MICROCONCRETE MODEL CONSTRUCTION

OF A

PRESTRESSED SUSPENDED ROOF

By

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1957

Submitted to the Faculty of the Graduate School
of the Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF ARCHITECTURAL ENGINEERING
May, 1965

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PREFACE

Suspended roof structures are not new. Nomadic tribes were camping in tents thousands of years ago. However, the use of concrete and steel as a replacement for canvas and rope requires many new design approaches by the structural engineer. The suspended roof lends itself to techniques for building simple, lightweight structures. The purpose of this study is to investigate a new technique for prestressing a lightweight suspended roof and to construct a reduced scale structural model of the roof.

Indebtedness is acknowledged to Professor F. C. Salmon for his advice and guidance during graduate study; to Dr. T. S. Dean for his counselling and assistance in the preparation of this study; to Mr. H. Burton, of Bethlehem Steel Company, for his technical assistance regarding wire rope; and to Mr. R. Courtney, of Western Waterproofing Company, for his advice about shotcrete techniques.

The author also wishes to express his appreciation to his engineering classmates who assisted in the construction of the microconcrete model.

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CHAPTER I

INTRODUCTION

General Discussion of Suspended Roofs

Within the last ten years a considerable number of structures have been designed and constructed which have used the suspension or hanging roof. The construction of the Raleigh Arena in North Carolina heralded this construction technique to the United States (1). Many notable suspended roof structures have gained the attention and admiration of the general public since the completion of this arena. Undoubtedly, the well-publicized gymnasiums by Tange at the 1964 Tokyo Olympics have aroused prospective clients as well as architects and engineers to the economic and aesthetic benefits to be gained by using cable-suspension roofs (2). The future holds limitless possibilities for hanging roofs and research must be expanded in the areas of design and construction techniques.

One logical structural solution to the design of the suspension roof is to transfer the principles of suspension bridge design to buildings. Unfortunately, along with the advantages of the suspension bridge also come its disadvantages. The disadvantage, or characteristic which is the most unpredictable and dangerous to the safety of the buildings' occupants is the roof's aerodynamic instability. This instability or "flutter" is the movement which is usually caused by wind forces acting on the roof surface in such a way as to make the roof oscillate and perhaps to collapse. This phenomena is particularly important in suspended roofs of single curvature. It may be helpful, at the beginning of this study, to discuss some of the more common ways to dampen roof oscillations.

There are several ways to eliminate vibrations of hanging roofs. Many designers attempt to eliminate flutter by the addition of a continuous mass such as cast-in-place concrete or precast concrete slabs attached to the cables, or by the addition of supplementary guy cables tying the roof to the ground (1). All of these methods help to stabilize the roof; however, the added cost of providing mass sometimes prices the roof out of competition, with, for example, compression shell construction.

The problem of dampening vibrations and eliminating flutter is considerably less in hyperbolic paraboloid and other anticlastic roof surfaces. Such roofs of double curvature may employ a system of orthogonal, interconnected cables, one set of which has downward curvature and the other an upward convexity. The tension of one set of cables is, thus, assured by the tension of the other group and vice versa. An example of this system is shown in Figure 1.

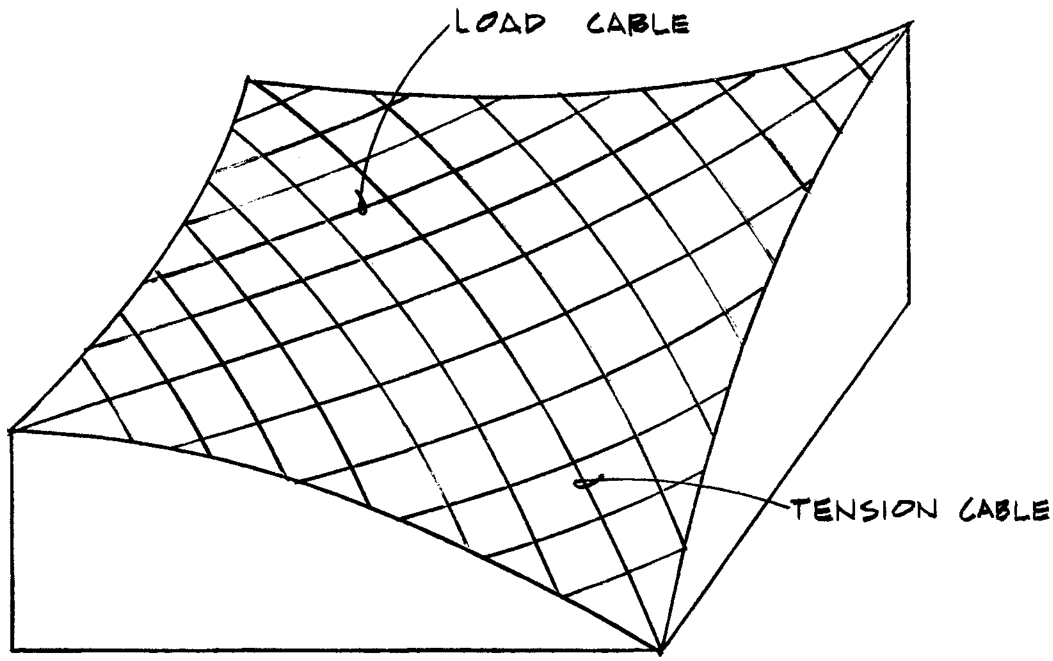


Figure 1. Doubly Curved Roof Employing Orthogonal Interconnected Cables

Some schemes employ a two surface cable system. The upper cable always assumes a different geometric configuration than the lower. Therefore, one cable will dampen the vibrations of the other. Figure 2 shows some typical two surface cable systems.

Since the choice of roof shapes is often an architectural decision, a method for the elimination of flutter in all suspended roof systems, including single layer surfaces, is of prime importance.

An interesting technique for the elimination of flutter in the design of a single layer suspension roof has been developed in which the roof cable network is prestressed. In this technique, precast concrete roof slabs are attached to the suspender cables (see Figure 3).

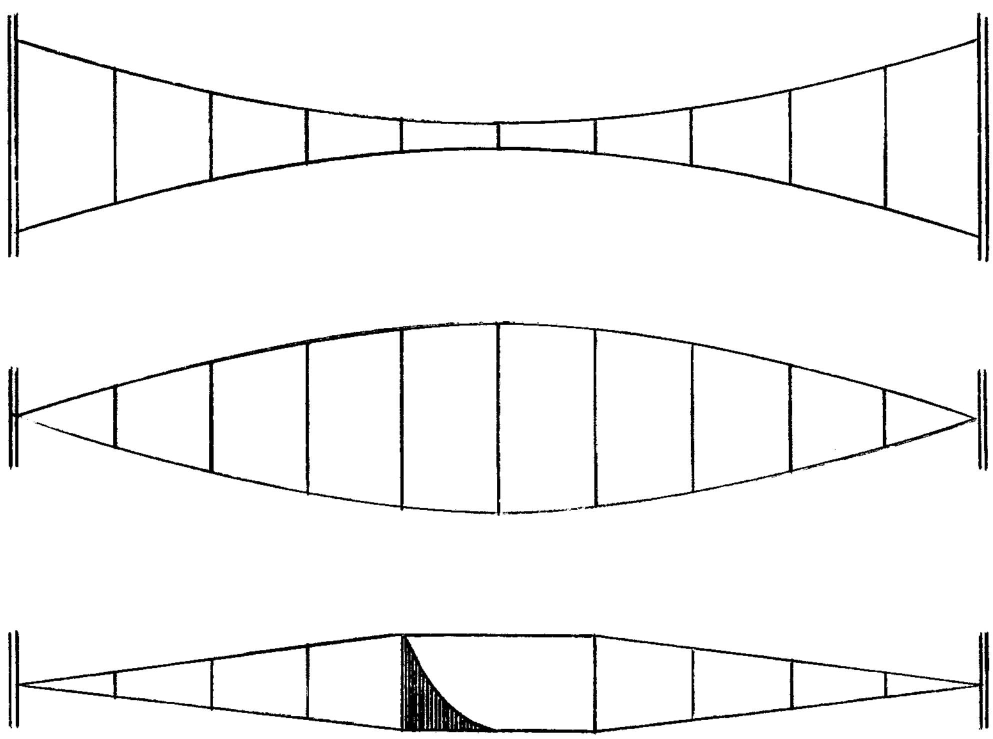


Figure 2. Typical Two Surface Cable Systems

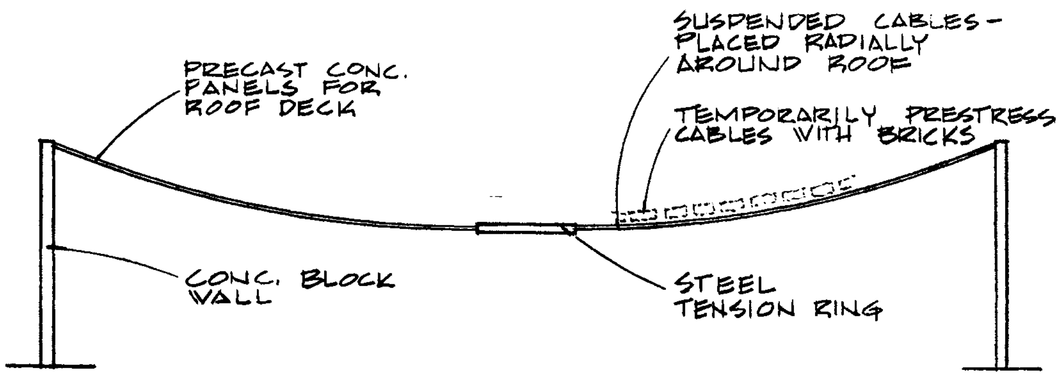


Figure 3. Montevideo Stadium Prestressing Technique

Then, small groups of bricks are placed on the slabs to temporarily overload the roof, causing the cables to elongate. While the temporary load is in place, the openings around the cables and between the slabs are filled with grout. After the grout has hardened, the bricks are removed. The result is that the inverted dome is radially stressed. This operation improves the monolithic quality of the roof and helps reduce its tendency to flutter under dynamic loads. Excellent cost reduction was achieved by using this roof construction technique on a 20,000 seat stadium completed in 1958 for the City of Montevideo, Uruguay (3). The Montevideo Stadium prestressing technique is what prompted the investigation, in this thesis, of a new method for prestressing.

Purpose of Investigation

This thesis has two purposes:

First, since the use of suspended roofs is not yet common, there is a great deal of research to be done in the areas of design, use of materials, and construction techniques. Therefore, in this thesis, a new construction technique is proposed for prestressing a single layer hanging roof. A structure whose dimensions are chosen arbitrarily is used as an example to illustrate the prestressing method.

Second, it is often difficult and expensive to conduct full scale tests of structural systems. Yet, it is necessary to determine the actual performance of construction methods before their widespread use is allowed. An often neglected, although valid engineering tool, in addition to mathematical analysis, is the construction of a reduced scale model of the structure. By using models, many of the actual loading conditions and strength characteristics of structures can be investigated. Therefore, in this thesis, certain model materials and techniques are tried in order to determine if they are apropos to the construction of models of hanging roofs. In order to test techniques on an actual case, a model of the proposed prestressing method is constructed.

CHAPTER II

PROPOSED TECHNIQUE FOR PRESTRESSING

Concepts

Certain advantages and disadvantages are noted in the prestressing technique used by Mondino, Viera, and Miller in the design of the Montevideo Stadium. The greatest advantage is, of course, the low cost of the roof. This technique of construction was several times lower in cost than the nearest competing systems. Also, the erection time of the roof was very short. According to Schupack (3), the breakdown of construction time was as follows:

Raising and positioning central ring: 1 day
Connecting the 256 radial cables: 6 days
Setting the 9000 slabs: 17 days
Placing the overload of bricks: 10 days
Filling between the slabs: 1 day (21 hours)
Unloading the overload: 5 days.

Among the disadvantages of the system is the questionable bond between the mortar and the cables when hand grouting is employed. Also, a true monolithic membrane does not result because the panel system inherently tends to divide the roof into discrete areas. And, finally, many independent operations are required to construct the roof.

The technique proposed in this study attempts to retain the advantages of the Montevideo Stadium, and to convert its disadvantages to advantages by modifying construction methods and materials.

Proposed Technique

A technique is proposed whereby a paper-backed metal lath screen is secured to the top of the wire ropes. This mesh is 2 x 2 - No. 14 x No. 14 mesh which is strong enough to accept a man's weight while securing it with "chairs" above the ropes. Weights, such as buckets of sand or pieces of steel, are temporarily hung at equal horizontal distances along the span. It is these weights which provide the prestress to the cables. The weights are hung far enough apart so they will not interfere with the application of the concrete. The concrete is first sprayed from below by pneumatic pressure; the method being known variously as the shotcrete or gunite method.

A thickness of three inches of concrete is sprayed to achieve watertightness. The shotcrete applicator begins by spraying on a one-fourth inch thick surface, letting this set about 24 hours. Then, the remaining thickness is applied in increments of one inch. As the concrete weight builds up, an equivalent weight of sand or steel is removed from the temporary weights. After the entire bottom surface has reached its initial set, the paper is stripped off the mesh, and a smooth surface is sprayed on the top. Shotcrete, because it is applied as dry as possible (i.e., with a low water/cement ratio), attains almost its full strength in 24 hours. ACI Standard 805-51, Recommended Practice for the Application of Mortar by Pneumatic Pressure, is used as the criterion for mixing and placing shotcrete.

Forty-eight hours after the last shotcrete application, the temporary weights are removed and the suspended roof is prestressed. The completed roof is, thus, a stable, monolithic mass which is capable of resisting flutter, uplift from wind loads and other dynamic forces. The metal lath, in addition to acting as a screen to catch the shotcrete, also acts to resist cracks caused by temperature and shrinkage.

The advantages of this application process are as follows:

First, only three basic operations are required -- positioning cables and weights, securing metal lath, and spraying concrete.

Second, all concrete is sprayed directly on the mesh; therefore, no concrete formwork is required.

Third, and perhaps most important, is that the relatively dry mix used in shotcreting results in compressive and tensile strength two to three times that of ordinary concrete (4).

Fourth, better bond between concrete and reinforcement and subsequent watertightness is assured.

Materials

A list of proposed materials is made so that the reduced scale model can incorporate them as realistically as possible.

A. Concrete

1. Aggregate. Natural sand, graded from coarse to fine within the limits as follows:

ASTM C33-46

Pass 3/8 sieve	100 per cent
No. 4 sieve	95-100 per cent
No. 16 sieve	45-80 per cent
No. 30 sieve	25-60 per cent
No. 50 sieve	10-30 per cent
No. 100 sieve	2-10 per cent.

Fineness modulus not less than 2.50 nor more than 3.30.

2. Cement. Portland cement conforming to ASTM specifications for Type II portland cement.

3. Water. Potable quality.

B. Reinforcing

1. Wire rope. Aircraft strand (1 x 19) or bridge strand (1 x 19). Modulus of elasticity is 24,000,000 psi if rope is prestressed.

2. Metal lath. 2 x 2 - No. 14 x No. 14 welded wire fabric with factory applied paper backing.

Prestressing Technique Illustrated

Figure 4, on the following page, shows a section through a proposed lightweight structure using the prestressed roofing technique. Materials, and the roof as it would appear when under prestressing is illustrated.

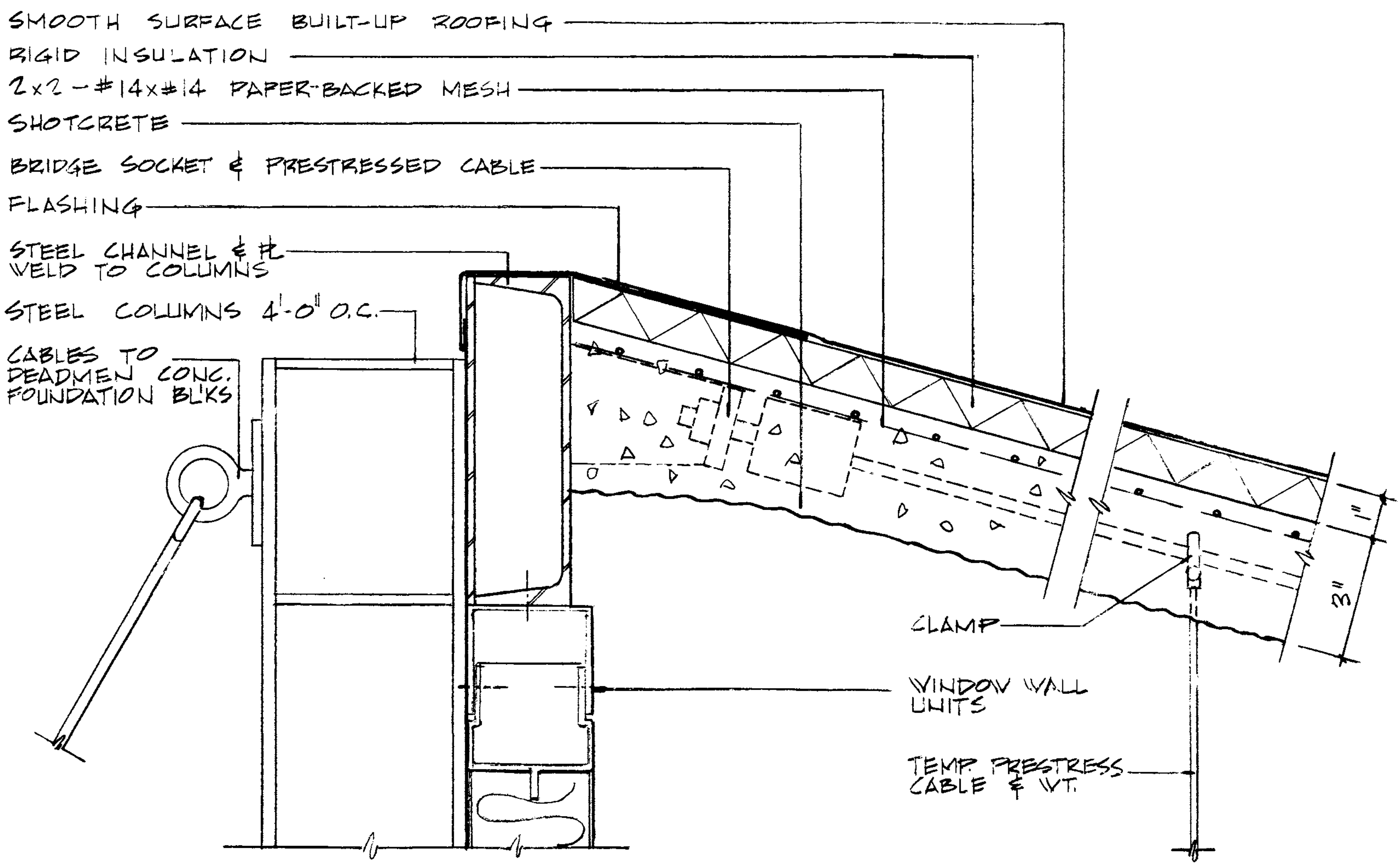


Figure 4. Section Through Proposed Prestressed Roof

CHAPTER III

NUMERICAL EXAMPLE

Statement of the Problem

A small structure is used in the following example in order to apply the proposed prestressing technique to an actual structure. The design of the rigid frame which would support the roof cables, and the foundation required to carry the loads to ground are not presented in this study. Their sizes, as shown on the accompanying drawings, are only approximate.

It is assumed that, in actual practice, the over-all dimensions of the building and the sag to span ratio for a given suspended roof would be determined architecturally. Hence, for analytic purposes, in this example, the dimensions of the structure are chosen for convenience of model construction.

The basic structure uses the suspension bridge principle. It is a simple hanging roof, of single layer construction and of single curvature. It is suspended from two rigid frames which are guyed by cables to "deadmen" in the ground. Economy of materials results from the fact that the structural elements follow the direct lines of force and bending stresses are minimized. The following data and figures indicate the design of the roof. This roof will be constructed later at reduced model size.

Data

A. Dimensions

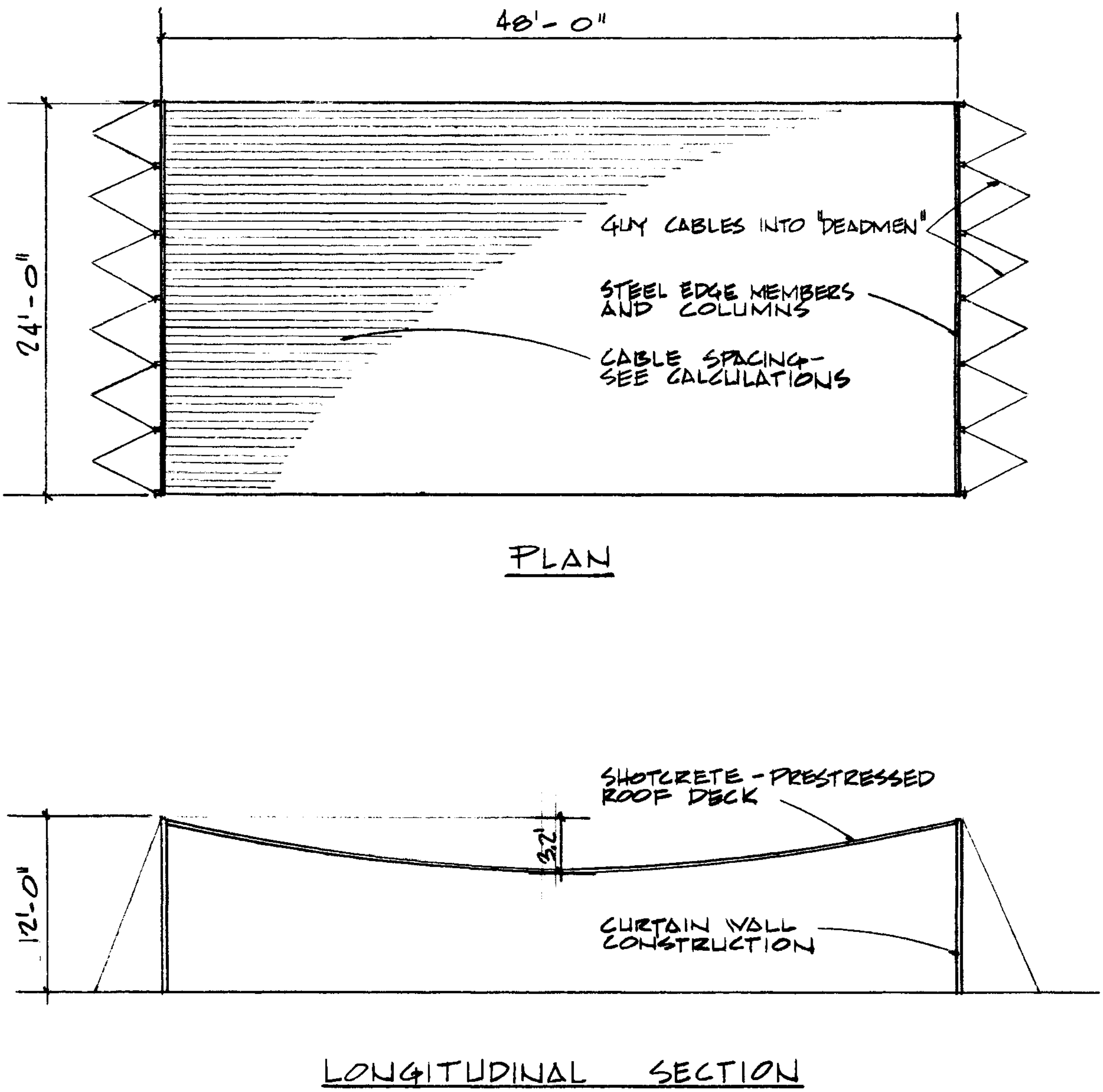


Figure 5. Schematic Plan, Elevation, and Section of Structure to be Analyzed

B. Loads

C. L. ...	Assume 3" concrete for adequate cover over wire rope	37 psf
	Assume total reinforcing weighs	1 psf
	Miscellaneous roofing . . .	2 psf
	Total Dead Load	40 psf
L. L. ...	Total per square foot of horizontal projection . . .	30 psf
T. L. =	D. L. + L. L.	70 psf

C. Cable Spacing

Assume cables can be spaced no closer than three inches O.C. for ease in erection. If cables are spaced closer than three inches, the end connections are difficult to make and the additional temporary weights required make shotcrete application more difficult.

The sag of the cables is selected as one-fifteenth of the span for architectural reasons.

Calculations

A. Tension in Cable and Selection of Cable Size

If sag (f) is $1/15$ of the span (L); $f = 1/15\,L$; $f = \frac{48}{15} = 3.20$ ft. Note: This is the sag of the cable before the application of loads, assuming the cable to be weightless.

The applied dead plus live load per lineal foot of horizontal projection (q) is:

$$q = (40 + 30)\ \frac{lb.}{ft.^2} \times .25\ ft. = 17.5\ \frac{lb.}{ft.}$$

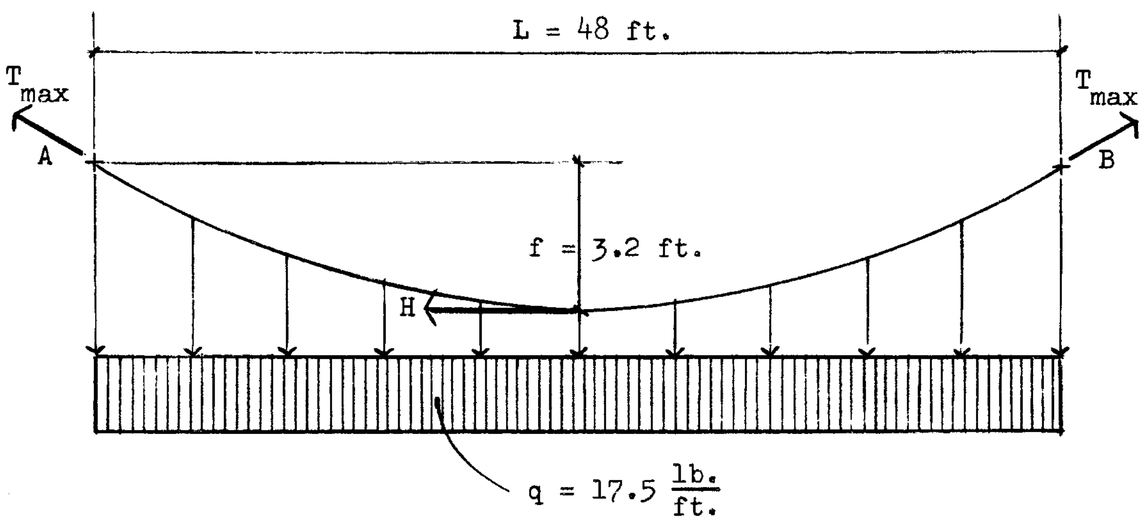


Figure 6. A Typical Cable, Showing Dimensions and Symbols

Referring to Figure 6, where A and B are at the same level, the maximum tension in the cable (T_{max}) is at A and B and is given by the equation:

$$T_{max} = H\sqrt{1 + \frac{16f^2}{L^2}}$$

where H is the tension in the cable at mid-span.

In this example:

$$H = \frac{qL^2}{8f} = \frac{(17.5)(48)^2}{(8)(3.20)} = 1575 \text{ lb.}$$

Therefore, $T_{max} = 1575 \sqrt{1 + 16(\frac{1}{15})^2} = 1620$ lb.

An aircraft strand is selected; choose Bethlehem (5):

$\frac{1}{4}$-inch diameter; 1 x 19 Aircraft Strand (Breaking Strength = 8200 lb.)

The actual tension along the cable varies from a maximum value at the anchorage point to a minimum value at the center of the span. However, for small sag-to-span ratios, it may be assumed that the cable is subjected to a uniform tension equal to T_{max}.

B. Prestress

The prestressing of the cables is accomplished by initially hanging dead weights on each cable equal to the dead load plus the live load. This procedure is similar in concept to the placing of bricks on the precast panels of the Montevideo Stadium.

A series of eleven weights spaced 4' - 0" O.C. along the length of a cable and each equal to

70 lbs. is used to prestress the system of cables. Figure 7 shows the arrangement of the weights.

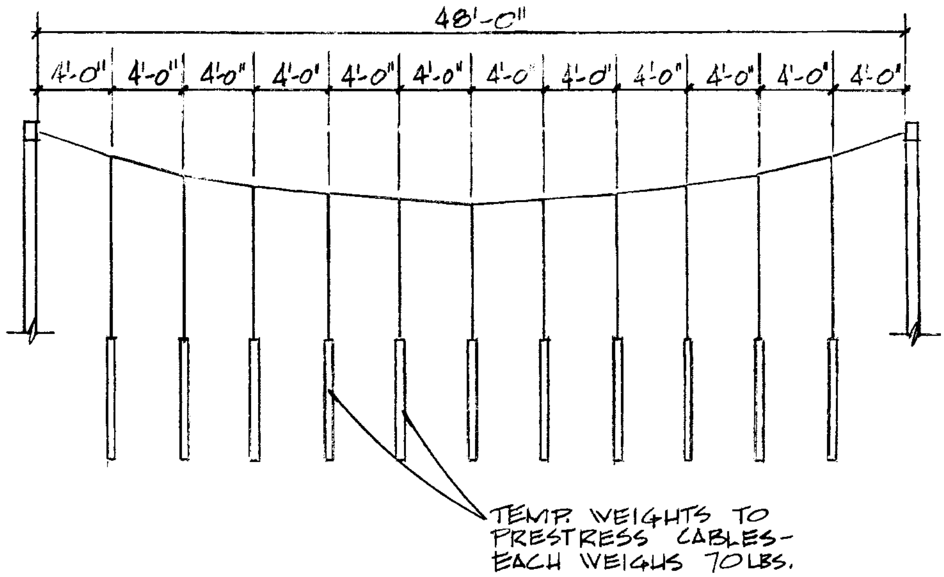


Figure 7. Loading of a Typical Cable

This provides a load of 17.5 lb./lin. ft. of horizontal projection before the shotcrete is applied. As the shotcrete is applied in increments of one inch, an amount of weight equal to the shotcrete increment is removed from the cables. After the roof is completely sprayed, a total weight of 30 lb./lin. ft. of horizontal projection remains. When the last increment of shotcrete has cured, the last 30 pound load is removed. Thus, the roof is prestressed until the full amount of live load is applied.

It is noted that, during preliminary analysis, this roof was designed providing an overload of 10 lb./lin. ft. of horizontal projection in addition to live and dead load. This design proved not feasible since it increased the moment in the frame considerably. It was felt that the increased cost of designing the frame and foundation to carry the temporary overload would not justify the benefits to be gained from the small additional amount of prestress.

The initial prestressing force (F_p) which a cable transfers to the shotcrete by bond is:

$$F_p = \frac{T_{max}}{A_c}$$

where A_c is the area of concrete across which the force acts, or:

$$F_p = \frac{1620}{9} = 18 \text{ psi.}$$

Therefore, 18 psi is the initial prestressing force in the concrete assuming no stress losses. These losses amount to about 12 to 20 per cent of the initial prestress and their summation will decrease any initial prestressing force. Stress losses as mentioned by Preston (10), are:

(1) Shrinkage - As the concrete cures, its volume decreases slightly and it shrinks. As the concrete shrinks, the wire rope is taken with it and shortens an amount equal to the total shrinkage. The wire rope, therefore, experiences a decrease in tension or stress loss. The use of an extremely dry shotcrete application holds this shrinkage to an absolute minimum since the most important factor in shrinkage is the amount of water per unit volume of concrete.

(2) Elastic compression - The concrete shortens due to the intensity of the stress and the modulus of elasticity of the concrete. Therefore, the pretensioned cable will shorten an amount equal to the total shortening of the member.

(3) Creep - Sometimes called plastic flow, this inelastic shortening of the concrete takes place over a period of time. Most sources indicate that creep is a function of the intensity of the compressive stresses and that it is inversely proportional to the concrete's strength. It may also be indirectly related to other

variables such as the age, curing, and type of cement. Creep does serve the useful function of relieving local overloads by redistributing and equalizing stresses.

(4) Relaxation - This is the loss of stress of the wire rope which occurs when it is tensioned to a high stress and then held at that length. This factor would not be important in this roof construction as the stresses in the wire rope are not very large.

The bond of the concrete to the wire rope is extremely important. According to Klieger (12), the bond increases with the compressive strength of the concrete. The relationship is curvilinear, bond strength increasing less rapidly as the compressive strength of the concrete is increased. In some tests of zero-slump vibrated concrete in the strength range of 7000 to 10,000 psi, the yield strength of the steel was developed in most of the tests before pull-out occurred.

For an exact mathematical analysis of the stresses in the roof, it would be necessary to formulate a differential equation incorporating all of the stress losses mentioned above. By equating the shortening of the wire rope to the shortening of the concrete for some time interval dt, a differential equation is formed which can, at best, only approximate the true stresses. Variables such as temperature, exposure conditions, etc., all tending to place the results in error.

The actual prestressing is of such a nominal nature that a reduced scale model is chosen as the means of preliminarily investigating the stress characteristics of this roof. Chapter IV discusses the process of planning the model study, the selection and testing of model materials, and the construction of this particular model.

C. Elastic Elongation of the Cable

Cable, in reality, cannot be considered inextensible. Its length will increase due to the loads applied to it. In the real structure, the sag that would result from the cable lengthening might approximate six inches with a cable elongation of about two inches. In constructing the structural model, this sag becomes important because, unlike in the prototype structure, a form must be built to hold the concrete until it reaches its initial set. Therefore, the length and elastic elongation of a cable is computed as follows:

(1) Length:

For small sag-to-span ratios, referring

to Figure 6, the length of the cable before the application of q is given in the <u>Wire Rope Handbook</u> (5) as:

$$\ell = L\left\{1 + \frac{8}{3}\left(\frac{f}{L}\right)^2\right\}$$

$$\ell = 48\left\{1 + \frac{8}{3}\left(\frac{1}{15}\right)^2\right\}$$

$$\ell = 48.57 \text{ ft.}$$

(2) Elastic elongation:

Using a one-fourth inch aircraft strand with cross-sectional area (A) of .04 in.^{2} and modulus of elasticity (E) of 24,000,000 psi, the elastic elongation of a cable ($\Delta\ell$) is given by the formula:

$$\Delta\ell = \frac{T_{max}L}{A_E}$$

$$\Delta\ell = \frac{(1620)(48)}{(.04)(24 \times 10^6)}$$

$\Delta\ell$ = .08 ft. or approximately one inch.

Therefore, the cable length after the application of the temporary weights equals 48.57 + .08 or 48.65 ft.

The new sag of the cable (Δf) is:

$$\ell = L\left\{1 + \frac{8}{3}\left(\frac{f}{L}\right)^2\right\}$$

$$48.65 = 48\left\{1 + \frac{8}{3}\left(\frac{f}{48}\right)^2\right\}$$

$$f = 3.68 \text{ ft.}$$

Referring to Figure 8, it can be seen that Δf is approximately equal to five and three-fourths inches.

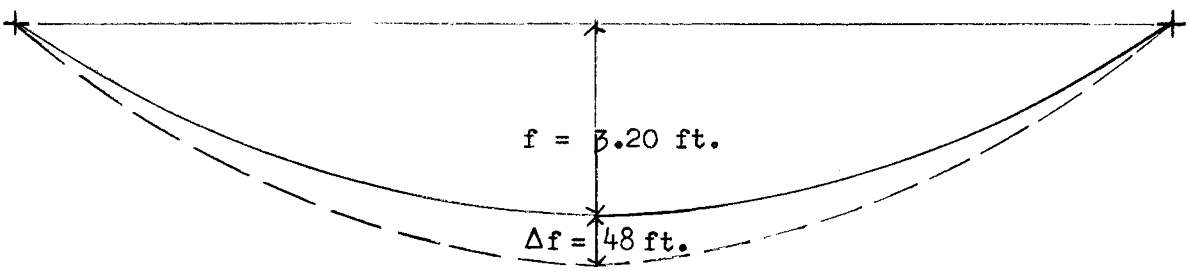


Figure 8. Elastic Elongation of a Typical Cable

Actually, the cable will be in equilibrium somewhere between 3.20 and 3.68 ft., because at f = 3.68 ft., the actual tension in the cable will be less than 1620 lb; hence, the cable will not sag the full 3.68 ft.

It may be noted at this point, in order to keep a constant prestress on the cables, an amount of weight equal to the dead load of shotcrete being sprayed on must be removed from the prototype structure. However, in the structural model, because the formwork carries the load of the concrete, the model weights remain constant throughout the construction and curing process.

Sufficient information has now been introduced so that the selection of the model materials and construction of the structural model can proceed.

CHAPTER IV

CONSTRUCTION OF THE STRUCTURAL MODEL

Determination of Model Materials (General)

The choice of the materials to use in constructing the model depends mainly on the purpose of the test. The purpose of testing this roof is to consider the behavior of a roof made of an anisotropic material, prestressed concrete, and to observe the performance of the roof until failure occurs. It is necessary, therefore, to establish a correlation between the stresses and strains in the model and those of the prototype structure in the stress/strain regions under investigation. It is anticipated that a tension failure will occur in the microconcrete before the breaking strength of the cable is reached. However, a wire rope connection in the model must be made to develop the yield strength of the cable in the event that this assumption is wrong. The following discussion is concerned with the selection of model materials; an evaluation of their structural characteristics; and the construction of the model.

Scaling the Prototype

The first step in the planning of the physical structural model is to determine its scale. The laws of similitude can be used to determine the model size if the dimensions of the prototype are known. The following tables list the prototype and model sizes.

TABLE I

PROTOTYPE SIZES

Prototype	Magnitude		Dimension
Width of roof	24	ft.	L
Length of roof	48	ft.	L
Sag of roof	3.20	ft.	L
Thickness of roof	0.25	ft.	L
Wire rope size	0.0208	ft.	L
Length of cable	48.57	ft.	L
Modulus of Elasticity (concrete)	6×10^6	psi	F/L^2
Modulus of Elasticity (wire rope)	24×10^6	psi	F/L^2
Dead Load	40	psf	F/L^2
Live Load	30	psf	F/L^2

A scale ratio of 1:8 is chosen. It has been found by previous experiments that microconcrete cannot be adequately placed if the roof thickness of the model is less than about three-eighths inch (7). In this model study, a reduction from three inches to three-eighths inch gives a scale ratio of 1:8. This ratio in turn dictates all the other geometrical relationships.

It may be noted that modulus of elasticity and load have the same units. When the model and prototype have the same geometrical scale factor throughout, Charlton (8) states that:

$$F = s^2 \frac{E}{E_m} F_m$$

where F and F_m denote force applied to the prototype and model, respectively; s is the scale factor, eight in this case; and E and E_m denote the modulus of elasticity of the prototype and the model, respectively. When the model is made of the same material as the prototype, the relationship between force on the model and force on the prototype becomes:

$$F_m = \frac{F}{s^2} .$$

This is the formula used in determining the loads placed on the structural model. These loads and the other geometrical reductions are shown in Table II (on the following page).

TABLE II

MODEL SIZES

Model	Magnitude
Width of roof	3.0 ft. = 36 in.
Length of roof	6.0 ft. = 72 in.
Sag of roof	0.4 ft. $\doteq 4\frac{13}{16}$ in.
Thickness of roof	0.0313 ft. = $\frac{3}{8}$ in.
Wire rope size	0.0208 ft. = $\frac{1}{32}$ in.
Length of cable	6.08 ft. = $72\frac{31}{32}$ in.
Modulus of elasticity (microconcrete)	6×10^6 psi
Modulus of elasticity (aircraft strand)	24×10^6 psi
Dead Load	0.625 psf
Live Load	0.469 psf

Model Materials

A. Microconcrete

1. General

It is decided to use microconcrete as a substitute for concrete. Microconcrete is a model material corresponding to concrete in its properties, but having its aggregates scaled down to model size by the laws of similitude. Ideally, the microconcrete is mixed to the same cement/

aggregate and water/cement ratio as prototype material.

A series of trial mixes must be made in order to gain an insight into the actual strength of the material. Trial mixes are necessary in determining the variance of locally available aggregate on the compressive strength of the microconcrete. Prototype shotcrete should develop, at least, a compressive strength of 3000 psi at seven days and 4000 psi at 28 days. Thus, the microconcrete must be designed to develop a compressive strength of 4000 psi at seven days.

2. Aggregates

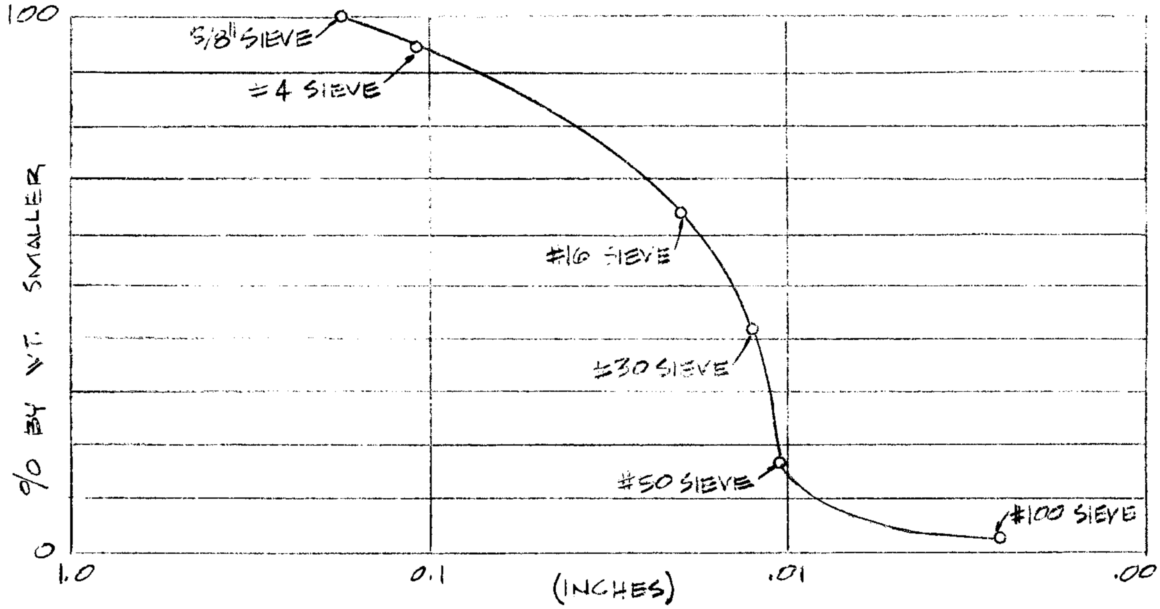
The aggregate sieve analysis for shotcrete, as stated in Chapter III, must be matched as closely as possible in the model material. A local Oklahoma river sand is used for aggregate in this microconcrete model. This material is selected because it is easily obtained and upon close inspection, the aggregates are well shaped even in the smaller sieve sizes such as the No. 50 and No. 80. When a crushed rock aggregate of small size is investigated, it is found that the individual particles are flaky and plate-like. With this type of particle more cement is required to cover all surfaces of the aggregates. This is considered less desirable than the more round or cubical aggregates.

A good concrete aggregate must be clean. Since the aggregate size is considerably scaled down, an excellent material at prototype size may not be clean at model size.

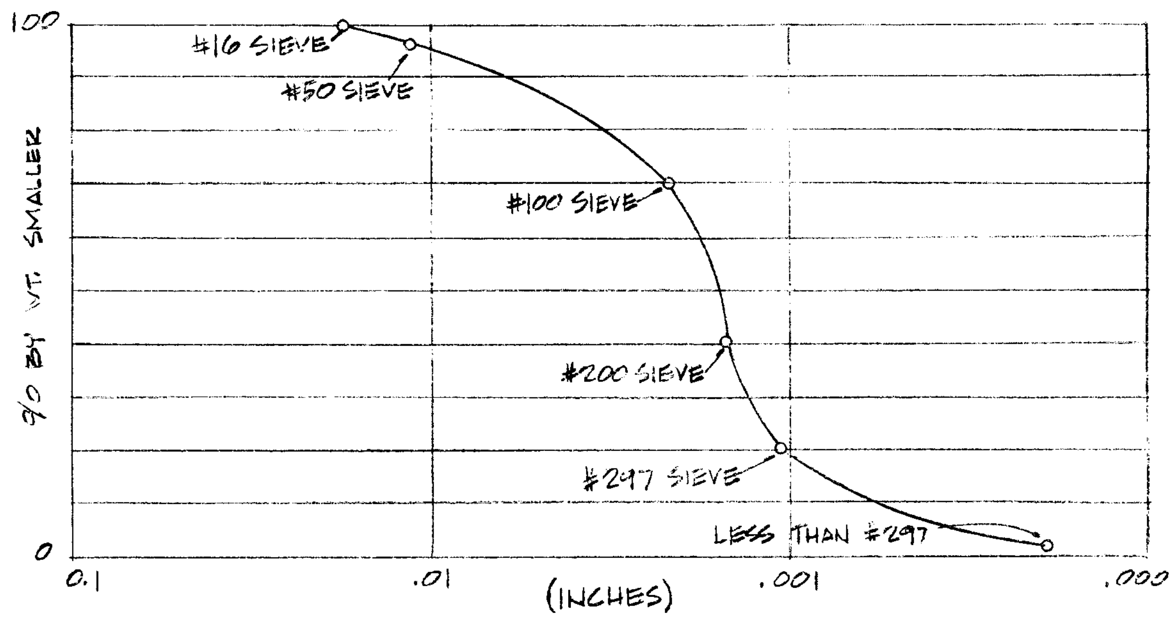
This over-all rise in percentage of impurities results because a great percentage of the large material is screened out, while the vast majority of the fine clay particles which are less than .002 mm are permitted to pass the sieves. A test must be conducted to determine the amount of organic impurities present. This test, ASTM C40-48 Standard Method of Test for Organic Impurities in Sands for Concrete, conducted on the river sand used in this model showed it to have a color not as dark as the reference standard color. It is, therefore, acceptable for use.

Having established that the aggregates are clean at model size, the material must now be tested to determine the effect of various proportions of large and fine material on the strength of the concrete. To do this, a series of trial aggregate mixes are made. Figure 9 shows the gradation curves of both the prototype material and an ideal model aggregate plotted on a semi-log scale. As can be seen from Figure 9b (on the following page), the model material becomes too fine to reproduce in sizes under the No. 100 sieve. Almost 70 per cent of the material would be of dust particle size and it would be extremely organic. Therefore, a simplified approximation must be made when scaling down sand aggregate.

The gradation curves, as shown in Figure 10 (page 33), are the result of simplifying the gradation and restricting the aggregate size to less than the No. 16 sieve and greater than the No. 100 sieve.

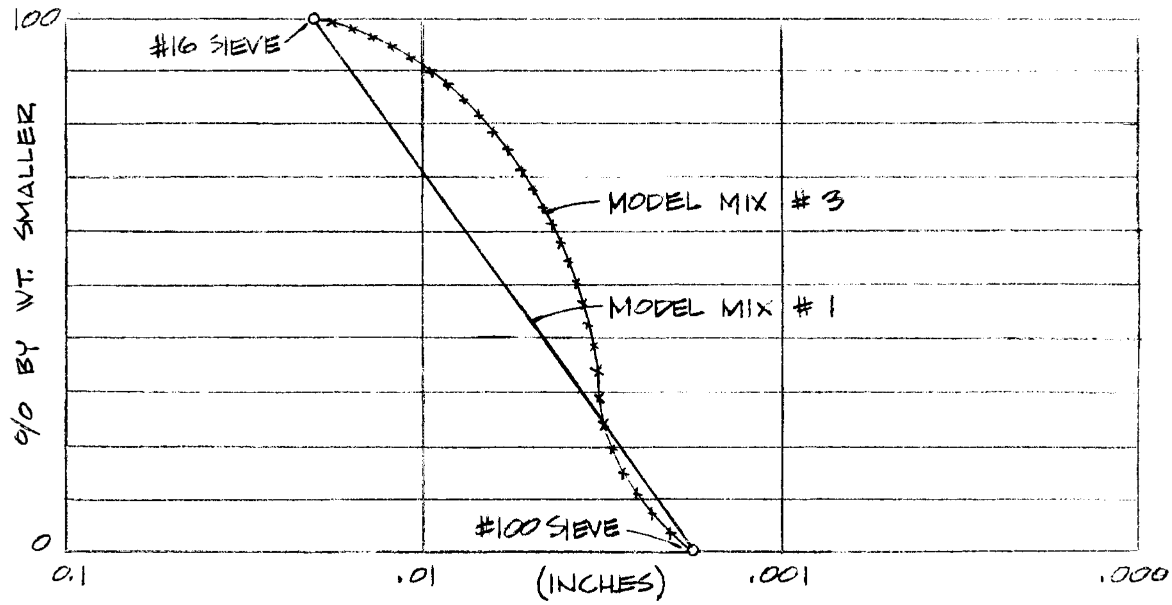


(a) Gradation Curve - Prototype Material

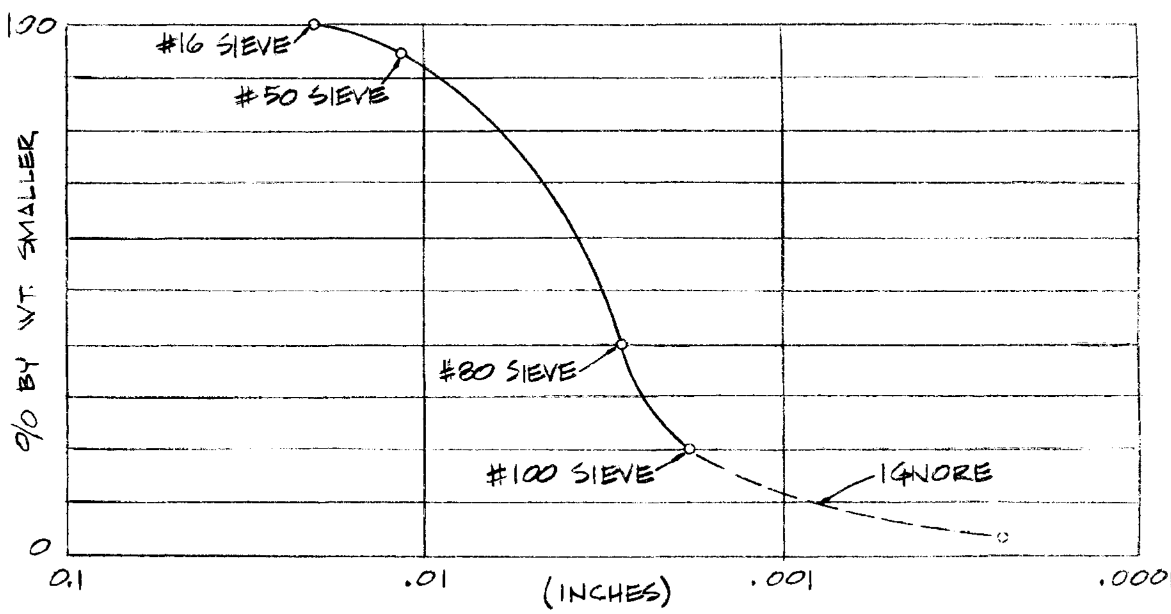


(b) Gradation Curve - Ideal Model Mix

Figure 9. Grain Size Distribution Curves, Prototype, and Ideal Microconcrete Model Mix



(a) Gradation Curve - Model Mix No. 1 and No. 3



(b) Gradation Curve - Model Mix No. 2

Figure 10. Grain Size Distribution Curves, Microconcrete Model Mixes

The gradation curve for Model Mix No. 1, as shown in Figure 10a (on the preceding page), is the result of using only two sieve sizes in the mechanical shaker. The assumption being that the material between the two sieves is reasonably well graded. Actually, there is a small amount of material which is less than the No. 100 sieve still retained in the mix, although the material was shaken approximately 2000 times in a mechanical shaker.

The gradation curve for Model Mix No. 2, as shown in Figure 10b, is the result of grading the aggregates between the sieve sizes as shown in the figure. Then, a blend of aggregate was mixed to approximate as closely as possible the ideal mix only in the region of maximum material. The 20 per cent of material below the No. 100 sieve is ignored in the mix.

The gradation curve for Model Mix No. 3, as shown in Figure 10a, is the result of blending 50 per cent by weight of the material hand sieved between the No. 16 and the No. 50 sieve and 50 per cent by weight of Model Mix No. 1. The attempt being to get a greater percentage of large aggregate into the mix. It is thought that this might improve the strength of the concrete.

3. Water

Ordinary tap water at approximately 70°F is used in mixing the microconcrete.

4. Cement

Cement used in the model study is ASTM C150 - Type III, high early cement, as contrasted to Type II, modified portland cement as recommended in ACI Standard 805-51 (13). High early portland cement is used because it reaches high strength in a short period of time. The Portland Cement Association (9) reports Type III cement to have approximately 190 per cent of the strength of normal portland cement in three days. Although good compressive strength is a definite advantage when conducting a series of microconcrete compressive test studies, because cylinders can be broken in seven days, it does not appreciably accelerate the testing of the actual model. Pahl (6) recommends that the model not be tested for 21 days to insure it is entirely cured even though high early cement is used.

5. Cylinders

In this study, two cylinder sizes are tried. One size is scaled according to the laws of similitude; that is, to a 1:8 reduction. The other size is double the height and diameter of the smaller cylinder. The purpose being to determine if varying the size of the cylinder has any effect upon the compressive strength of the material.

There are definite advantages in using a larger size cylinder. It was found to be very difficult to fill a cylinder of three-fourths inch diameter, so no voids result in the concrete. Also, there is more inaccuracy achieving dimensions close to tolerance in the smaller cylinders.

The cylinder size may be changed at will, so long as the ratio of the diameter of the cylinder to the maximum size aggregate is not less than 3 to 1. The model cylinders, as shown in Figure 11, are the type used in this test. The larger cylinder is one and one-half inches in diameter and three inches long. It is cut from a standard cardboard mailing tube, prescored for easy removal of the speciman, and dipped in paraffin. The smaller cylinder is handmade from layers of construction paper, formed on a wood dowel core, and coated with crayon.

6. Curing

Test cylinders can be cured in several ways. In all cases, they should be allowed to cure at air temperature during the first 24 hours, the ends being covered with a glass or metal plate to prevent evaporation. After the initial 24 hour period, the cylinder is stripped off of the speciman and it is stored in a manner to guarantee that free water is maintained on the surface of the speciman at all times. This may be done by either placing the speciman in a "fog room" or merely placing it in a bucket of water with a temperature of 65° to 75°F. A saturated lime solution is used to remove any sulfate action of the water on the concrete. However, some authorities feel that ordinary tap water is sufficient. It is noted that samples of the actual

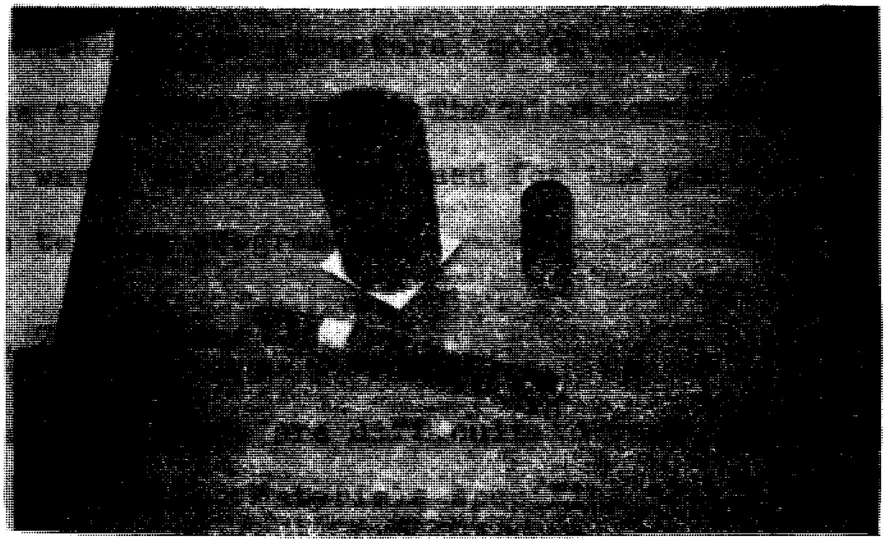


Figure 11. Model Cylinders

Figure 12. Typical Microconcrete Cylinders After Compression Testing

concrete used in the structural model are cured in the same manner as the model itself. The microconcrete specimans cured in water are the ones used for the preliminary micro-concrete testing program only.

7. Capping

Small cylinders are difficult to cap. The American Society for Testing Materials specifies that capped surfaces of the prototype six inch by twelve inch cylinder shall not depart from a plane 0.002 inch, and shall be at approximately right angles to the plane of the speciman. These tolerances when reduced to model size are of the order .00025 inch and are impossible to achieve in any practical manner. Tests on large cylinders have shown that a convexity of 0.01 inch gives results from 20 to 35 per cent lower than tests of specimans having plane ends (9).

In order to try different capping techniques and arrive at the most desirable cap, the following methods were used.

First, a liquid sulfur mixture, as used on prototype cylinders, was tried. A problem developed because the small amount of sulfur required to cap a cylinder end solidified too quickly to give a plane surface. This method was considered unsatisfactory.

Second, plaster of paris was used. This method worked fairly well, but again a problem developed because the plaster sets up so quickly. When a "wet" mix was used, the shrinkage became a problem. About one-half of the test cylinders were plaster capped.

Third, a thin layer of stiff, neat portland cement paste was applied to the specimans after the concrete had ceased settling in the cylinders, which is about four hours. This cap was formed by smoothing on a thin layer of cement and placing a one-fourth inch plate glass on top. The glass was oiled so it could be easily removed after the 24 hour air curing period. This method proved most satisfactory and was used in the final phase of the microconcrete tests.

8. Testing

In all cases, testing techniques for microconcrete followed as closely as possible ASTM C31-49, Standard Method of Making and Curing Concrete Compression and Flexure Test Specimans in the Field and ASTM C39-49, Standard Method for Compressive Strength of Molded Concrete Cylinders. Table III shows the result of varying cylinder size, aggregate/cement and water/cement ratio, and model mix design upon the seven day compressive strength of the microconcrete. This table is used as a basis for the design of the microconcrete mix used in the structural model.

Trial No. 7 is selected from Table III (on the following page) as the mix design used in the model. This mix is used because it has the advantages of being a relatively dry mix; hence, less subject to shrinkage, a workable mix for easier placement, a strong microconcrete, as anticipated from the seven day compressive strength.

TABLE III

MICROCONCRETE CYLINDER TESTS

Trial	Aggregate Model Mix	Cap	Cylinder Size (in.)	Conc. Mix Ratio (by wt.) Agg.	Cem.	Water	Max Load 7 Days (lbs)	Compressive Strength (psi) 7 Days
1	2	Pl.	$\frac{3}{4}$ x $1\frac{1}{2}$	2.50	1	.5	870	1970
2	1	Pl.	$\frac{3}{4}$ x $1\frac{1}{2}$	3.25	1	.7	3410	1950
3	1	Pl.	$1\frac{1}{2}$ x 3	3.25	1	.7	1015	2300
4	1	Pl.	$\frac{3}{4}$ x $1\frac{1}{2}$	3.00	1	.6	1075	2440
5	1	Pl.	$1\frac{1}{2}$ x 3	3.00	1	.6	5680	3240
6	1	Pl.	$\frac{3}{4}$ x $1\frac{1}{2}$	2.50	1	.5	2040	4650
7	1	Pl.	$1\frac{1}{2}$ x 3	2.50	1	.5	7475	4250
8	3	Cem.	$1\frac{1}{2}$ x 3	3.00	1	.6	4720	2700
9	3	Cem.	$1\frac{1}{2}$ x 3	2.50	1	.5	7400	4200
10	1	Cem.	$1\frac{1}{2}$ x 3	2.50	1	.6	6630	3770
11	1	Cem.	$1\frac{1}{2}$ x 3	2.00	1	.5	9660	5500

As a matter of interest, Figure 12 (page 37) shows a series of the microconcrete cylinders after compression testing. The model breaks are very typical of prototype speciman breaks. Except for their small size, it is difficult to observe any difference between prototype and model cylinders after testing.

It is noted that these particular mix designs simulate a concrete which is really a mortar because of the small size of the largest aggregates. Consequently, it is difficult to tell if the specimans break through the aggregates. It appears that they do not.

A study was also made to determine if a decrease in aggregate/cement ratio would strengthen the concrete. It is known that for concrete to be made properly, each aggregate must be completely surrounded by cement. It was, therefore, theorized that, as the aggregate size is reduced, the surface area of aggregate for a given weight of material is appreciably increased. Hence, the strength of the concrete is reduced because the cement must spread itself over a greater surface area of aggregates.

Referring to Table III, trials 10 and 11 which use a smaller cement/aggregate ratio show a seven day compressive strength to be significantly greater than trials 4 and 6. However, trials 10 and 11 are much more "soupy" when mixed. It is felt they will shrink more than trials 4 and 6 which contain more aggregate per volume of water and, therefore, they were not used as a design mix for the actual structural model.

B. Reinforcement

The usual way of reinforcing microconcrete structures is by bending the model reinforcement from annealed wire. It has been found that annealed wire simulates, very closely, the stress/strain characteristics of deformed steel bars. Researchers at the Massachusetts Institute of Technology have made extensive investigations into the properties of annealed wire used for reduced scale models and their bonding characteristics (6). However, annealed wire is not an appropriate model material when simulating wire rope.

A search for a material that would closely simulate both the geometric and elastic properties of prototype wire rope revealed that small diameter aircraft control cable would be excellent.

The prototype wire rope must be modified at model size in order to accommodate manufacturers' standard material. The prototype cable is designated 1 x 19. This means it has 19 strands and one wire per strand. The model cable is designated 1 x 7. In sizes as small as one-thirty-second inch, 1 x 19 cable is not made. Figure 13 (on the following page) shows a cross-section of the prototype and model reinforcement. The model cable, in effect, lumps several wires of the prototype cable into one strand.

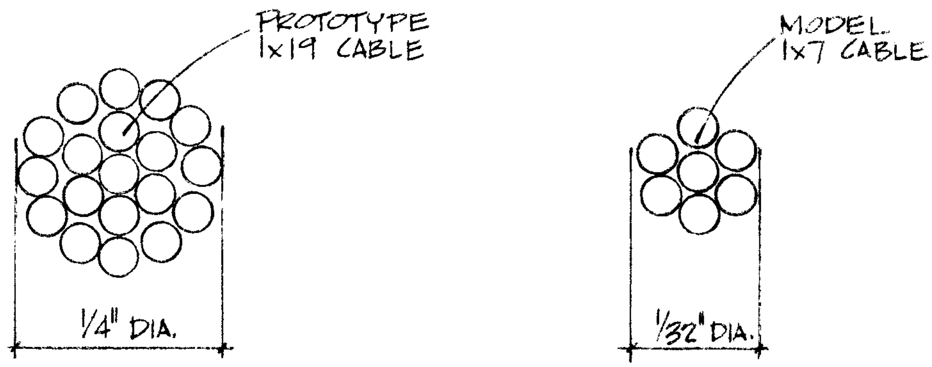


Figure 13. Cross-Section of Prototype and Model Cable

A factor of consequence in wire rope design is whether the cable is prestressed or not prestressed. Normally, cable is prestretched to remove the constructional stretch and produce a cable with elastic stability and a defined modulus of elasticity. This is particularly true when using cable for a prestressed roof. Aircraft cable is constructed very tightly and constructional stretch is at a minimum; however, it is present. The model must, therefore, be poured soon after weights are positioned so constructional looseness will not occur.

A sample of material is tested with end conditions as proposed for the model (see Figure 14). Anchorage of cable to tubing was tried by four methods:

1. Solder cable to tubing by resin core solder.
2. Solder cable to tubing by acid core solder.
3. Glue cable to tubing with epoxy glue.

4. Solder cable to tubing by silver solder.

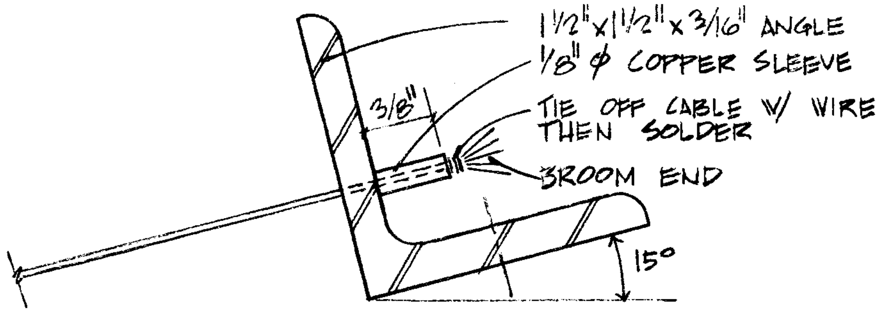


Figure 14. End Connection of a Typical Model Cable

The first two types of solder would not adhere to the cable, which is stainless steel. The epoxy glue appeared to be strong enough but when tested in a tension machine after the glue had dried for 24 hours, the cable pulled out of the tubing at 70 pounds tension. This is considered unacceptable.

Silver solder does bond to the stainless steel. Two samples are tested to determine the strength of this connection, and to see if heat appreciably changes the properties of the cable. When tested in the tension machine, the cable broke in the strands at 160 pounds tension. The amount of heat required to complete the connection apparently had no effect on the strength of the cable. The cable manufacturer lists breaking strength at 110 pounds. Therefore, this connection is used in the model construction.

Construction of Model

A. General

It is the purpose of the model to faithfully reproduce the geometrical and structural characteristics of the prototype. Great care must, therefore, be taken to fabricate the model to as close dimensional tolerance as possible. A prime error in model construction is the "scale effect." Scale effect will occur if there are imperfections in similarity in the design or construction of the model or if significant variables are overlooked. Using hand tools and semi-skilled labor, it is felt that plus or minus one-thirty-second inch is as close as the model can be made to desired dimensions. This is plus or minus one-fourth inch in the prototype.

B. Formwork

The problem in designing the formwork is to devise a form which will fit the final shape of the roof; be relatively easy to fabricate and assemble; and be economical in cost.

Thus, hardboard supported on plywood is chosen as the form material. To be more certain that the microconcrete will not bond to the hardboard when the form is dropped during the curing process, a plastic coating is sprayed on before the cables are placed.

The particular parabolic shape that the form assumes is determined by first calculating the tension (H) at the center of the span for the full sag condition of 3.68 feet. Thus:

$$H = \frac{qL^2}{8f} = \frac{(17.5)(48)^2}{(8)(3.68)} = 1370 \text{ lb.}$$

Using the value of H, the equation which describes the shape of the parabola is given by:

$$y = \frac{1}{2}\frac{q}{H}x^2 = \frac{1}{2}\frac{(17.5)}{(1370)}x^2$$

$$y = .0064\ x^2 .$$

For any given x value, the corresponding y, or height, is thus determined.

The model loads are determined from the equation:

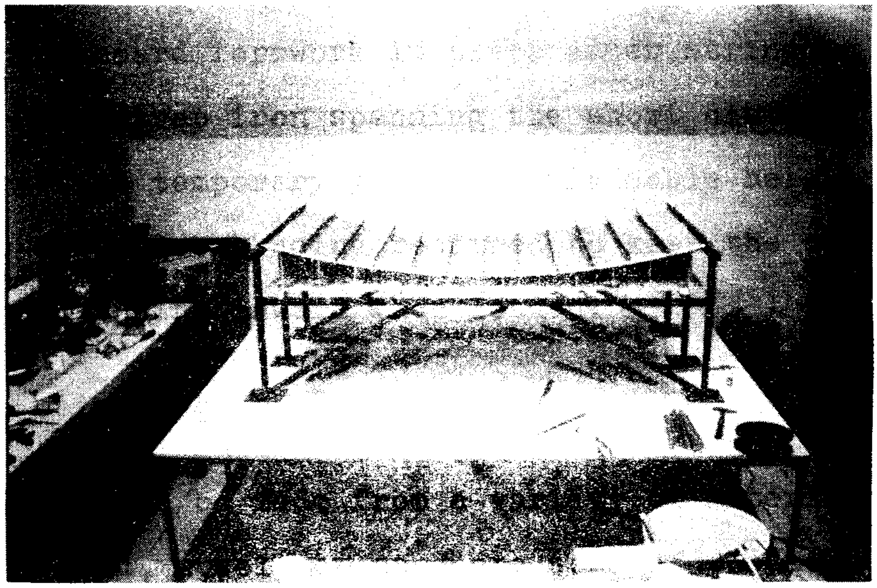
$$F_m = \frac{F}{s^2} = \frac{(17.5)(4)}{64}$$

$$F_m = 1.1 \text{ lb.}$$

Loads of 1.1 pounds are spaced six inches O.C. along each cable, giving a total load of 990 pounds.

C. Frame

A steel frame is used to support the roof and the temporary weights. It must be made quite heavy because the total weight hanging from the model is of the order of 1000 pounds. Figure 15 (on the following page) shows the frame



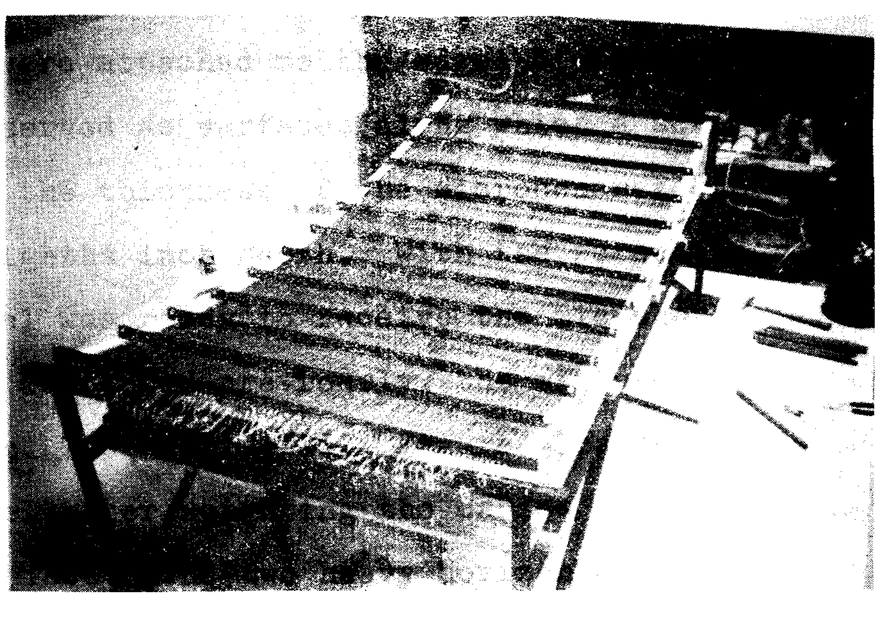


Figure 15. [illegible] Construction

and the hardboard formwork in place after stringing the cables. The strap iron spanning the short distance of the form serves as temporary guides to fix cable heights. Note also the extensive bracing required to keep the cable supports from bending inward when loaded.

D. Weighting the Cables

Weights can be made from a variety of materials. Concrete, lead, steel, or sand are some of the more common materials used. For this model, No. 5 reinforcing bars cut to one foot lengths and weighing approximately 1.1 pounds were used. The reinforcing bars were hung from the cables by annealed wire strung through holes in the form. When the cables were completely weighted, the strap iron guides were removed from over the cables and three-eighths inch plywood strips were attached to the edges of the forms. These strips served as surfaces along which a screed board was run to hold the thickness of the microconcrete to a constant three-eighths inch depth. With the screed boards in place, the model was ready to receive the microconcrete.

As mentioned previously, the mix used corresponded to trial No. 7 of Table III. Figures 16a and 16b show views of the model after weighting the cables and as pouring was taking place. The two heavy horizontal boards spanning the steel frame are additional temporary supports placed to prevent the edge frame from bending inward under the load.

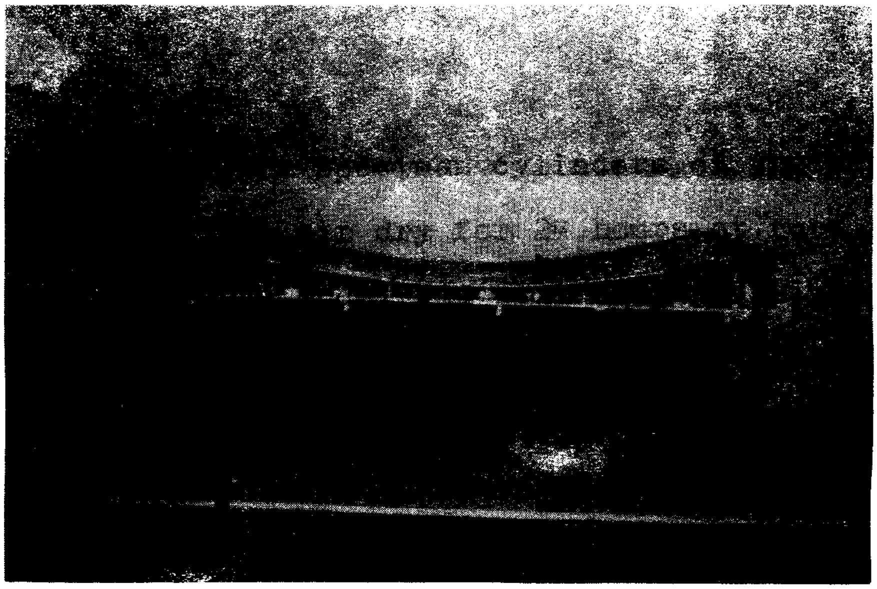


Figure 16. Model as Microconcrete is Placed

E. Curing

The model and six speciman cylinders of the microconcrete were allowed to air dry for 24 hours at room temperature. The top of the model was well dampened with water after initial set of the microconcrete. A polyethylene cover was placed over the roof so that free water would stand on the model during the seven day curing period.

At the end of four days, two of the cylinders were broken to determine the compressive strength of the concrete. It was found that the average compressive strength was 4000 psi. The temporary weights were removed and the model was allowed to cure for three more days.

F. Instrumentation and Testing

At the end of seven days, two more cylinders were tested to determine the compressive strength. The results showed an average compressive strength of 5200 psi.

The model can now be instrumented; however, Pahl (6) recommends it be allowed to cure for a total of 21 days to assure uniform curing of the entire microconcrete mass. The instrumentation and the testing of the model are not within the scope of this study; however, the purpose of the testing program will be to investigate and measure the roof's progressive fissurization and final collapse under increased loading.

CHAPTER V

SUMMARY AND CONCLUSIONS

For practical purposes, if factors which contribute to self-exciting vibrations are eliminated or substantially reduced from hanging roofs of single curvature, then investigation of, and design for flutter becomes irrelevant. This is the purpose of prestressing a suspended roof by hanging weights from the cables.

By constructing a structural model of the prestressed roof, it was possible to test materials and techniques for constructing the prototype cable reinforced structure. The use of the small scale model permits the investigation of the behavior of structures of too great a size to be reproduced full scale in the laboratory. The cost of testing is reduced and such factors as the weather are removed.

In regard to this particular model construction, it was found that the microconcrete performed excellently as a substitute for concrete, although extensive testing of design mixes was required. The aircraft cable also worked well, although it is necessary to devise an adjustable end connector.

The frame required for this model was massive. Had the roof shape been circular rather than rectangular in plan, the frame would have been much lighter. When the building plan follows a smooth curve it is possible to find a compression contour which will work with very little bending under large loads.

Suggestions for Future Study

A more complete study of microconcrete might prove beneficial to future researchers. By varying water/cement and aggregate/cement ratios; types of aggregates; curing conditions; capping devices; cements; etc., something of a handbook could be developed which would tabulate the results the variables in concrete have on the strength of the mix.

Another area of research might be to investigate the bond characteristics of small diameter aircraft cable in microconcrete. Studies have been made of the bond characteristics of annealed wire to microconcrete, but it is believed there have been no investigations of cables.

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