Sensitivity of Reflector Backup Structure Weight to Variable Wind Speed Loadings

R. Levy and D. Strain
DSN Engineering Section

Backup structures for paraboloidal reflectors were designed for three diameters to support combinations of gravity, seismic, wind or snow loads. Changes in structure weights were determined as a function of change in wind speed. Low wind speeds were found to have only minor influence on weight, and extremely high hurricane-type wind speeds had only a moderate effect on the weight. One of the backup structure designs was evaluated for performance and judged to be satisfactory for use either as a microwave antenna or solar collector.

I. Introduction

Paraboloidal reflector structures used within microwave antennas or solar collector systems are required to provide structural integrity and suitable performance accuracy at specified operating wind speeds and to maintain structural integrity at specified higher survival wind speeds. Typically, the operating performance requirement for an azimuth-elevation type steerable reflector applies at any elevation angle from horizon to zenith, but the survival wind speed applies with the structure oriented in an advantageous elevation attitude (stow position) that offers the most protection from wind loading.

In view of operating and survival conditions there are three wind speeds to be considered for design:

(1) The maximum speed at which performance is to be maintained while the structure is at any elevation angle.

(2) A slightly higher speed than above that applies during the time the structure is being driven to the stow attitude from any other elevation attitude.

(3) A survival wind speed that applies at the stow attitude.

The present investigation covered the design and weight of reflector backup structures needed to maintain structural integrity for a spectrum of wind speeds. Performance requirements, which entail examination of the deformation patterns at the operating wind speeds, were not a primary subject for investigation. Consequently, wind speed ranges only for category (2) above, at which the antenna can be at any elevation, and for category (3), at which the structure is stowed, were investigated. To simplify the number of parameters investigated, the survival wind speed was always taken to be twice the maximum drive-to-stow wind speed, which is representative of customary specifications. As the result, we can characterize any of the wind speed parameters by the survival speed, with the understanding that the structure must withstand one-half of this speed at any arbitrary elevation attitude. Other loadings on the structure included with wind were the gravity loading (which depends upon the elevation attitude), earthquake loading, and snow loading. Details of how specific loading requirements were assembled will be described in conjunction with the description of the design procedure.

II. Backup Structure Configuration

Backup structures were studied for reflector diameters of 15m (50 ft), 26m (85 ft) and 40m (132 ft). Mounts to support the structure were omitted, but the structures were constrained at nodal junctions which were presumed to be logical attachment points to azimuth-elevation (AZ-EL) type mounts. Since gravity loading for a reflector structure supported by an AZ-EL mount is symmetrical about the vertical plane perpendicular to the elevation axis, and since the wind loading here was also assumed to maintain the same symmetry, it was necessary to model and design only one-half of the backup structure.

Backup structure configurations consisted of radial rib trusses with interconnecting circumferential hoop trusses. This is the traditional microwave antenna ring and rib construction that has successfully evolved during the past 20 years. The reflecting surface is provided by individual panels that are assumed to be capable of supporting their own weight plus any additional tributary wind, snow, or earthquake loading. Panel designs, however, were not undertaken. The method of attachment of panels to backup was assumed to transfer mechanical only, and not thermal loading, to the backup and to prevent participation of the panels in the structural response of the backup to its imposed loading.

Figure 1 illustrates details of the backup structure construction. The reflector diameter for this figure is considerably larger than diameters considered here, so that the numbers of rings and ribs exceed those of the reflectors of the current study. The actual layout of the top surface of the three reflectors for this study and their rib profiles are shown on Fig. 2. The rib and ring layout was set for surface panels of approximately 4-m^2 (45 sq-ft) area. The coordinate system shown on this figure is a local set fixed to the reflector and moves with the reflector as it changes in elevation attitude.

In the schematic layouts of Fig. 1, which, although proposed (Ref. 1) for a 64-m-diameter reflector is typical of the configurations for this study, it can be seen that the backup structure is developed from replicative modules. As shown in Fig. 1d, the main rib truss bar members occur in four categories: top, bottom, diagonal, and post. As shown in Fig. 1b and 1c, the hoop truss bar members occur in three categories: top, bottom, and diagonal. The intermediate ribs, which consist of a single top bar supported by the hoop trusses occur only at the outer-most rings, and alternative main ribs are omitted at the innermost rings. Three additional categories of interrib bracing are: top surface diagonal bracing between adjacent rib tops and bottom surface diagonal bracing between adjacent rib bottoms, and inclined bracing from the top of one rib to the bottom of the next adjacent rib. Consequently, all members of reflector backup structures can be classified within only 10 distinct category types. To emphasize manufacturing economy by means of replication, all members of the same category that occur at the same ring or within the same ring annulus can optionally be assembled into the same design variable group. Each member within a design group is then designed to have the same structural cross section. As an illustration, antenna backup model of Fig. 1, which has over 5000 individual bar members, requires less than 130 detailing variations to manufacture all of the bars.

Because of the great emphasis on symmetry and repetition in this design, data generation is readily automated. Most of the data input required for subsequent design and analysis is generated within a special computer program in less than a minute of 1108 computer central processing unit (CPU) time. For the structure of Fig. 1 there are about 4000 data card images. These are computer-produced on the basis of a relatively small number of input parameters to define key dimensions plus configuration and arrangement options. Another computer program automatically generates data to describe wind loading on the structure by interpolating from our existing wind tunnel pressure data. Loading data that represents the weight of surface panels and additional snow loads is also automated.

Figure 2a shows the projections of the reflector support points, which occur at the bottom chords of main rib trusses. Three support points (at the corners of an equilateral triangle) are provided for the full 15-m-diameter structure, four (at the corners of a square) are provided for the 26-m-diameter structure, and eight (at the corners of an equilateral octagon) are provided for the 40-m-diameter structure. In all cases, the central radius to the support point is 40 percent of the reflector radius. Although these points are unyielding in their support of the backup structure, they are effectively equivalent to simulating an attachment between mount and reflector that has equal stiffness at each of the attachment points.

Computer models of the backup omitted the customary additional structures associated with counterweights or with supporting of subreflectors or receivers. It was assumed that these structures could be attached very closely to the supports so that they would have little, or only local, influence upon backup structure weight. Furthermore, they are customarily open, latticed structures, with only small exposure to wind loading.

III. Member Design Specifications[1]

All backup structure members were of structural steel, ASTM-A36 quality. The design specification adopted for these members was taken from an "ASCE Design Guide" (Ref. 2). Compression members are governed by either of two formulas, depending on whether or not they are long or short columns: The long column formula for allowable compression stress is

$$Fa = 286{,}000/((KL/r)^2)$$

in which KL/r is the effective slenderness ratio, L is the length of the member, r is the radius of gyration of the cross-sectional area, and Fa is the allowable compression stress in ksi.

The short column formula is

$$Fa = (1 - (KL/r)^2/(2Cc^2))F_y$$

in which $Cc = 126.1$ (for ASTM A-36 Steel) and $F_y = 36.0$ (for ASTM A-36 Steel).

The long column formula applies for KL/r greater than Cc, and the short column formula applies when KL/r is less.

For members with normal framing eccentricities, the effective slenderness ratio for L/r less than 120, is given by

$$KL/r = 60 + 0.5L/r$$

For greater L/r, K is taken as 1.

The guide recommends that the maximum value of L/r for members carrying calculated compression stress be limited to 200. Our design procedure restricts all members to this value in anticipation of possibilities of stress reversals.

For tension members this code recommends the full yield stress on the minimum net cross-section. To allow for end connections, we have assumed a 15 percent reduction in tension member areas, so that we used 30 ksi as the allowable tension stress, rather than the yield stress of 36 ksi. These specifications do not include safety factors and members designed accordingly will approach failure by yielding or buckling. Consequently, overload factors on the anticipated loading should be used according to designer's judgement.

The load factors used here were

Type	Nominal loading	Loading factor
Gravity	1.00 g	1.20
Seismic	0.25 g	1.20
Snow	20 psf	1.00
Wind	Stagnation pressure	1.00

Selection of backup structure member cross-sections for these design specifications is automated within the JPL-IDEAS (Ref. 3) computer analysis and design program. A loading deflection analysis is performed for a finite element model of the structure from which member forces are computed for a set of environmental loadings. The maximum tension and maximum compression force are identified for each member. The program then consults one of several self-contained tables of commercially available structural shapes and selects one to meet the specifications. An excerpt of the table used in this study is shown in Table 1. In this table, the heading HANDBOOK SHAPE contains a cryptic description of the member. For example, shape No. 1 is a .75 in. nominal standard pipe with 1.05 in. outside diameter (OD) and a .113 in. wall. Shape No. 2 is a 1 in. schedule 10 pipe with 1.315 in. OD and a .109 in. wall. The cross-sectional area and radius of gyration are tabulated under the headings AREA and RAD. The table is arranged in the order of increasing area. Allowable compression loads (kips) are tabulated as a function of span length (inches). These tabulated loads are used in the member selection algorithm to expedite the selection of candidate members. The tabulated loads are used to locate trial shapes that are tested for the ability to carry the maximum compression load according to the preceding formulas. Zero values of the loads indicate span lengths for which L/r exceeds 200.

IV. Design Procedure

The JPL-IDEAS program was constructed to automate optimum design of lattice-type structures for a compliance type of performance criteria. At the same time, structural integrity is maintained by selecting only members that have the ability to withstand all the tensile and buckling stresses for a user-supplied set of loading vector cases. As an available

[1] Design codes, material specifications, and descriptions of commercially available structural members in industrial practice are currently described by traditional English units. Consequently, the discussion here will be in terms of the traditional units, rather than S.I. units. These would cause undue confusion by dealing with quantities that are not meaningful in present practice.

option, a subset of this design capability examines only loading carrying capability independent of performance. This option is called the "Stress" design mode option and actually is equivalent to the fully stressed design method.

The objective of a fully stressed design is to have each member reach its maximum allowable load in at least one loading condition. The computer approach is to examine member forces for each loading vector and select an appropriate member from the table in accordance with the most critical requirement for each member for any of the loads. However, in a redundant structure, changes in member areas will cause an internal redistribution of loading. As the result, the approach must be performed iteratively, rechecking and correcting the newly sized members at each iteration. However, experience shows that this method will usually converge rapidly and require fewer design iterations for a moderately redundant structure than when performance criteria are also included. In the IDEAS program, the individual members are assembled into design-variable groups and the group member size is set according to the most severely loaded member within the group. By assigning fewer members into the groups and more groups, a lighter weight design could result, but at the expense of increased fabrication complexity.

For each of the three diameters studied, the IDEAS program was executed twice, as follows:

(1) The first execution loading consisted of four cases to represent the antenna at the horizon and at the zenith elevations with seismic loading from the front and from the rear. The seismic loading was superimposed upon gravity loading, which consisted of the weights of the members plus a reflecting surface weight of 14.6 kg/m^2 (3.0 lb/ft^2) to simulate the effect of reflecting panels. The "Stress" design mode option was used to determine member sizes to support these loads (at a load factor of 1.20). Member group sizes so determined were written into a file for future recovery and reference as the minimums and were not allowed to be reduced during further loading analysis and design.

(2) The second execution contained nine loading cases that were analyzed to determine the member forces, which were stored on a file for subsequent postprocessing. Two loadings were used to represent gravity loading in the Z-axis direction and in the Y-axis direction (Fig. 2). By forming linear combinations of member forces for these two loadings, it is possible to compute the member forces from gravity at any arbitrary elevation attitude. Six wind loading cases represented wind from the front with the structure at elevations of 0, 60, and 90 deg, and wind from the back at these same elevations for an arbitrary reference speed. The last loading case was a snow loading of 97.5 kg/m^2 (20 lb/ft^2) of surface area applied in the negative direction of the Z-axis.

Completion of the study of backup structure weight for variable wind speed loading is performed by a postprocessor program written especially for the present study. This program (a) reads in the member forces from the file written during the second execution above, (b) synthesizes the member loading by forming combinations of the Z- and Y-axis loadings gravity appropriate to the particular elevation angle, (c) multiplies the wind loading force read in for this elevation by a factor equal to the square of the ratio of wind speed to be investigated to the reference speed, (d) adds the gravity and factored forces wind loading forces, and (e) finally selects an appropriate member for this loading by using the same table of commercial shapes and design algorithms as the IDEAS program. When snow loading was to be considered, this was added to the wind and gravity loadings for the 90-degree elevation case. In employing this postprocessor, the user supplies the desired factors to be used in the superposition of loadings.

During the selection, no member size is permitted to become smaller than the size determined during the first IDEAS execution. This is the size found necessary for resistance to the seismic loading.

Table 2 shows the wind speeds considered. Gravity loading combined with these wind loads included a load factor of 1.2 applied to the weight of the structure designed in the first IDEAS execution, which also included the mass of reflecting surface panels. There is a small approximation entailed in computing the weight of the backup structure to resist the higher wind speeds, because the added weight of members with increased area is not included in the gravity loading portion of the factored load. Another approximation occurs because the synthesized member loading is subject to redistribution because of internal structural redundancy. The effects of both of these approximations have been verified by additional IDEAS program designs using some of the higher wind speed loadings and starting from member sizes developed within the postprocessor. It was found that although some members were increased, others were reduced, and the total weight of backup structure varied by less than 1 percent from the weight computed in the postprocessor program.

V. Results

Table 3 contains reference data and statistics to describe the three diameters investigated. The focal-length-to-diameter ratio for the 15-m-diameter model can be determined as 0.424, which is typical of antenna requirements. The ratio of 0.6, which was used for the 26-m and 40-m structures is more nearly in keeping with requirements for solar collectors. However, other investigations performed in the past have shown that the structure weight and performance is not significantly sensitive to much larger changes in focal-length-to-diameter ratios than these. The panel surface weight is typical of the panel weights in current DSN antenna usage and with current proposals for the design of collector panels. The snow loading, when subsequently applied in addition to wind loading, is uniformly distributed over the reflecting surface (not projected) area when the reflector is at the stow-survival (90 deg) elevation. Actual snow loading distribution would presumably be more intense near the center of the aperture than at the rim. The reference weight for the backup structure was determined by the fully stressed design option within the IDEAS program. Gravity and fore-and-aft seismic loadings (0.25 *g*) were combined for horizon and zenith reflector elevations with a load factor of 1.20 applied to the combined loadings. Note that all physical quantities in Table 3 are for one-half of the backup structure and should be doubled to represent the complete structure.

A. Weights of Backup Structure Designs

Table 4 shows the results of the studies of backup structure weight to wind speeds. Figure 3 is a plot of these data. The tabulated percentages of weight increases are based upon the weight of the reference structure as described in the preceding paragraph. All of the wind loading designs also included gravity loading at a load factor of 1.20, but no seismic loading. Smaller weight increases could have been found at some of the lower wind speeds if these designs had not been constrained to prevent reduction of any member below the requirements of the reference design. The percentage increases for snow loading are determined only from the zenith elevation wind and snow requirements. Data in Table 4 were determined from the severest requirements for wind at any of six relative wind orientations (see Table 2).

No increased load factors were applied to the wind to represent gust loading or safety factors for the design. The effect of such factors could be invoked by a downward reinterpretation of the tabulated speeds.

B. Auxiliary Evaluation of Performance

Although the primary objective of this study was to determine the weight of backup structures to support the various loadings, some data were developed to determine sample performance characteristics for the 15-m-diameter reflector structure. The information was based upon the particular design for gravity and wind loading at the 22.3-m/sec (50-mph) operating condition and 44.7-m/sec (100-mph) survival wind speed conditions. The performance evaluations for this structure were made for wind at 13.4 m/sec (30 mph).

As an X-band microwave antenna operating at the frequency of 8.45 GHz, the efficiency of the backup structure, which is a function of the pathlength length errors caused by structure distortion, was computed to be at least 96 percent for all of the orientations for either wind or gravity loading. The corresponding reduction of antenna gain for this minimum efficiency was 0.15 dB. This gain reduction is expected to be well within error budget allowances that would normally be assigned.

Performance as a solar collector was evaluated by using a computer program that executed the geometric optics calculations and traced the energy reflected from each surface panel to its eventual location on arrival at the receiver plane. The application of this computer program assumes that panels undergo rigid body deformations caused by the displacements of the attachment points at the backup structure. Additional panel distortions caused by the local gravity and wind loading on the panel would have to be applied separately. It can be determined that with a distortion-free reflecting surface, all of the energy would be captured within a 6.4-cm (2.5-in.) receiver radius. The worst case of wind and gravity (simultaneous) loading was found to increase the capture radius required by about 2.5 cm (1 in.). Consequently, a receiver diameter of about 18 cm (7.0 in.) would have a 100 percent intercept factor, assuming no other errors. This would be equivalent to a concentration ratio of about 7300, but of course other errors, such as panel surface deformations, alignment, and pointing, that have not been considered here, would reduce the efficiency and concentration ratio.

VI. Summary and Conclusions

The sensitivity of structure weight to increasing wind speed was considerably smaller than expected at the inception of the study. It can be seen that the lower speeds have only minor effect on the weight, and weight sensitivity does not become pronounced even at the higher speeds. The relative insensitivity of weight to wind speed can possibly be explained as follows:

(1) The reference design, which included seismic loading, inherently provides sufficient strength to resist the lower wind speed loads.

(2) The weight of many of the members is set by the maximum permitted L/r ratio of 200. The allowable compression stress for this ratio provides significant load-carrying capability that is sufficient for many of

the lower wind speeds. In view of this, structure weight could be reduced by changing the layout to use more, but shorter members. This could add to the fabrication costs, since the present number lengths are reasonable with respect to current fabrication, ordering, and handling practice.

(3) The format adopted for the configuration and layout is structurally efficient and has the capability of distributing the effects of and supporting loads of high intensity.

The postprocessor program used to develop these designs indicates which of these wind orientations sets the design for each member group design variable. As the result of scanning the lists of critical orientations for the individual member groups, no general conclusion can be developed for which orientations tend to be the most critical. However, a tendency observed was that the horizon elevation with wind from the front and the 60-deg elevation with wind from the rear were not often critical.

A sample evaluation of the performance for one of the 15-m-diameter backup structures designs indicated that the accuracy of the structure when subjected to representative operating gravity and wind loads would be acceptable when used either in a microwave antenna or solar collector system.

References

1. Levy, R., "Conceptual Studies for New Low-Cost 64-M Antennas," in *The Deep Space Network Progress Report 42-33*, pp. 55-67, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1976.
2. "Guide for Design of Steel Transmission Towers," ASCE Manual and Report on Engineering Practice, No. 52, 1971.
3. Levy, R., "Computer-Aided Design of Antenna Structures and Components," *Computers and Structures*, Vol. 6, Pergamon Press, 1976 pp. 419-428.

Table 1. Excerpt from commercial member size table

HANDBOOK PROPERTIES FOR PIPES			******LOAD TABLE******							
NO. HANDBOOK SHAPE	AREA	RAD	SPAN LENGTHS							
			25.	50.	75.	100.	125.	150.	175.	200.
1..75STD,1.05X.113	.333	.330	8.4	4.1	.0	.0	.0	.0	.0	.0
2.1.0-10,1.315X.109	.413	.430	11.2	8.3	3.9	.0	.0	.0	.0	.0
3.1.0STD,1.315X.133	.494	.420	13.3	9.8	4.4	.0	.0	.0	.0	.0
4.1.25-10,1.66X.109	.531	.550	15.0	12.4	8.2	4.6	.0	.0	.0	.0
5.1.5-10,1.90X.109	.613	.630	17.7	15.2	12.2	7.0	4.5	.0	.0	.0
6.1.25STD,1.66X.140	.669	.540	18.8	15.5	9.9	5.6	.0	.0	.0	.0
7.2.0-10,2.375X.109	.776	.800	22.9	20.6	17.9	14.2	9.1	6.3	.0	.0
8.1.5STD,1.90X.145	.799	.620	23.0	19.7	15.5	8.8	.0	.0	.0	.0
9.2.5-10,2.875X.120	1.039	.970	31.1	28.7	25.9	22.8	17.9	12.4	9.1	.0
10.2.0STD,2.375X.154	1.075	.790	31.7	28.5	24.6	19.2	12.3	8.5	.0	.0
11.3.0-10,3.50X.120	1.275	1.200	38.7	36.5	33.9	31.0	27.8	23.3	17.1	13.1
12.3.5-10,4.00X.120	1.463	1.370	44.8	42.5	40.0	37.2	34.2	30.9	25.6	19.6
13.4.0-10,4.50X.120	1.651	1.550	50.8	48.6	46.2	43.5	40.6	37.5	34.1	28.4
14.2.5STD,2.875X.203	1.704	.950	51.0	47.0	42.3	36.9	28.1	19.5	14.4	.0
15.3.0STD,3.50X.216	2.228	1.160	67.6	63.4	58.7	53.4	47.5	38.1	28.0	21.4
16.5.0-10,5.563X.134	2.285	1.920	70.8	68.5	65.9	63.1	60.1	56.9	53.4	49.8
17.3.5STD,4.0X.226	2.680	1.340	81.9	77.7	73.0	67.8	62.0	55.7	44.9	34.4
18.6.0-10,6.625X.134	2.732	2.300	85.1	82.8	80.3	77.7	74.9	71.8	68.6	65.2
19.4.0STD,4.50X.237	3.174	1.510	97.5	93.2	88.4	83.1	77.3	71.1	64.3	51.7
20.4.5STD,5.00X.247	3.688	1.680	113.8	109.4	104.5	99.1	93.3	87.1	80.3	73.1

Table 2. Wind speeds and load factors

Reflector elevation, deg					
Front wind			Rear wind		
0	60	90	90	60	0
Speeds, m/sec (mph)					
4.5 (10)	4.5 (10)	9.0 (20)	9.0 (20)	4.5 (10)	4.5 (10)
Load factor = 1					
9.0 (20)	9.0 (20)	17.9 (40)	17.9 (40)	9.0 (20)	9.0 (20)
Load factor = 4					
13.4 (30)	13.4 (30)	26.8 (60)	26.8 (60)	13.4 (30)	13.4 (30)
Load factor = 9					
17.9 (40)	17.9 (40)	35.8 (80)	35.8 (80)	17.9 (40)	17.9 (40)
Load factor = 16					
22.3 (50)	22.3 (50)	44.7 (100)	44.7 (100)	22.3 (50)	22.3 (50)
Load factor = 25					
26.8 (60)	26.8 (60)	53.6 (120)	53.6 (120)	26.8 (60)	26.8 (60)
Load factor = 36					
31.3 (70)	31.3 (70)	62.6 (140)	62.6 (140)	31.3 (70)	31.3 (70)
Load factor = 49					

Table 3. Backup structure reference data (half structure models)

		Diameter, m (ft)		
		15 (50)	26 (85)	40 (132)
Aperture area	m^2	91.2	263.6	635.7
	ft^2	981.7	2,837.3	6,842.4
Surface area	m^2	98.7	274.8	626.7
	ft^2	1,065.0	2,958.4	7,133.0
Focal length	m	6.4	15.5	24.1
	ft	21.2	51.0	79.2
Panel surface load	kg	1,449.0	4,025.0	9,704.0
	lb	3,195.0	8,875.0	21,399.1
Reference weight for backup structure	kg	989.0	3,039.0	7,333.0
	lb	2,181.0	6,701.0	16,169.0
Snow loading (when applied)	kg	9,660.0	26,832.0	103,516.0
	lb	21,300.0	59,168.0	228,260.0

Table 4. Backup structure weight increases for wind loading

Reflector diameter	Survival wind speed,[b] m/sec (mph)						
	9.0 (20.0)	17.9 (40.0)	26.8 (60.0)	35.8 (80.0)	44.7 (100.0)	53.6 (120.0)	62.6 (140.0)
	Weight increase from reference design,[a] percent ph)						
15 m	0.0	0.4	0.4	0.4	6.7	not computed	
With snow load	3.7	3.7	4.6	7.7	9.5		
26 m	0.0	0.7	1.1	3.2	8.9	17.0	23.6
With snow load	6.9	8.1	9.1	10.3	13.0	19.4	27.2
40 m	0.6	0.8	2.3	4.5	11.1	20.7	36.9
With snow load	8.1	8.1	9.2	12.2	17.4	20.7	36.9

[a]Reference design was for gravity and seismic only.

[b]These designs are also based upon half the survival speed at elevations other than stow (90° elevation).

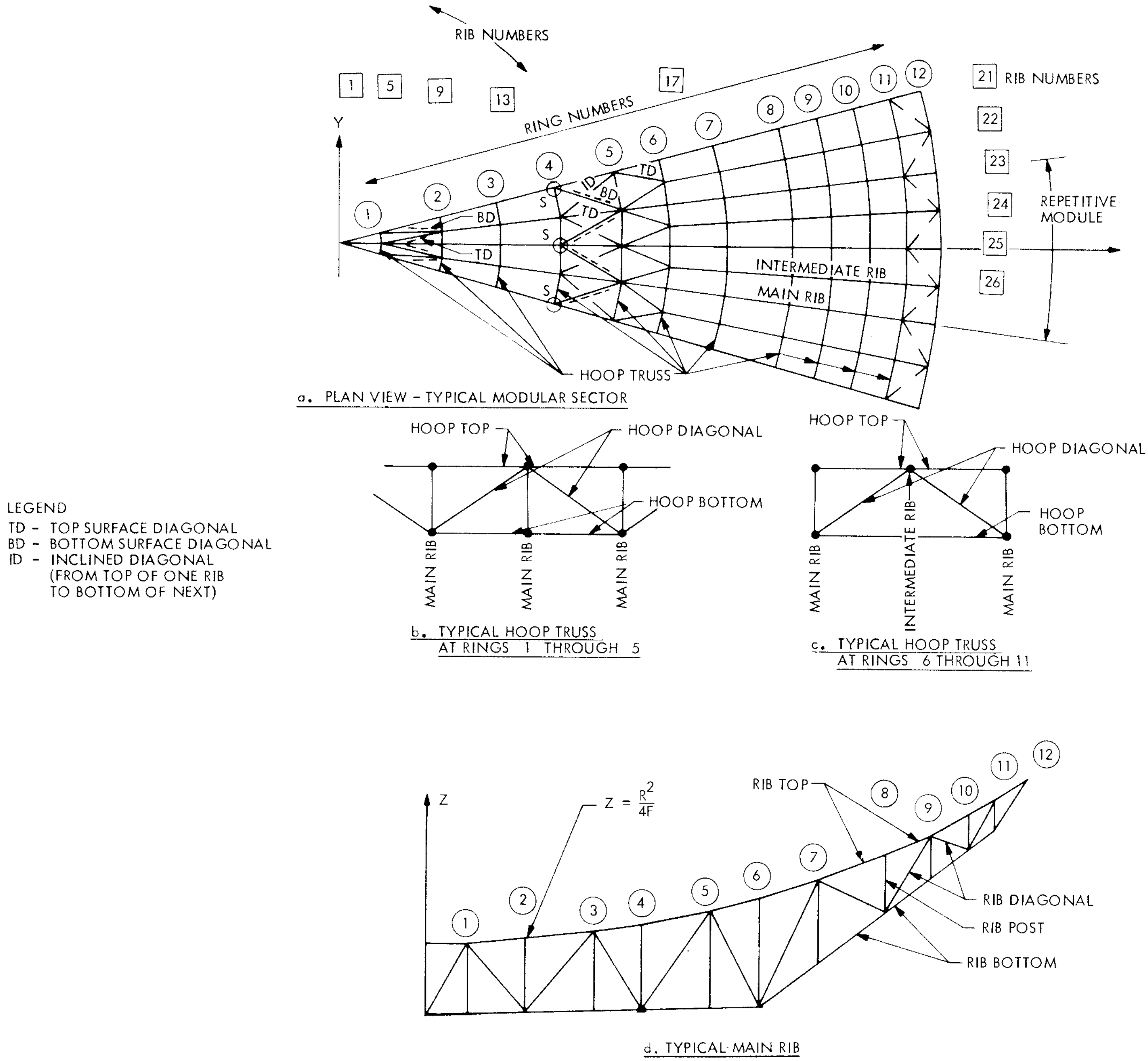

Fig. 1. Backup structure framing members

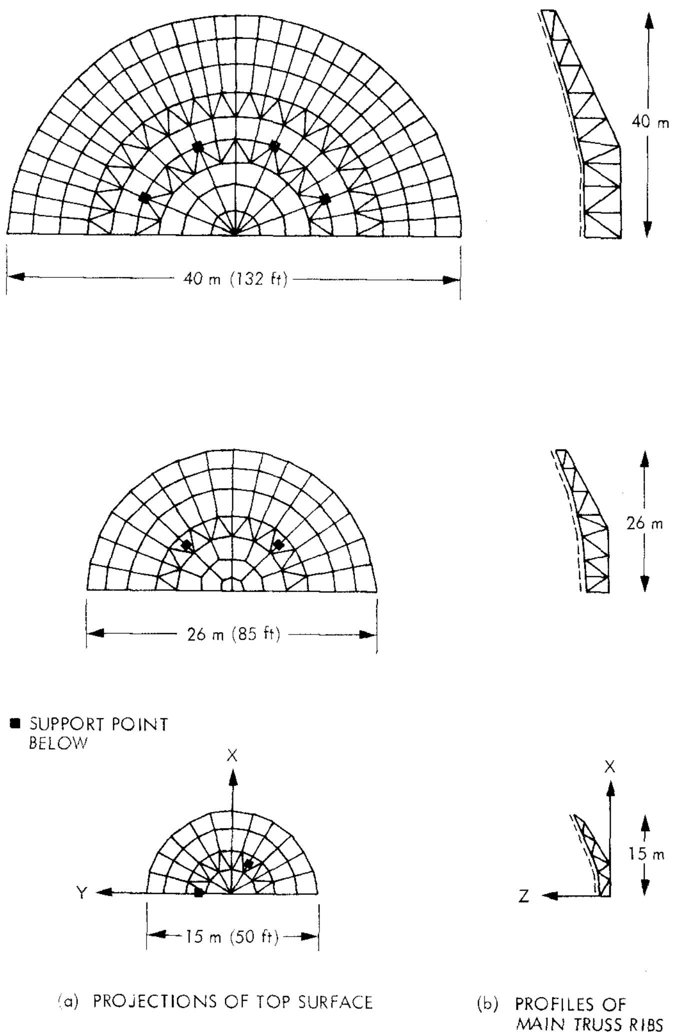

Fig. 2. Backup structure layouts

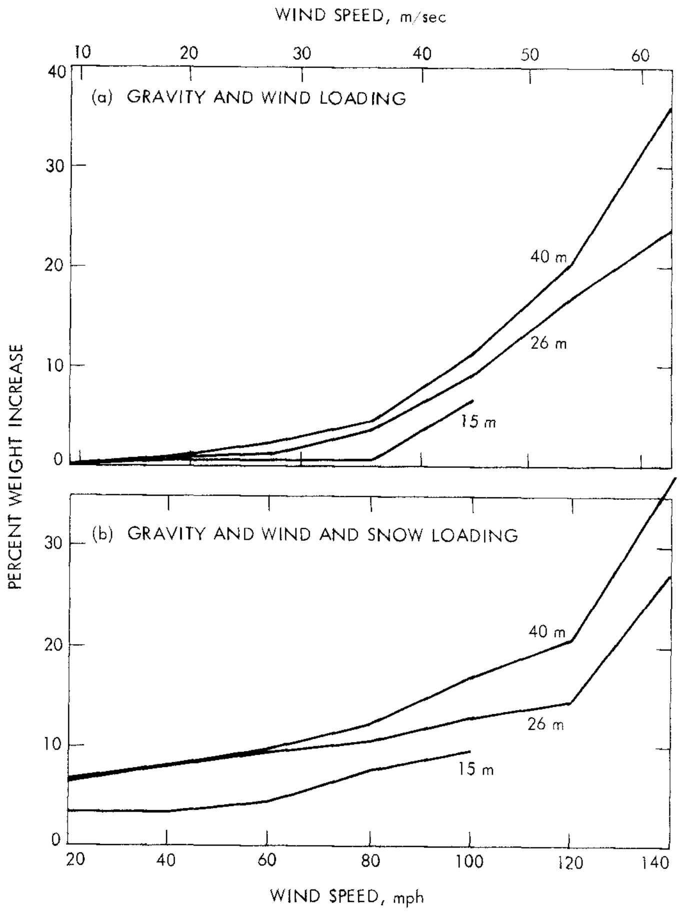

Fig. 3. Backup structure weight increase for varying wind speeds