would be produced by persons in the building. This sound will be attenuated in a horizontal direction by the presence of the persons creating the sound.

3. Mechanical Equipment and Services

All mechanical equipment will wherever possible be placed underground or at some distance from the structure.

    a. All air handling duct work wherever possible to be incorporated within the structural or floor system.

    b. A forced air system is contemplated whidh would require supply at floor level with return air accommodations at ceiling level - preferably at the high points of the ceiling plane. Exhaust system to be underground at some distance from the building.

    c. Waste, soil, and water supply systems to be underground and as such not a part of the design program.

4. Thermal Insulation

    a. Where possible to be incorporated into the structural system.

5. Roofing

    a. High quality roof in conjunction with overall character of the structure.

IV. PRELIMINARY PROPOSAL

The proposal consists primarily of the study of a cable roof network supporting concrete panels.

A. Dimensional Characteristics

A cable network plan projection of approximately 150 x 200 feet.

B. Structural Characteristics

    1. Cable Network

        The cable network consists of two families of cables perpendicular and at opposite curvatures to one another producing a doubly curved surface whose separate parts are essentially square.

        a. Suspension cables hang between two equal parallel lines 200 ft. apart and at equal distance above the ground plane and describe 22 equal divisions in the lines of 6.318 ft. each. Cable sags are determined by a parabola at the centerlines and perpendicular to the suspension cables. The parabolas' low points are at the outside cables with its high point at the center-line of the central suspension cable.

        b. The stressing cables are perpendicular to and at opposite curvatures to the suspension cables and are spaced at intervals that vary from 6.783 ft. at the centerline suspension cable to 6.896 ft. at the outside cables.

    2. Concrete Roof Panels

        Roof panels are solid three inch thick slabs spanning two ways between canted integral edge beams. The edge beams provide stiffness to the panel during fabrication and erection, and become a forming expedient for the concrete poured around the cables. The lattice formed by these edge members, the cables, and the concrete pour serves to distribute unequal live loads across the cable network, and provide rigidity to resist the forces of uplift.

    C. Functional Characteristics

    1. Lighting

        The possibility of lighting conduit runs is

provided by the articulated joint between panels.

2. Acoustics

The possibility of applying absorptive material within the coffered portion of the roof panel is provided.

D. Criticism

1. Building Size

Depending upon method of support, cable network may dictate enclosed building area under that determined in design criteria.

2. Structural Characteristics

a. Cable Network

1. Spanning cables in longitudinal rather than transverse direction are inefficient. If possible spanning cables should be in transverse direction with stressing cables in longitudinal direction.

2. Transverse curvature is insufficient to provide resistance to flutter and uplift.

3. Transverse curvature at network extremities is insufficient to apply prestress to suspension cables.

b. Concrete Roof Panels

1. Solid concrete panels have inefficient span to weight ratio and as such will reflect in total cable area required for assumed roof area.
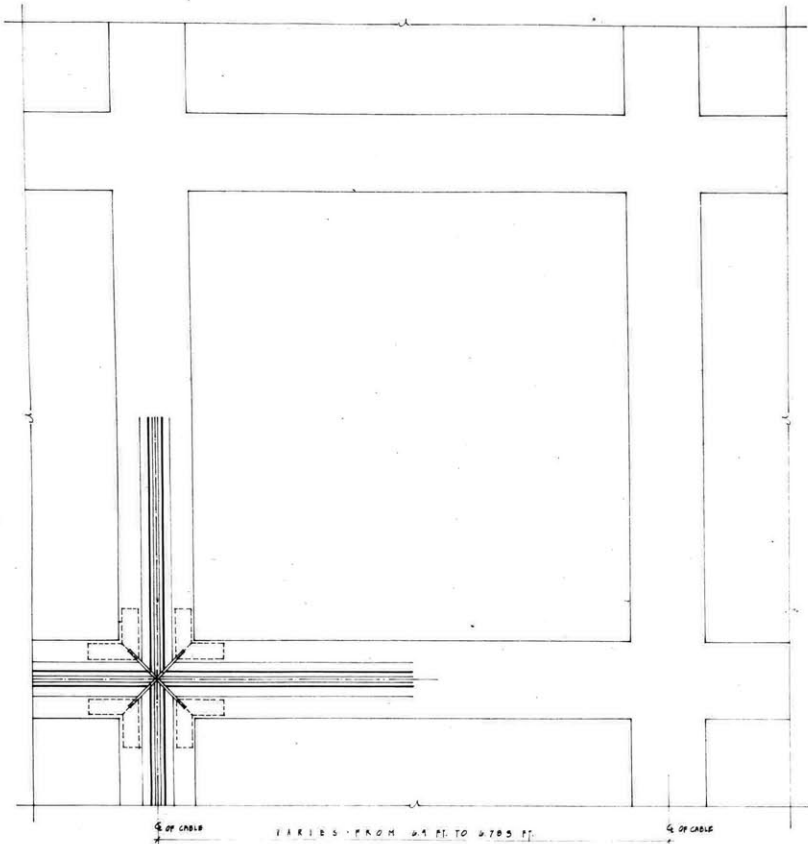
3. Functional Characteristics
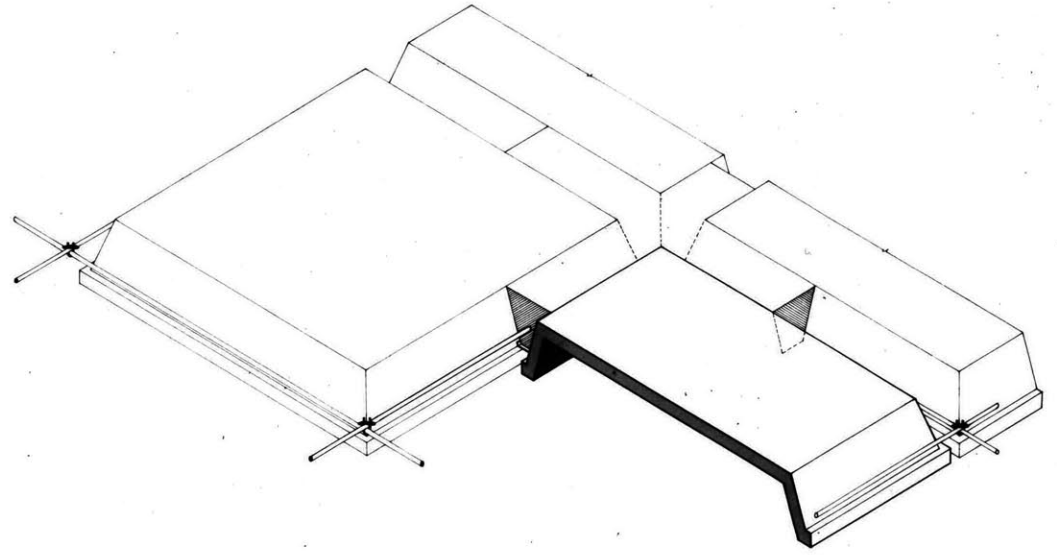
a. Thermal Insulation

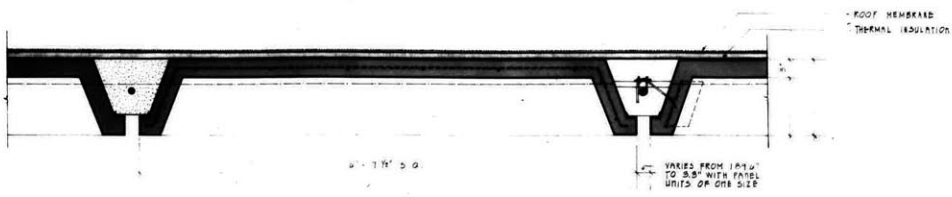No provisions are made for the incorporation of thermal insulation into the roof panels.

b. Mechanical

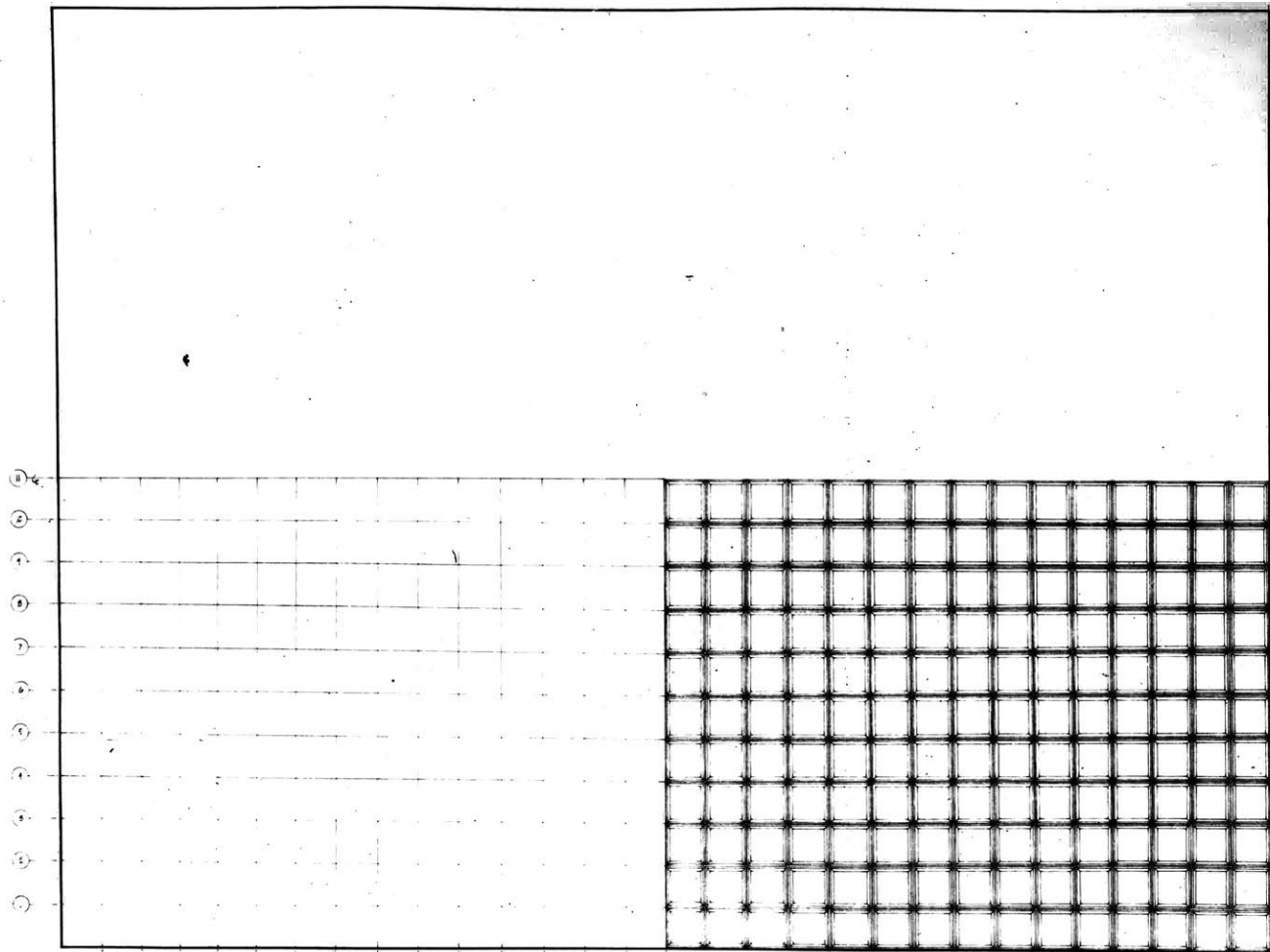No provisions are made for the incorporation of mechanical services into the structure.

PLAN OF TYPICAL UNIT
1/2"

₵ OF CABLE   VARIES FROM 6.9 FT. TO 6.783 FT.   ₵ OF CABLE
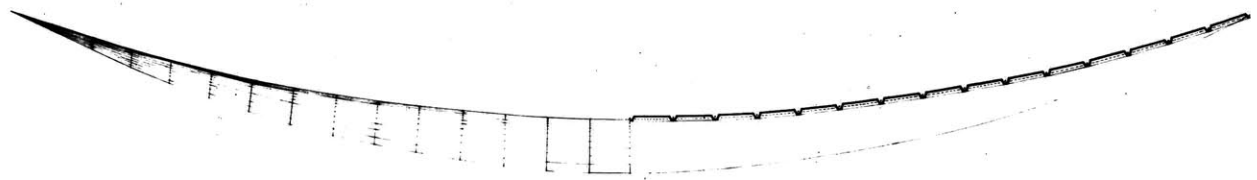
ISOMETRIC

ROOF MEMBRANE
THERMAL INSULATION

SECTION OF TYPICAL UNIT
1/2"

6'-7¼" SQ   VARIES FROM 18'-0"
                   TO 9.3" WITH PANEL
                   UNITS OF ONE SIZE
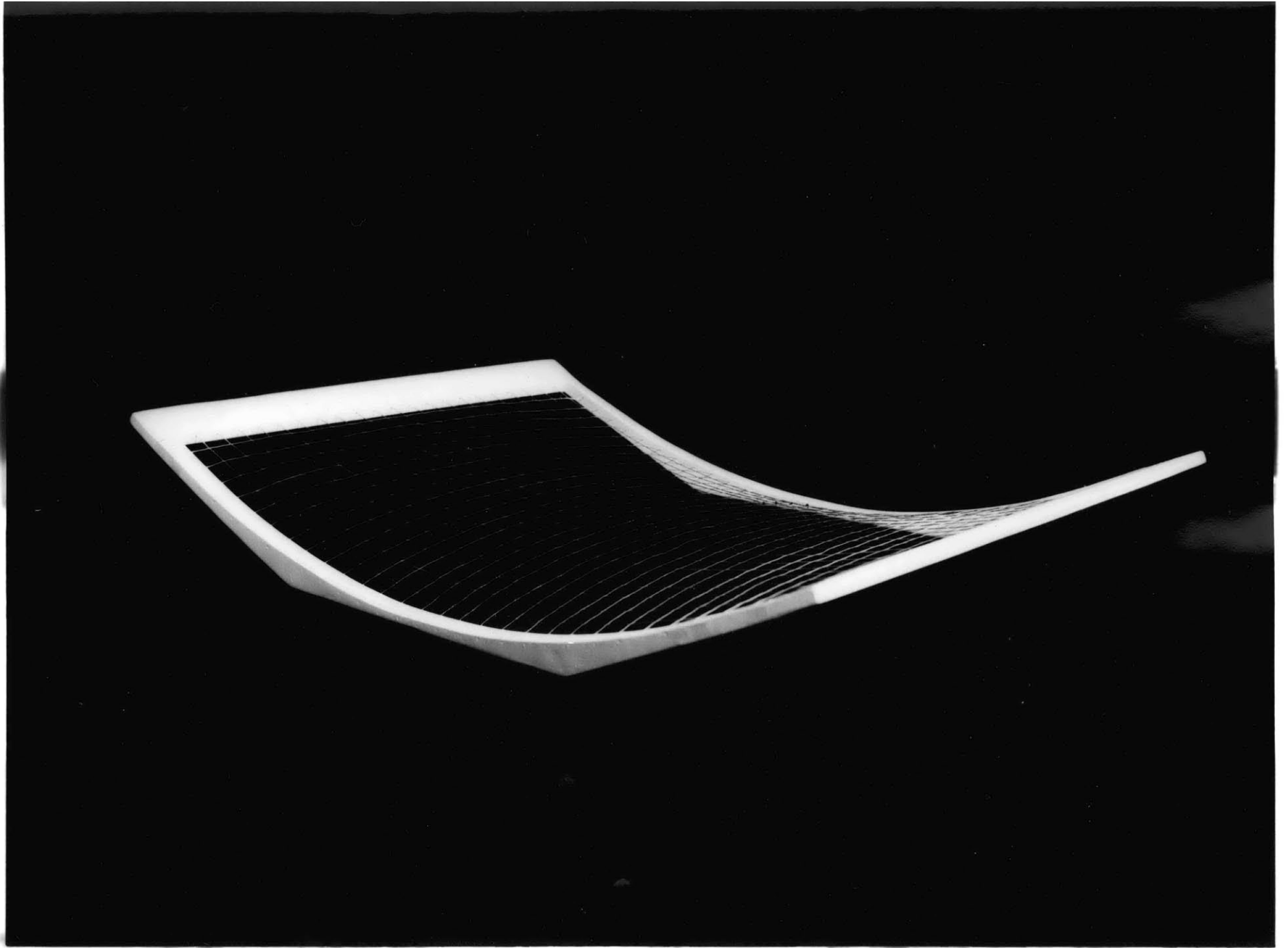
25

150'-0"

SECTION TRANSVERSE
1/8"

PLAN OF CABLE NETWORK   REFLECTED CEILING
1/8"
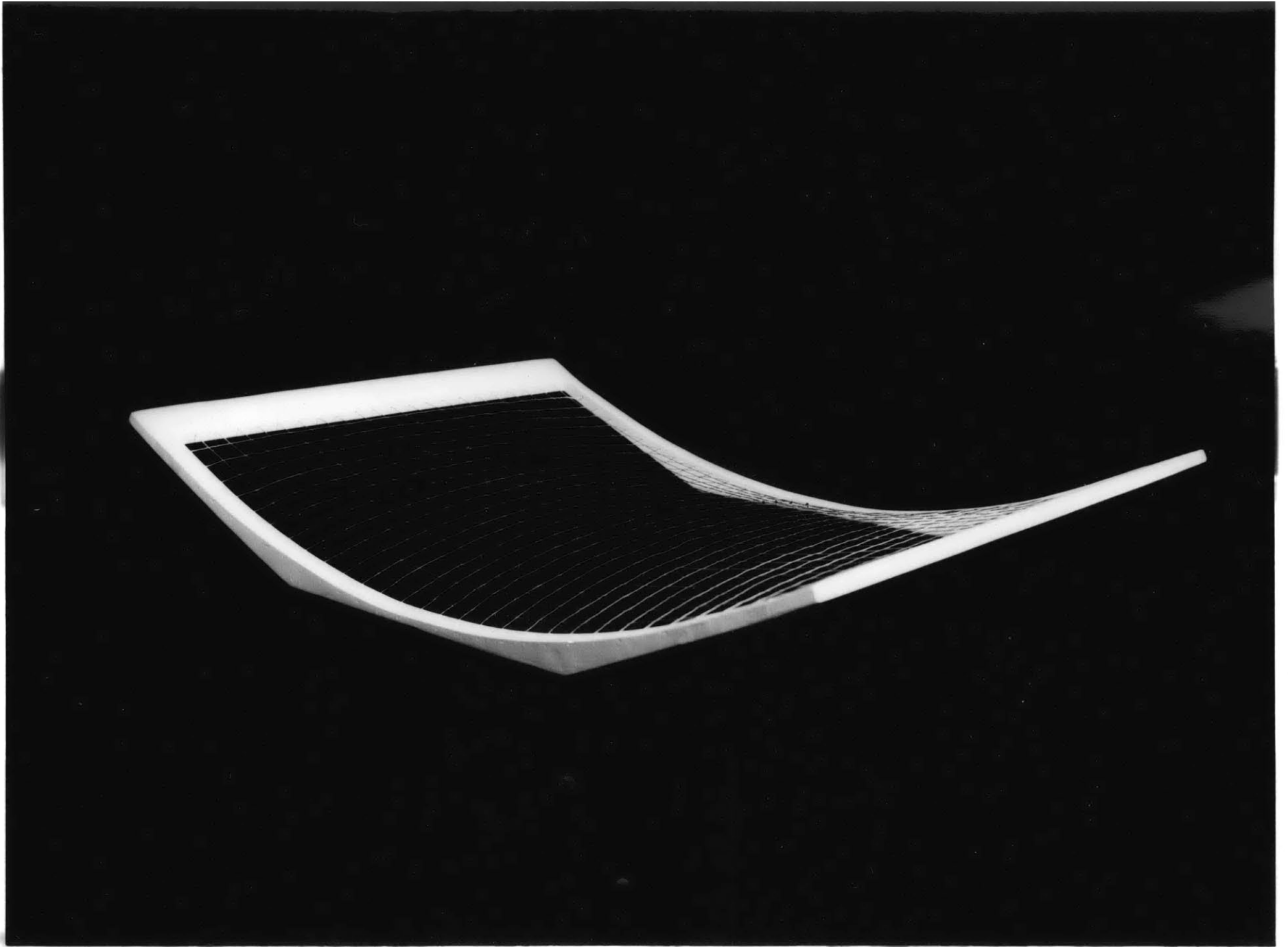
ELEVATION-SECTION LONGITUDINAL
1/8"
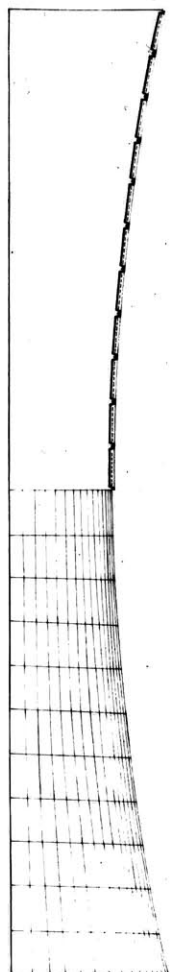
V. THE FINAL PROPOSAL

A. General Description

The building is a free-standing clearspan structure wherein the roof is constructed of precast concrete slabs supported by a doubly curved network of steel cables. The cables deliver the roof loads to the ground through a system of reinforced concrete edge beams and supporting members.

B. Dimensional Characteristics

1. Floor area at ground plane is determined by a rectangle 140 ft. by 224 for an enclosed area of 31360 sq. ft.

2. Ceiling heights and corresponding volume vary with the geometry of the roof structure.

C. Structural System

1. Cable Network

The cable network consists of two families of cables perpendicular and at opposite curvature to one another. The geometric breakup produces a doubly curved surface whose parts are sufficiently uniform to permit a repetition of similar building components and a resulting ease of fabrication and erection.

a. The suspension family of "I Cables" are suspended at nine foot intervals from two parallel lines 185 feet apart and at a height of 54 feet above the finish floor line. These cables vary in sag from 37 ft. at the outside cables to 18 ft. at the centerline cables. The sags of the intermediate cables are determined by a parabola at the center-

line and perpendicular to the suspension cables, with a chord length of 207 feet and a rise of 19 feet.

b. The stressing family of "II Cables" are perpendicular and at opposite curvature to the suspension cables and are spaced at equal intervals which scale approximately 9 feet 6 inches at their ends and 9 feet 0 inches at their centerline.

c. One family by being essentially perpendicular and at opposite curvature to the other family, exerts a prestress to its opposite when it is tensioned. An initial prestress is given to the suspension cables by the roof dead load, while tension introduced into the stressing cables by means of jacks provides additional load to the suspension cables to assure their continued prestress throughout the live load cycle. Further, by tensioning the stressing cables a sufficient amount, it is possible to assure that they will continue to act beyond the maximum live load deflection of the suspension cables.

2. Roof Panels

a. The roof panels are prefabricated flat slab units of a sufficiently small number of different sizes to permit efficient shop fabrication and assure visual uniformity. Slight differences will be taken up in the joints that occur between panels.

b. Since the amount of steel cable utilized in the
   cable network will be almost directly proportional
   to the span to weight efficiency of the roof
   panels, these panels have been designed with a
   light weight foamed poly-urethane core which
   reduces slab weight while retaining sufficient
   material at the extreme fiber to cover the rein-
   forcing steel and assure slab action. This de-
   sign has the advantage of producing a greater
   spanning capacity for weight of panel than a
   solid slab, while at the same time incorporating
   thermal insulation into the panel unit.

c. The flat two-way portion of the roof panel is
   surrounded by an inclined integrally poured
   edge beam which serves to stiffen the panel
   during fabrication and erection, and when sus-
   pended from the cable network, becomes a forming
   expedient for concrete poured around the cables.
   The lattice thus formed becomes a diaphragm for
   distributing unequal loads in the completed
   structure.

3. Roof Supporting System

   The roof surface of cable network and concrete
slabs is supported by a composite system which consists of
alternately similar pairs of structural elements surrounding
the perimeter of the rectilinear plan.

a. Major Support Structures

All forces, both vertical and horizontal,
generated within the total structure are ul-
timately resisted by a system of regularly
spaced column members which occur on alternate
long sides of the rectilinear plan. These
members perform their combination of struc-
tural requirements in the following manner.

1. Six columns of translational shape
   spaced at 45 ft. o.c. along each of the
   two longitudinal elevations ultimately
   carry all forces produced in the struc-
   ture to the ground by moment and com-
   pressive resistance.

2. The six columns on each major elevation
   translates in form upward, increasing
   in width, and outward from the building
   centerline in a cantilevered, fan shaped,
   doubly curved surface. The resulting
   shape gives added column resistance to
   twisting, and serves to shorten the
   span between columns.

3. The remaining 18 ft. between columns is
   spanned by an integral concrete beam
   in what is now the same plane as the
   translational column. This beam
   carries the relatively small live and

dead loads that occur above it in the
supporting structure, and serves to tie
the columns together so that twisting
stresses introduced by unequal forces
delivered in each column panel by the
cables are more equally distributed to
the six columns. In addition, the beam
ties the six columns together into a
rigid frame so that wind leads are not
taken solely by the first column adjacent
to the wind exposed side.

4. Directly above the previously mentioned
beam, and translating from it and the
columns along the length of each long
elevation, is a horizontal concrete
section or beam which resists the cable
tension between the columns. Where this
horizontal beam continues across the top
of the column, it serves as a transitional
element to deliver the cable forces that
occur within the column width at the roof
line intersection.

b. Suspended Side Trusses

Between the two major supporting columns
systems at the extremities of the suspension
cables on the two minor sides of the plan rec-
tangle is a suspended truss of precast concrete

elements. The truss elements are suspended
from cables in a manner similar to the roof
panels. After joints between the elements
are grouted, the truss is post tensioned with
separate wires placed for that purpose. When
completed, the trusses resist the stressing
cable tensions which are introduced by jacks
positioned between the separate truss elements
before grouting. The trusses deliver the
tension forces thus resisted to the major sup-
porting structure from which they are suspended.

D. Functional Characteristics

1. Lighting

a. Natural Light

1. No provisions are made for the utilization
   of skylighting. The possibility of adding
   skylights exists, as the overall negative
   curvature of the roof presents no drainage
   problems, while the modular breakup of the
   cable network and prefabricated concrete
   panels would permit the introduction of
   specially constructed skylight panels.

2. Extensive vertical open area throughout the
   structure permits total utilization of glass
   in the two minor elevations with approxi-
   mately 65% glass area possible on major
   elevations. The effective control of these

large glass areas is accomplished in part by overhangs of approximately 15 ft. on minor elevations and 30 ft. on major elevations. The relative effectiveness of this overhang varies with the geometry of the structural form.

The demand for further control of light admitted through glass area would vary with specific site conditions and functional requirements, and as such would require specialized solutions. It is possible that these would include the following:

    a. Heat and glare reducing glass.

    b. Louvers or deep window mullions incorporated into the fenestration.

    c. The replacement of areas indicated herein as glass with opaque material.

b. Artificial Light

Provisions for the installation of artificial lighting, for general and specialized illumination are provided in the roof construction as an integral part of the structure. This is accomplished by providing a continuous slot below the joint between roof panels. This slot provides a semi-concealed two directional conduit chase which offers complete flexibility in the position and extent of lighting.

2. Acoustics

The following provisions or accommodations are made to assure a proper acoustic environment as outlined under design criteria section:

 a. The doubly curved surface of the roof structure serves to break up sounds directed at the ceiling plane, avoiding flutter.

 b. Coffered roof panels provide a ceiling configuration which permits the installation of sound absorbing material necessary for proper reverberation time without compromising structural and visual order.

 c. Contemplated air handling equipment would be sufficient to provide desired ambient sound background of 30 to 40 decibels.

3. Mechanical Equipment and Services

 a. Mechanical Equipment

  Heating, ventilating and air cooling equipment is to be housed separately or underground and as such is not a part of this problem. Accommodations for ductwork are provided in the following manner:

  1. Supply and exhaust ducts arrive underground or originate at basement level. Supply, return, and exhaust air registers are at floor level or above, as dictated by special functional requirements.

2. Exhaust and return air intakes occur at high points of the roof surface along the two major interior elevations. Ductwork for these services would be cast into the reinforced concrete columns and would reach mechanical equipment under ground.

An estimate of total cross sectional area required for this function is 24 sq. ft. which would necessitate 2 sq. ft. of duct per column. It is assumed that the structural mass of the column is sufficient to accommodate this total area if it is in a sufficient number of increments.

b. Waste, Soil and Water Supply Systems

Systems will be underground and as such are not a part of this problem.

c. Electrical

Service to be supplied to floor slab underground, and to roof by means of conduit runs set in concrete columns.

4. Thermal Insulation

a. Thermal insulation for roof is incorporated into the precast slabs, and would be of lightweight foamed poly-urethane of 4 inch thickness.

5. Roofing

    a. Proposed roofing is of sheet copper with standing seams and matching crimps at regular intervals following lines parallel to the stressing cables.

    b. The geometry of the roof surface assures drainage to the minor elevation gutters which possess sufficient capacity to handle the run off delivered. Water from the gutter is delivered toconcrete receptacles at both minor elevations by precast concrete down spouts.of sufficient vertical depth to eliminate undue splashing.

E. Construction Sequence

    It is assumed that prefabrication of structural elements where possible, can be scheduled so that components would be available when required in the construction sequence. A general order of construction of building components is as follows:

    1. Site preparation, placement of service facilities, pouring of fittings, and other preliminary requirements not studied herein.

    2. Pour major elevation structural supports, employing standardized forms in number consistent with economic considerations. Columns could be poured individually employing movable forms, or additional duplicate formwork can be constructed consistent with

economic considerations. Each column would incor-
porate the necessary ductwork, conduit runs and
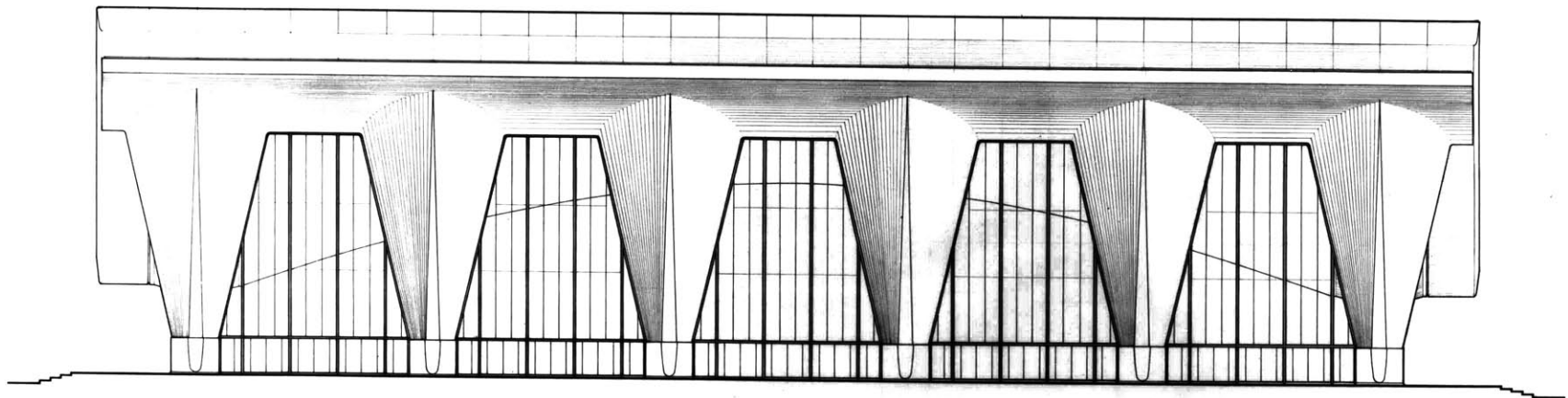attachment accommodations for suspension cables.

3. Hang cables for suspended precast concrete side
   trusses.

4. Attach precast concrete truss members, place post
   tensioning wires and tensioning jacks for stressing
   cables and grout joints.

5. Post tension concrete side trusses, using temporary
   vertical tension members to assure truss remains in
   proper position.

6. Hang suspension cables employing falsework at
   centerline to assure proper sag.

7. Position stressing cables and stress to predeter-
   mined partial tension.

8. Place concrete roof slabs by means of crane. Me-
   chanical attachment to be accomplished by workmen
   raised to cable network by crane in building in-
   terior.

9. Place sandbag overload on panels to simulate added
   dead load of concrete lattice to be poured.

10. Adjust tension in suspension and stressing cables to
    final predetermined stresses, and secure mechanical
    attachment of cables at crossing points.

11. Pour concrete lattice, removing overload on panels
    as pours are made.

12. Attach precast facia members.

13. Roof structure and make final check of roof position and cable tension.

14. Replace temporary tension restraint at centerline of side truss and replace with permanent mullions .
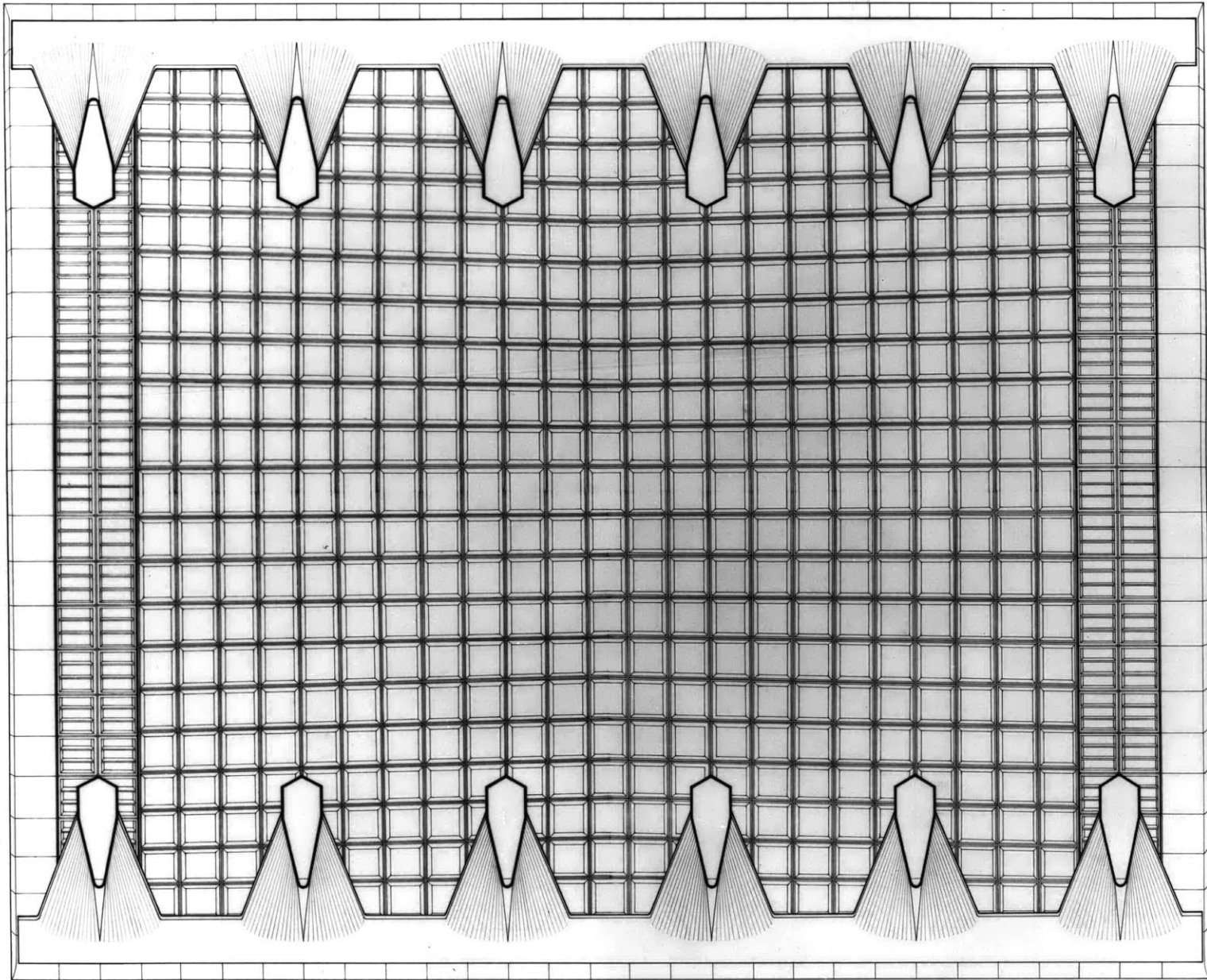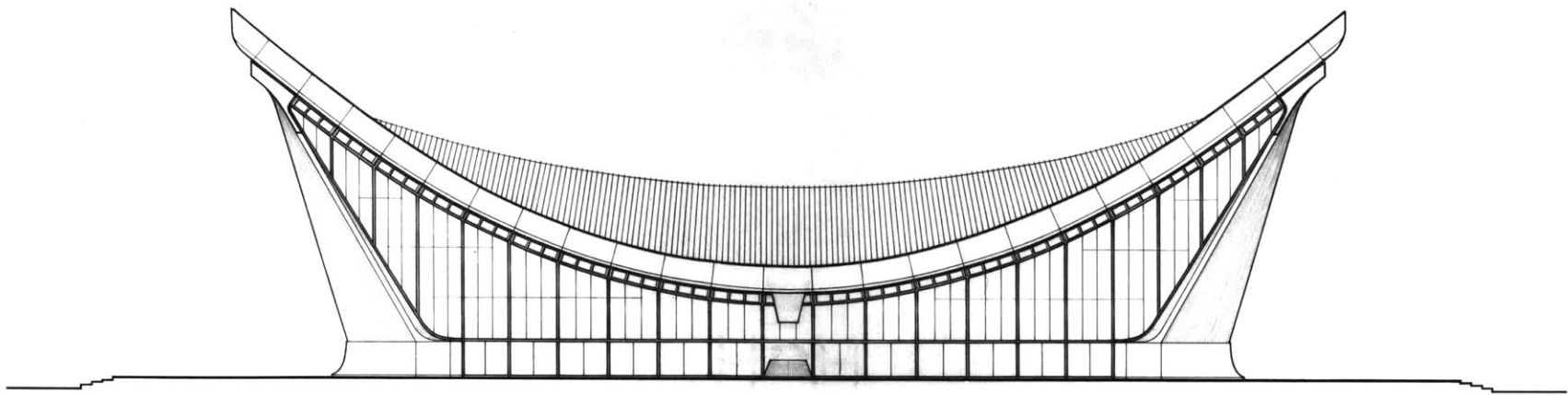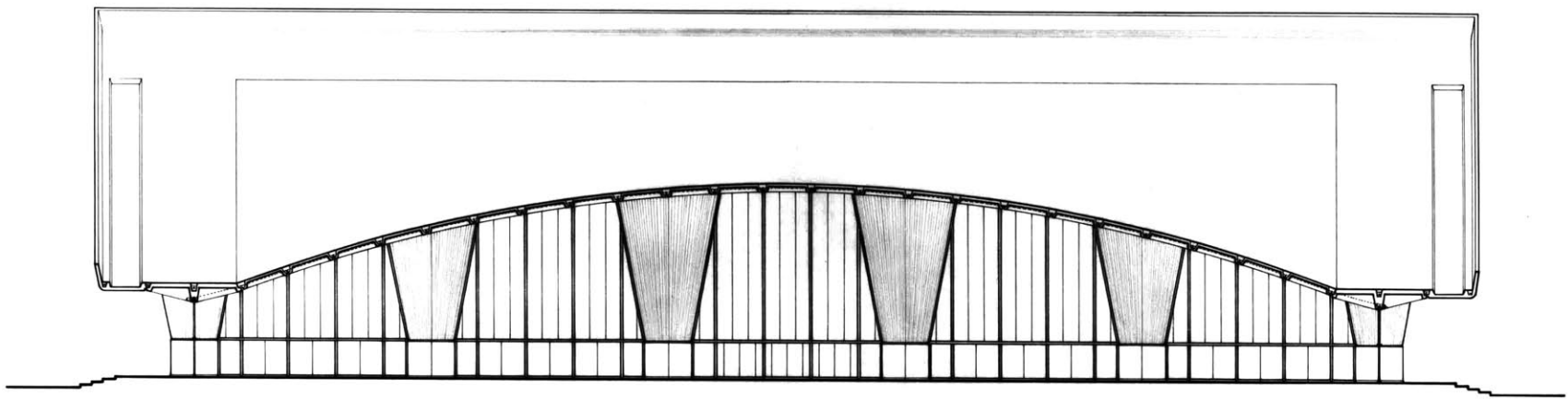
REFLECTED CEILING PLAN

0   10   20   30   40

SCALE

1

2

42

TRANSVERSE ELEVATION

0   10   20   30   40
SCALE

TRANSVERSE SECTION

0   10   20   30   40
SCALE

A REINFORCED CONCRETE STRUCTURE
WITH CABLE SUPPORTED ROOF
MASTER IN ARCHITECTURE THESIS
RICHARD L MARTIN   MIT   1962
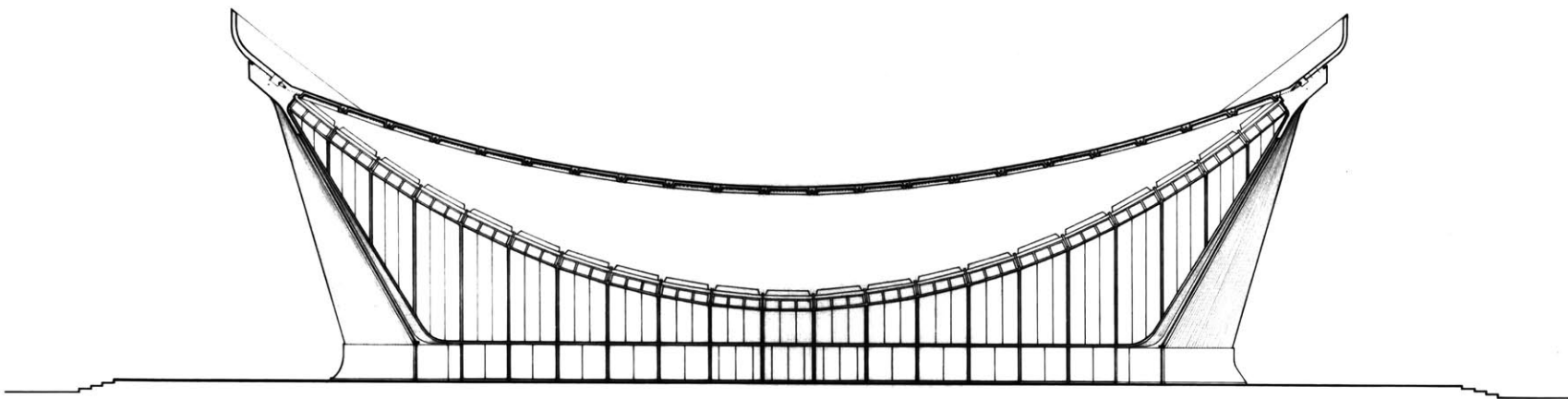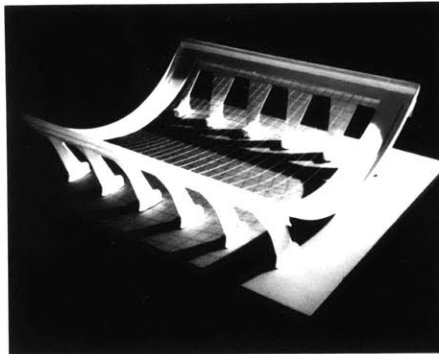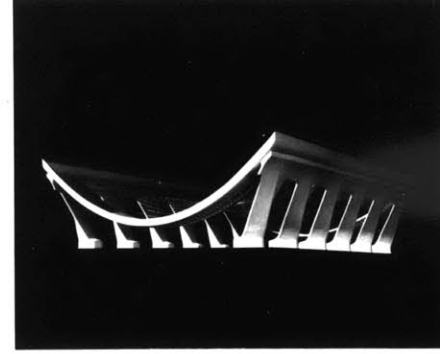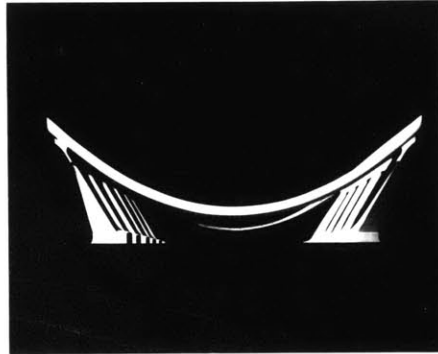
45

5

A REINFORCED CONCRETE STRUCTURE
WITH CABLE SUPPORTED ROOF

6
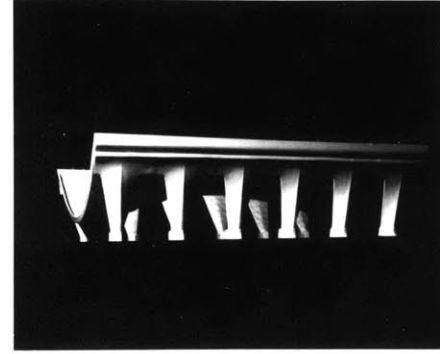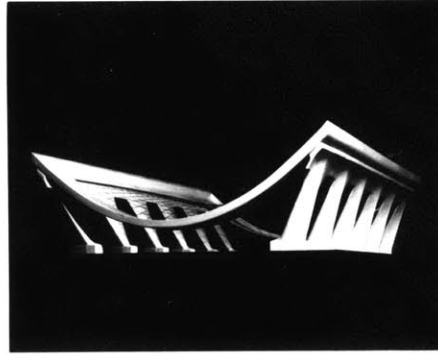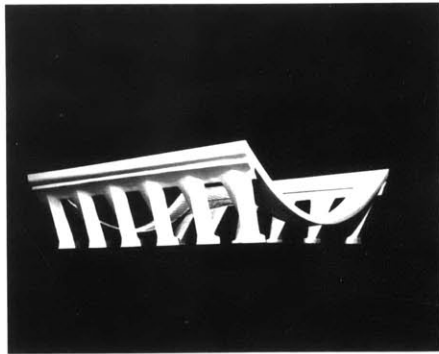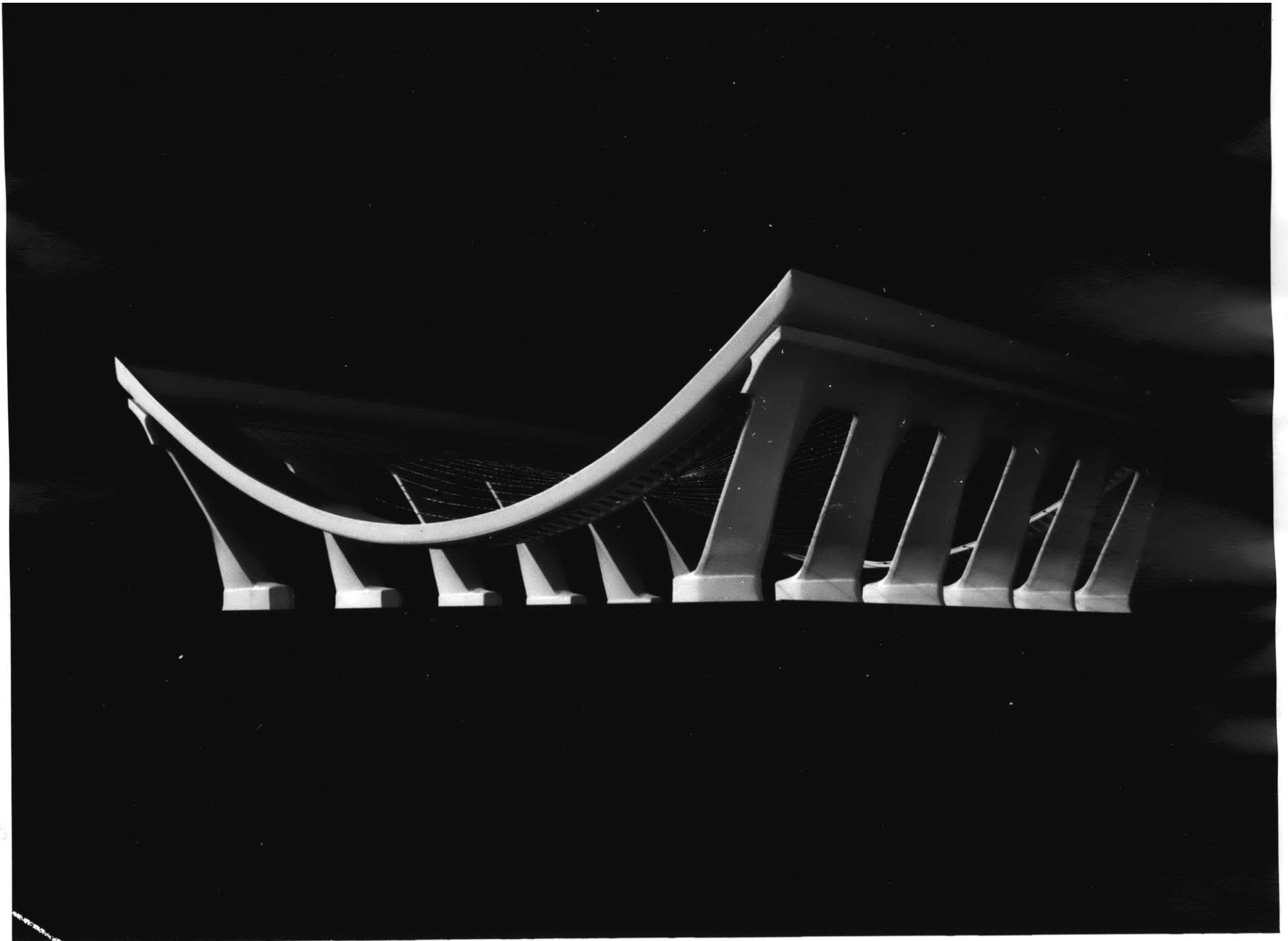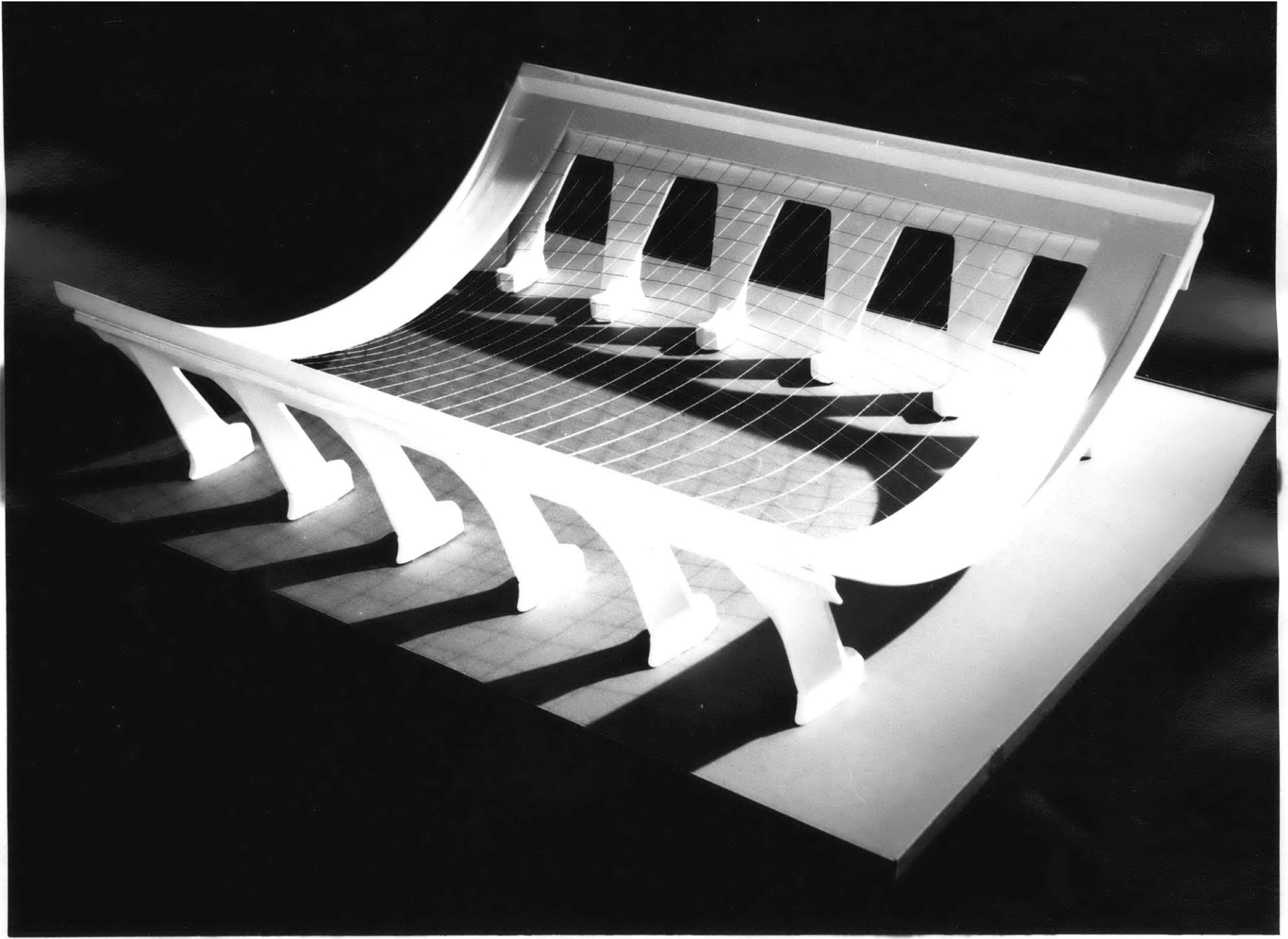
VI STRUCTURAL ANALYSIS

A. CONCRETE ROOF PANELS

4" THICK THERMAL INSULATION OF FOAMED POLY-URETHANE

7"

9"

10"

ASSUMED 9'-0" SQ.

(ACTUAL DIMENSIONS VARY SLIGHTLY)
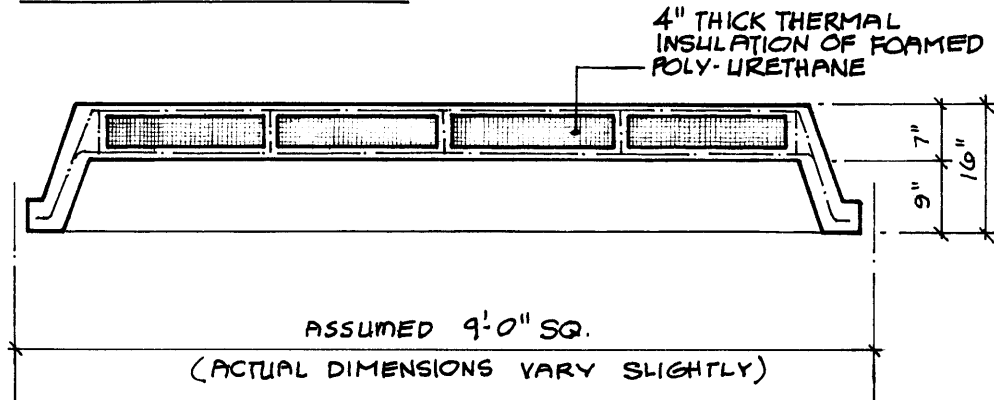
PANEL SECTION : 1/2"=1'-0"

IT IS ASSUMED THAT GREATEST STRESSES WILL OCCUR IN PANEL DURING FABRICATION AND ERRECTION HANDLING. THEREFORE DEPTH OF SECTION IS DETERMINED BY THICKNESS OF DESIRED THERMAL INSULATION AND EXTREME FIBER CONCRETE NECESSARY FOR STEEL COVERAGE. CAPACITY OF SECTION AS TWO-WAY SLAB WITH FOUR EDGES DISCONTINUOUS IS CHECKED IN CALCULATIONS. A 9'-0" CLEARSPAN IS ASSUMED TO BE MORE CRITICAL THAN THE ACTUAL EDGE BEAM CONDITION, AND IS ASSUMED FOR EASE OF CALCULATION.

3000 psi CONC. $\times .45 = 1350 = f_c$

$20,000$ psi STEEL

LIVE LOAD 40 #/SQ. FT.

DEAD LOAD 45 #/SQ. FT.

TOTAL LOAD 85 #/SQ. FT

DESIGN MOMENT

$$M = \frac{w L^2}{20}$$

OR .050 MOMENT COEFFICIENT FOR TWO-WAY SLAB FOUR EDGES DISCONTINUOUS POSITIVE MOMENT AT MIDSPAN.

$$M = \frac{85\# \times 64 \times 12}{20}$$

$$M = 3264 "\#$$

ALLOWABLE MOMENT

$$M = 1061 psi \times 12" \times 1.5"$$

$$M = 19,098 "\#$$

12"

1350#

3.5"

1.5"

2"

772#

1061#
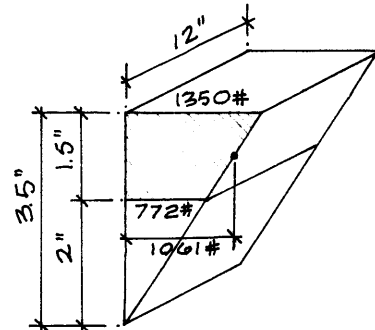
SECTION STRESS DIAGRAM

STEEL REQUIRED

$$T_{max} = \frac{3264}{5.5" (COUPLE ARM)} = 595\#$$

$$A_s \text{ Req'd.} = \frac{595}{20,000} = .0298 \text{ SQ. IN.}$$

USE : 6×6 - 6/6 SQ. WELDED WIRE FABRIC = .058 SQ. IN

TOP AND BOTTOM

51

VI. <u>STRUCTURAL ANALYSIS</u> (continued)

    B. <u>Cable Network</u>

        1. General Cable Information and Assumptions

            a. The strength and physical characteristics of
               cable vary with the method of their fabrica-
               tion and the materials employed. A more de-
               tailed study of the various types of cables
               available would be required to determine the
               best type of cable for this particular design.

            b. In practice the load capacity is determined
               by test of particular cable size rather than
               applying allowable unit stress values to the
               cross section area. Cable makeup is such
               that this load capacity does not have a
               simple relationship to the amount of material
               in cross section.

            c. For the purposes of design in this problem it
               is assumed that the cable used is factory
               prestretched galvanized wire bridge rope with
               the following properties:

                  1. $E = 20,000,000$ psi
                  2. Maximum breaking strength in tension =
                     250,000 psi
                  3. Design strength in tension = 125,000 psi

            d. Sizes of cable determined in the calculations
               will remain in the form of area of effective
               steel required. In selecting cables from
               manufacturer's handbooks, the maximum tension

value for the particular cable rather than the effective steel area required would be used.

2. General Prestressing Design Approach

Supporting cables must be designed for both live and dead loads. Under most circumstances, however, they will be subjected to dead loads only. Thus, this loading will dictate their normal state of repose unless the stressing cables are employed to introduce additional load.

Since it would be desirable for the structure to remain as close as possible in a constant shape; and since it would also be desirable to have the supporting cables under a downward or "tiedown" stress independent of the normal roof dead loads, a portion of the cable deflection which would result from live loads will be introduced by the stressing cables.

This prestress is possible since the stressing cables are essentially perpendicular to and at opposite curvature to the supporting cables, and thus when placed under tension will exert a downward component upon the supporting cables.

The total procedure by which the design of the cable network is accomplished includes both the sizing of the individual cable members and the balancing process which determines the final position of the overall network.

A detailed outline of this process, with the theory and formulae involved follows this section.

CABLE DEFLECTION THEORY

THE UPWARD DEFLECTION, Δi, WHICH THE SUSPENSION CABLES WOULD HAVE IF THEY WERE FREE FROM THE LIVE LOADS AND/OR THE COUNTER ACTION OF THE STRESSING CABLES, WILL TAKE PLACE ONLY FOR A CERTAIN PROPORTION, $\Delta i/n$, DUE TO THE PRESENCE OF THE STRESSING CABLES. WHEN THE SPANNING CABLES ATTEMPT TO LIFT FROM THEIR DESIGNED POSITION (WITH CAPACITY FOR BOTH LIVE AND DEAD LOAD), THE STRESSING CABLES WILL BE LOADED AT CROSSING POINTS BY A CERTAIN LOAD, P, WHICH CAN BE DETERMINED BY TRIAL AND ERROR. THIS IS ACCOMPLISHED BY GUESSING WHAT MIGHT BE THE ACTUAL $\Delta i/n$, AND CHECKING IF THE "GUESS" IS CONFIRMED BY THE APPLICATION OF FORMULA α.

POSITION OF SUSPENSION CABLES WITH DEAD LOAD ONLY

POSITION OF SUSPENSION CABLES WITH DEAD LOAD AND STRESSING CABLE LOAD

POSITION OF SUSPENSION CABLES W/ BOTH LIVE AND DEAD LOADS. (IN THEORY LOAD IN STRESSING CABLE IS ZERO AT THIS POINT)

POSITION OF SUPPORTING CABLES WITH LOAD OF SUSPENSION CABLES.

POSITION OF STRESSING CABLES WITH NO LOAD. (I.E. WHEN SUSPENSION CABLES ARE SUBJECTED TO BOTH LIVE AND DEAD LOADS.

NORMAL ATTITUDE OF STRESSING CABLES.

DERIVATION OF FORMULA α

BALANCING THE ELONGATION OF THE SUSPENSION CABLES WITH THAT OF THE STRESSING CABLES IS ACCOMPLISHED BY MEANS OF A FORMULA REFERED TO HEREIN AS FORMULA α.

THE FORMULA IS IN ACTUALITY TO DIFFERENT FORMULAE FOR ELONGATION EQUATED ONE TO THE OTHER. THE TWO FORMULAE ARE THOSE OF "GEOMETRIC VARIATION" AND "ELASTIC ELONGATION" AND ARE AS FOLLOWS:

GEOMETRIC VARIATION

$$\Delta \ell = \frac{8}{3} L \left(\frac{h_1^2}{L^2} - \frac{h_2^2}{L^2} \right) \quad OR \quad \frac{8}{3L} \left(h_1^2 - h_2^2 \right)$$

WHERE :
- L = CHORD LENGTH
- h_1 = GREATER DEFLECTION
- h_2 = LESSER DEFLECTION
- $\Delta \ell$ = CHANGE IN ACTUAL CABLE LENGTH

ELASTIC ELONGATION

$$\Delta \ell = \frac{(T_1 - T_2) L}{E \Omega} \quad OR \quad \frac{L^3}{8 E \Omega} \left(\frac{P_1}{h_1} - \frac{P_2}{h_2} \right)$$

WHERE :

$$T_1 = \frac{P_1 L^2}{8 h_1}$$

$$T_2 = \frac{P_2 L^2}{8 h_2}$$

- $\Delta \ell$ = CHANGE IN ACTUAL CABLE LENGTH
- P_1 = GREATER UNIT LOAD
- P_2 = LESSER UNIT LOAD
- h_1 = GREATER DEFLECTION
- h_2 = LESSER DEFLECTION
- E = MODULUS OF ELASTICITY
- Ω = CROSS SECTIONAL AREA OF CABLE ST'L. (EFFECTIVE AREA)

$\therefore$ EQUATING ONE FORMULA TO THE OTHER :

$$\frac{8}{3L}\left(h_1{}^2 - h_2{}^2\right) = \frac{L^3}{8E\Omega}\left(\frac{P_1}{h_1} - \frac{P_2}{h_2}\right) \quad OR$$

$$h_1{}^2 - h_2{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_1}{h_1} - \frac{P_2}{h_2}\right)$$

FOR FORMULA $\propto$ SUBSTITUTING:

$$P_1 = P_i \text{ (INITIAL)}$$
$$P_2 = P_f \text{ (FINAL)}$$
$$h_1 = h_i \text{ (INITIAL)}$$
$$h_2 = h_f \text{ (FINAL)}$$

$\therefore$ FORMULA $\propto$ =

$$h_i{}^2 - h_f{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h_f}\right)$$
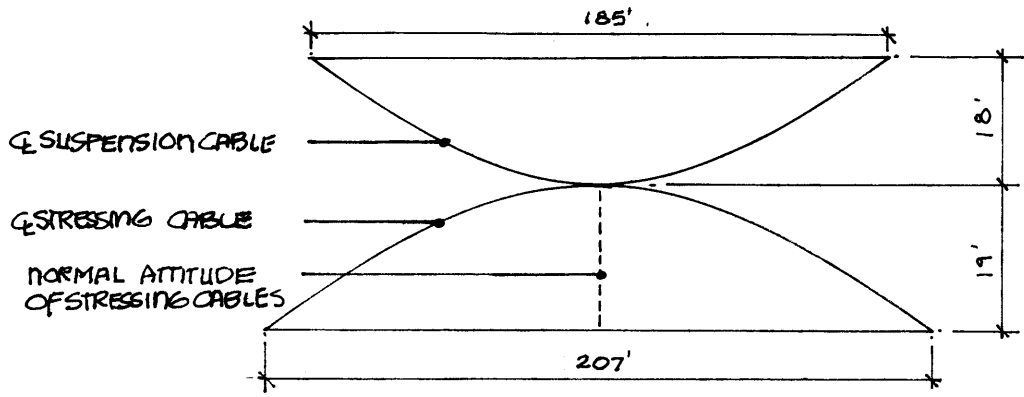
CABLE NETWORK CALCULATIONS

DIAGRAM OF CENTERLINE CABLES

UNIT PANEL LOADS:

    LIVE LOAD = 40 #/SQ.FT.

    DEAD LOAD = 63.4 #/SQ.FT.

LIVE LOAD	= 360 #/FT.
DEAD LOAD	= 570 #/FT.
TOTAL LOAD	= 930 #/FT.

SOLVE FOR HORIZONTAL COMPONENT OF THEORETICAL ₵ SUSPENSION CABLE

$$H = \frac{PL^2}{8h} = \frac{930 \times 185^2}{8 \times 18} = \frac{31,800,000}{144}$$

$$H = 221,000 \#$$

SOLVE FOR MAXIMUM TENSION IN CABLE

$$T_{max} = H(1 + 16\Theta^2)^{1/2}$$

$$= 221,000 (1 + .15)^{1/2}$$

$$= 221,000 (1.07)$$

$$T_{max} = 237,000 \# \text{ (MAX. TENSION IN } ₵ \text{ SUSPENSION CABLE)}$$

$$\Theta = \frac{h}{L} = \frac{18}{185} = .097$$

$$\Theta^2 = .0094$$

$$16\Theta^2 = .15$$

SOLVE FOR REQUIRED EFFECTIVE CABLE AREA

$$\Omega = \frac{T_{ACTUAL}}{T_{ALLOWABLE}} =$$

$$= \frac{237,000}{125,000}$$

$$\Omega = 1.9 \text{ SQ. INCHES}$$

SOLVE FOR SUSPENSION CABLE HEIGHT DUE TO REMOVAL OF LIVE LOAD.

$$h_i^2 - h_f^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h_f}\right) \quad \text{(FORMULA } \alpha\text{)}$$

$$18^2 - h_f^2 = \frac{3 \times 185^4}{64 \times 20 \times 10^6 \times 1.9}\left(\frac{930}{18} - \frac{570}{h_f}\right) \quad \text{OR} \quad 324 - h_f^2 = \frac{3509 \times 10^6}{2432 \times 10^6}\left(51.7 - \frac{570}{h_f}\right)$$

$$324 - h_f^2 = 75 - \frac{825}{h_f} \quad \text{OR} \quad 249 - h_f^2 = \frac{825}{h_f}$$

$$h_f^3 - 249\,h_f = 825 \qquad \text{EQUATION CAN BE SOLVED BY QUADRATICS, BUT IS MORE READILY DONE BY TRIAL } \& \text{ ERROR}$$

TRY $x = 17$ FOR $x^3 - 249x = 825$

$$4913 - 4270 = 643 < 825 \qquad \text{no}$$

TRY $x = 17.2$

$$5088 - 4280 = 808 \cong 825$$

$$h_f = 17.2 \text{ FT.}$$

SOLVE FOR Δi

$$\Delta i = h_i - h_f = 18 - 17.2$$

$$\Delta i = .8 \text{ FT.}$$

SINCE THE STRESSING CABLES REINTRODUCE A PORTION OF THE LIVE LOAD, IT IS POSSIBLE TO SAY THAT THE "FINAL POSITION" WILL BE SOMEWHERE BETWEEN 0 AND .8 FT.. BY TRYING VARIOUS VALUES BETWEEN 0 AND .8, IT IS POSSIBLE TO DETERMINE WHAT THE ACTUAL Δi WOULD BE FOR A GIVEN SIZE OF STRESSING CABLE CAPIBLE OF TAKING THE LOADS APPLIED UPWARD BY THE SUSPENSION CABLES WHEN THEY TRY TO MOVE FROM THEIR "h INITIAL" TO "h FINAL" POSITION. SINCE THERE ARE A NUMBER OF VARIABLES INVOLVED, THIS IS NECESSARILY A TRIAL AND ERROR PROCESS. THEREFORE, START BY TRYING $\Delta i/2$ AND CHECK WHAT WOULD BE THE SHAPE OF THE STRESSING CABLES WHEN THE SUPPORTING CABLES LIFT AND TRANSFER THEIR LOADS.

NOTE: IT IS NECESSARY TO RETAIN THE SAME SIZE CABLE "Ω" SELECTED FOR STRESSING CABLES AT $\Delta i/2$ THROUGH-OUT THE CALCULATIONS. THIS RESULTS IN EXCESS LOAD CARRYING CAPACITY IN STRESSING CABLES WHICH WILL BE UTILIZED TO GIVE AN ADDITIONAL STRESS TO ASSURE THAT STRESSING CABLES DO NOT GO SLACK UNDER TOTAL LIVE AND DEAD LOADS.

TRY $\Delta i/2$

$$\Delta i/2 = \frac{.8}{2} = .4$$

SOLVE FOR h_3 (h FOR $\Delta i/2$ ASSUMPTION)

$$h_3 = h_i - \Delta i/2 = 18 - .4$$

$$h_3 = 17.6 \text{ FT.}$$

SOLVE FOR P_3 (P FOR $\Delta i/2$ ASSUMPTION)

$$h_i^2 - h_3^2 = \frac{3L^4}{64 E \Omega}\left(\frac{P_i}{h_i} - \frac{P_3}{h_3}\right) \text{ OR } 324 - 310 = \frac{3 \times 185^4}{64 \times 20 \times 10^6 \times 1.9}\left(\frac{930}{18} - \frac{P_3}{17.6}\right)$$

$$14 = 1.45\left(51.6 - \frac{P_3}{17.6}\right) \text{ OR } 14 = 75 - \frac{1.45 P_3}{17.6} \text{ OR } \frac{61 \times 17.6}{1.45} = P_3$$

$$\frac{61 \times 17.6}{1.45} = P_3$$

$$P_3 = 740 \text{ \#}$$

DETERMINE P FOR STRESSING CABLES

$$P_3 - P_f = 740 - 570$$

$$P_3 - P_f = 170 \text{ \#/FT.}$$

SIZE STRESSING CABLE @ $\mathbb{C}$

$$H = \frac{PL^2}{8h} = \frac{170 \times 207^2}{8 \times 19} = \frac{7,300,000}{152}$$

$$H = 48,000 \text{\#}$$

$$\Theta = \frac{h}{L} = \frac{19}{207}$$

$$\Theta = .092$$

$$T_{MAX} = H(1 + 16 \Theta^2)^{1/2} = 48,000 (1.064)$$

$$T_{MAX} = 50,600 \text{ \#}$$

$$A_{REQ'D.} = \frac{T \text{ ACTUAL}}{T \text{ ALLOWABLE}} = \frac{50,600}{125,000}$$

$$\Omega = .41 \text{ SQ. IN.} \quad \text{AREA REQUIRED FOR } \mathbb{C} \text{ STRESSING CABLE}$$

CHECK $\Delta i/2$ ASSUMPTION
SOLVE FOR h'_f

$$h_i^2 - h_f'^2 = \frac{3L^4}{64 E \Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h_f'}\right) \quad \text{WHERE } P_i = 0$$

$$19^2 - h_f'^2 = \frac{3 \times 207^4}{64 \times 20 \times 10^6 \times .41}\left(0 - \frac{170}{h_f'}\right) \text{ OR } 361 - h_f'^2 = \frac{5509 \times 10^6}{525 \times 10^6}\left(-\frac{170}{h_f'}\right)$$

$$361 - h_f'^2 = 10.6\left(-\frac{170}{h_f'}\right) \text{ OR } h_f'^3 - 361 h_f' = 1800$$

SOLVE FOR h'_f BY TRIAL AND ERROR

$$x^3 - 361x = 1800$$

TO CHECK, h'_f WOULD EQUAL 19.4 $(19 + .4)$ $\therefore \longrightarrow$

TRY $x = 19.4$

$$7301 - 7000 = 301 < 1800 \quad \therefore \text{ CHECK NOT GOOD}$$

AND STRESSING CABLE WILL DEFLECT GREATER THAN .4 FT. UNDER 170#/FT. LOAD.

TRY $x = 21.1$

$$9394 - 7620 = 1774 \cong 1800 \quad OK$$

SAY $h'_f = 21.1$ FT.

STRESSING CABLE WOULD DEFLECT 21.1 FT. UNDER 170#/FT. LOAD. $\therefore$ ASSUME DIFFERENT PROPORTION OF Δi THAT WILL PRODUCE A LOWER VALUE OF $P_3 - P_f$ AND CHECK AGAIN.

TRY 3/4 Δi

$$3/4 \times .8 = .6$$

SOLVE FOR h_3

$$h_3 = h_i - 3/4 \Delta i = 18 - .6$$
$$h_3 = 17.4$$

SOLVE FOR P_3 (FOR 3/4 Δi ASSUMPTION)

$$h_i^2 - h_3^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_3}{h_3}\right) = 324 \cdot 303 = 1.45\left(51.6 - \frac{P_3}{17.4}\right)$$

$$21 = 75 - \frac{145 P_3}{17.4} \quad OR \quad \frac{54 \times 17.4}{1.45} = P_3$$

$$P_3 = 650\#$$

DETERMINE P FOR STRESSING CABLES

$$P_3 - P_f = 650 - 570 = 80\#/FT.$$

CHECK 3/4 Δi ASSUMPTION

SOLVE FOR h'_f

$$h_i^2 - h'_f{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h'_f}\right)$$

$$361 - h'_f{}^2 = 10.6\left(-\frac{80}{h'_f}\right) \quad OR \quad h'_f{}^3 - 361 h'_f = 848$$

$$x^3 - 361x = 848 \quad \text{WHERE } x = h'_f$$

SOLVE FOR h'_f BY TRIAL AND ERROR.

$$x^3 - 361x = 848 \quad \text{WHERE } x = h'_f$$

TO CHECK h'_f WOULD EQUAL 19 + .6 OR 19.6

TRY $x = 19.6$

$7530 - 7080 = 450 < 848$ NO ∴ CHECK NOT GOOD AND STRESSING CABLE WILL DEFLECT MORE THAN .6 FT UNDER 80#/FT. LOAD.

TRY $x = 20$

$8000 - 7230 = 770 < 848$ NO

TRY $x = 20.1$

$8121 - 7250 = 871 \cong 848$ OK

SAY $h'_f = 20.1$

STRESSING CABLE WOULD DEFLECT 20.1 FT. UNDER 80#/FT. LOAD ∴ ASSUME A DIFFERENT PROPORTION OF Δi THAT WILL PRODUCE A LOWER VALUE OF $P_3 - P_f$ AND CHECK AGAIN.

TRY $5/6 \Delta i$

$$5/6 \times .8 = .67$$

SOLVE FOR h_3

$$h_3 = h_i - 3/4 \Delta i \quad \text{OR} \quad 18 - .67$$
$$h_3 = 17.33$$

SOLVE FOR P_3 (FOR $5/6 \Delta i$ ASSUMPTION)

$$h_i{}^2 - h_3{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_3}{h_3}\right) = 324 - 300 = 1.45\left(51.6 - \frac{P_3}{17.33}\right)$$

$$24 = 75 - \frac{1.45 P_3}{17.33} \quad \text{OR} \quad \frac{51 \times 17.33}{1.45} = P_3$$

$$P_3 = 610\#$$

P FOR STRESSING CABLES

$$P_3 - P_f = 610 - 570 = 40 \#/FT.$$

CHECK $5/6 \Delta i$ ASSUMPTION

SOLVE FOR h'_f

$$h_i{}^2 - h'_f{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h'_f}\right) = 361 - h'_f{}^2 = 10.6\left(-\frac{40}{h'_f}\right)$$

$$h'_f{}^3 - 361 h'_f = 425 \quad \text{OR} \quad x^3 - 361x = 425 \quad \text{WHERE } x = h'_f$$

SOLVE FOR h'_f BY TRIAL AND ERROR

TO CHECK h'_f WOULD EQUAL 19 + .67 OR 19.67

TRY 19.67

$7600 - 7100 = 500 > 425$ NO - STRESSING CABLE WILL DEFLECT LESS THAN .67 UNDER 40#/FT LOAD.

TRY 19.6

$7530 - 7070 = 460 \cong 425$

$$h'_f = 19.6 \text{ FT.}$$

FROM THE PREVIOUS CALCULATIONS IT IS POSSIBLE TO SAY THAT THE ACTUAL Δi PROPORTION IS BETWEEN 3/4 AND 5/6 Δi, THAT THE ACTUAL STRESSING CABLE LOAD (P_3-P_f) IS BETWEEN 80 AND 40#/FT. AND THAT THE ACTUAL $h_i f$ IS BETWEEN 20.1 AND 19.6 FT.

ASSUME VALUES BY INTERPOLATION AND CHECK

$$h'_f = 19.8$$
$$P_3 - P_f = 58 \#/FT \quad (P_f \text{ FOR STRESSING CABLES.})$$

$$h_i{}^2 - h'_f{}^2 = \frac{3L^4}{64E\Omega}\left(\frac{P_i}{h_i} - \frac{P_f}{h'_f}\right)$$

$$361 - 392 = 10.6\left(0 - \frac{56}{19.8}\right) \quad OR \quad -31 = -\frac{10.6 \times 58}{19.8}$$

$$31 = 31 \quad \therefore \text{ ASSUMPTION OK}$$

FINAL CABLE SYSTEM STATE OF REPOSE WOULD BE CONTROLLED BY THE CENTERLINE SUSPENSION AND STRESSING CABLES (BOTH THEORETICAL IN THIS CASE SINCE NETWORK HAS AN ODD NUMBER OF SPACES IN TRANSVERSE AND LONGITUDINAL DIRECTIONS), THE SUSPENSION CABLES AT THE OUTSIDE OF THE CABLE NETWORK (I.E. THE LINE OF THE SUSPENDED SIDE TRUSS), AND THE TWO EQUAL PARALLEL LINES FROM WHICH THE SUSPENSION CABLES HANG. CALCULATIONS FOR SUSPENSION AND STRESSING CABLES ARE FIGURED BY MEANS OF DIMENSIONS ON DIAGRAM AT BEGINNING OF CABLE NETWORK CALCULATIONS, WHILE THE FINAL NETWORK SHAPE IS CONTROLLED BY THE LINES IN THE FOLLOWING DIAGRAM:
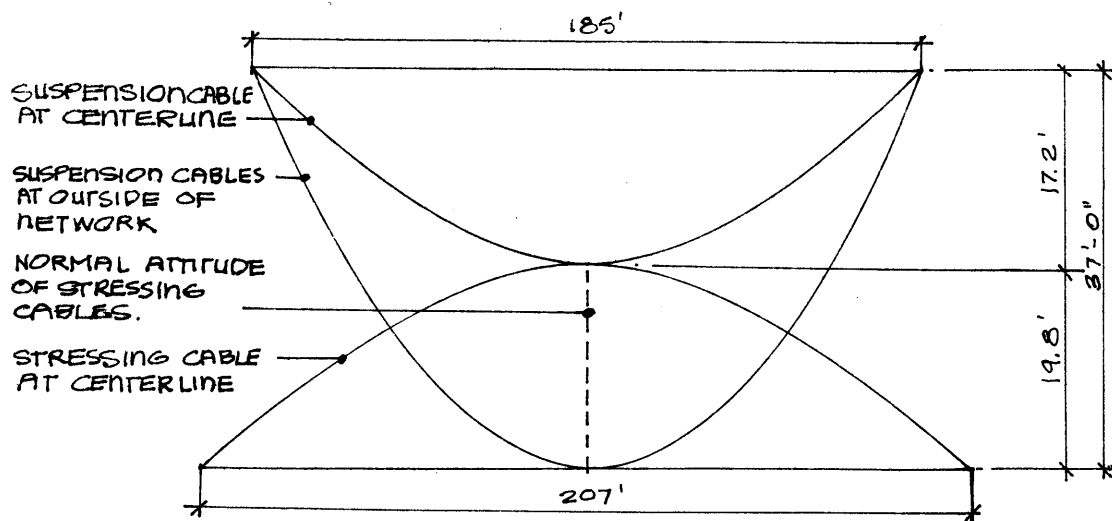
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