STRUCTURAL EVALUATION
OF YAGI ELEMENTS

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Try this simple analysis procedure

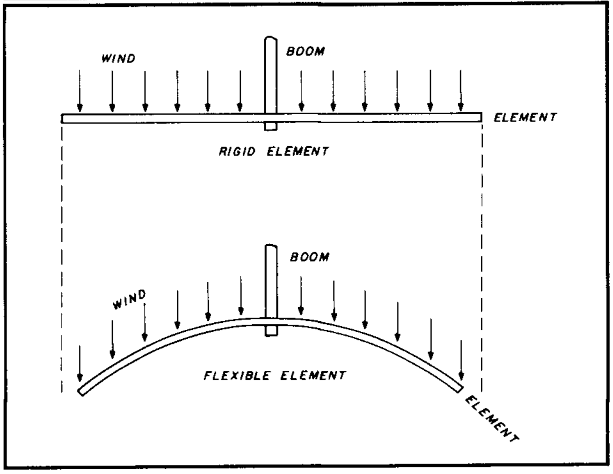
Over the past year or so, I've been working on a design procedure for developing structurally sound Yagi elements. I spent many hours with Bob Mitchell, N5RM, analyzing the structural integrity of his "Forty-Meter Flame Thrower"[1] and developing the first steps of my procedure. After I completed my initial work, Gerald Williamson, K5GW, used the process to design the elements of two full-size 40-meter beams which are stacked on his rotating tower. He also used it to build his shortened-element 80-meter beam and is now designing a full-size 80-meter beam.

In late spring of 1987, I heard that Dick Fenwick, K5RR, had several identical Yagis elements break in high winds. I asked Dick to send me a sketch of the elements that failed, but not to tell me where they broke. After entering the data into my analysis program and letting it run, I found the element's weakness. Dick confirmed the correctness of my "after the fact" prediction. The elements of his identical beams failed at the exact spot the program indicated. This procedure should help you evaluate the mechanical integrity of your existing designs or design a homebrew Yagi.

Failure modes

An element has failed if it breaks off or is bent enough to render it useless. There are several causes of in-service failures. The element could be covered with too much ice, the wind hitting the element may impose a load which causes it to fail, or the element may break off because of wind-induced vibration or fluttering. The first two causes have to do with direct loading of the element due to ice and wind; the third generally happens at very low wind speeds. My procedure deals only with the loading of the element, *not* with vibration-induced fatigue failures.

FIGURE 1



Graphic illustrations of both the Rigid Element Model and the Flexible Element Model, and how each reacts to a theoretical wind.

The environment and survivability

To determine survivability, give careful consideration to the Yagi's environment. The main environmental problem is loading due to ice and wind. The weight of the ice loads the element and its thickness increases the element diameter. The increased diameter of the element results in a higher wind load.

You must make several choices when designing or evaluating an element. It's necessary to determine or select the extreme ice and wind conditions the element will have to handle. Consider whether the element is expected to survive those conditions, or have an additional margin of safety. Some manufacturers state their design will survive specific wind speeds. In a strict engineering sense, survivability means that if the stated conditions are exceeded, there will be a failure. If there is a margin of safety, failure will occur at conditions of higher severity. It's wise to understand all aspects of the loads on an element, the materials used in its construction, and their safety factors. Without this, you could construct an element that costs and weighs more than it needs to survive its environment. This design might place unnecessarily higher loads on the tower and rotator.

Element analysis

You can mathematically construct two element models. I call them the Rigid Element Model (REM) and the Flexible Element Model (FEM). REM is an approximation of the more exact and complex FEM version. The REM model assumes the element doesn't deflect when loaded with ice or wind. It also assumes that all parts of the element are perpendicular to the wind. FEM accounts for the deflections of the element at all points along its length. The actual element length exposed to the wind decreases as it deflects. **Figure 1** shows the REM and FEM assumptions applied to an element. With FEM, the wind loading isn't perpendicular to the element at all points. This decreases the loading on the element as compared to REM. The wind loading of the element is less severe with FEM, but more accurate.

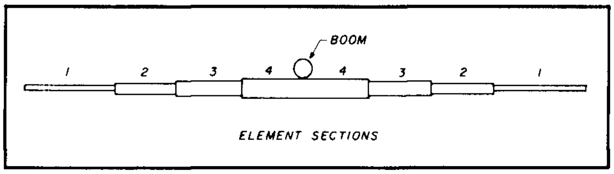
While the FEM version gives a precise description of the actual conditions, modeling is complex and time consuming. REM is easier and faster. The errors introduced by the REM assumptions result in a design more conservative than one using FEM.

General approach

Begin your element analysis by selecting the wind and ice conditions it is to survive and calculating the loads these conditions will place on the element. The loads are related to the element's size. You must know the relationship between the wind, ice, and tubing sizes used in the element to find the resulting loads. Once you've determined the loads, find the resulting stress by ascertaining the type of material used to make the element along with its geometric properties. Compare the stress to the maximum allowable value for the material used. If the resulting stress is lower than the maximum acceptable level, the design is conservative. If the stress is over the maximum acceptable level, the design won't survive the wind and ice conditions.

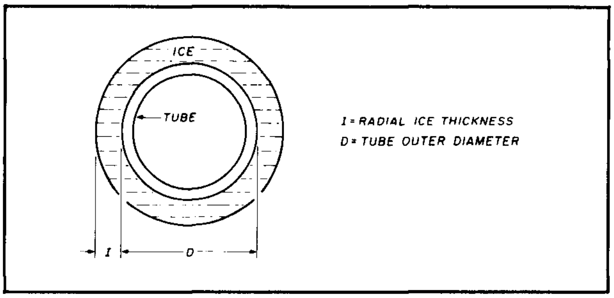
You can identify weak spots when analyzing an existing design or compare it with the relative merit of others. If an existing design is weak, you may choose to reinforce it or purchase another. When planning an element, you can alter the design by using different sizes and lengths of tubing in the element makeup until you find an acceptable combination.

FIGURE 2



A typical Yagi element constructed from telescoping sections of aluminum tubing.

FIGURE 3



Yagi element shown with "ice loading." If you know the tube outer diameter and the thickness of the ice on the element, you can closely approximate the amount of loading being placed on the element.

Element description

Figure 2 shows a typical element constructed from various tubing sizes. The outermost element section is called 1; the numbers increase as they approach the boom. Because the element is symmetrical relative to the boom, the other half of the element will have the same numbering scheme. An element section is a part of the element that has the same outer diameter and wall thickness. If one part of the element telescopes into another, a new section is formed. A section can be long or short, but its entire length must have the same wall thickness and outer diameter. If a tube is reinforced either on the outside or inside, a new section is created because its geometric properties are different. **Figure 2** shows a four-section element. Because the sections are the same on both sides of the boom, the analysis procedure will be applied only to one.

Element loading

There are three components to the loading of an element: the weight of any ice on the element section, the weight of the tubing making up the section, and the wind load on the section. They must be determined and summed to yield the total loading. The first step is to break the element into sections as shown in **fig. 2**. Then find the total load on each individual section.

Two types of ice can form on the element. The most common is solid ice; the least common is rime ice. My equations are based on solid ice weight. Solid ice weighs 56 pounds per cubic foot, rime ice about 30 pounds per cubic foot.[2] Generally, ice accumulation on round tubes is stated in terms of "radial thickness." For example, if a 1-inch diameter tube has 0.25 inch of radial ice, the effective diameter for the wind loading is 1.5 inches. The inch weight is determined by the volume of ice surrounding the tube as shown in **fig. 3.**

For solid ice, Wi can be found using **eqn. 1.**

$Wi = 0.102 \times L(D \times I + I^2)$ **(1)**
Wi = weight of ice on section (pounds)
I = radial ice thickness (inch)
L = section length (inch)
D = tube outer diameter (inch)

To find the tubing weight in a section take one of two approaches. Either look up the weight of the tubing in a supplier's catalog or calculate it directly. The weight per foot is given on most tubing charts. Calculating the weight directly may be easiest because this method doesn't depend on having a catalog. Because most Yagi elements are made from aluminum tubing, use **eqn. 2** to find the section weight. This ignores the weight of the tubing inside the overlap of two telescoped sections.

$Wa = 0.31 \times L\,(D \times T - T^2)$ **(2)**
Wa = weight of aluminum tubing section (pounds)
T = tubing wall thickness (inch)
L = section length (inch)
D = tube outer diameter (inch)

The last load on the element section is wind induced. When the wind strikes a surface, pressure is created by the impact of the air stream on the surface. The wind load depends mainly on the wind velocity and the shape of the impacted surface; some shapes are more or less streamlined than others. Use **eqn. 3** to find the wind load on a round tubing section. The drag coefficient is included in the equation to account for the streamlined effect of a round tube,[2] along with the conversion of units for wind pressure.

$Fw = 0.0047 \times L \times De \times P$ **(3)**
Fw = wind load on round section (pounds)
L = section length (inch)
P = wind pressure perpendicular to a flat surface (pounds/square foot)
De = effective outer diameter of tube (inch)

The effective diameter of the tube (De) accounts for an increase in diameter due to ice. If there's no ice, the tube's outer and effective diameter are the same.

$De = D + I + I$ **(4)**
De = effective outer diameter of tube (inch)
I = radial ice thickness (inch)
D = tube outer diameter (inch)

The total load on a section (Ft) is the sum of the ice weight, element weight, and wind load.

$Ft = Wi + Wa + Fw$ **(5)**
Ft = total load on section (pounds)
Wi = weight of ice on section (pounds)
Wa = weight of aluminum tubing section (pounds)
Fw = wind load on section (pounds)

You could argue that the two weights added together are at right angles to the wind load and shouldn't be added directly. There's no guarantee that this will be the case; upward and downward wind streams are a common occurrence.[3]

Wind pressure

Calculate the wind pressure striking a flat surface with **eqn. 6.**[2] This isn't the wind pressure on a round tube, but a flat surface. **Equation 3** includes a "drag coefficient" to alter the wind pressure found in **eqn. 6. Equation 6** also includes a gust factor of 1.30 to account for short duration gusts peaking above the mean speed of V. If you select a wind speed and use **eqn. 6**, you are actually calculating for a wind speed 1.30 times higher. For example, when you select a wind speed of 86.6 mph, you are actually accounting for a peak wind of 112.6 mph.

$P = 0.004 \times V^2$ **(6)**
P = wind pressure on flat surface with 1.30 gust factor (pounds/square foot)
V = wind speed (miles/hour)

If you don't want to use a gust factor, you can modify **eqn. 6** to find the wind pressure at the exact wind speed entered. Removing the gust factor gives you **eqn. 7.**

$P = 0.0024 \times V^2$ **(7)**
P = wind pressure on flat surface (pounds/square foot)
V = wind speed (miles/hour)

What's the proper wind load an element should be expected to handle? You can make the selection in several ways. Research the history of wind speeds in your area. Go back about 20 to 50 years to see what the worst wind has been. Find out if the wind information should have the gust factor applied.

Consult local building codes covering towers and similar structures. EIA standard RS 222c contains information on the wind loading towers should be designed to handle, based on their geographical location. You can also consult the American Standard Building Code. Both EIA RS 222c and the American Standard Building Code include maps of the United States recommending design wind loads. There are small differences between the codes, but for Amateur applications they are basically the same.

According to RS 222c, most of the United States should expect a 50-year mean reoccurrence wind of 86.6 mph. Certain coastal areas have a 100 mph or higher recommendation. The wind speeds found in EIA RS 222c are mean wind speeds, and are to be used with **eqn. 6.** The most common wind speed is 86.6 mph; 100.0 and 112.0 mph are the extreme values. **Table 1** shows wind pressures at various mean wind speeds and their corresponding peak value with a 1.30 gust factor.

Because the REM procedure errs on the conservative side, using a mean wind speed of 86.6 mph results in a conservative design for most areas and would be a rigid

TABLE 1

Wind pressures at various mean wind speeds and their corresponding peak value with a 1.30 gust factor.

Mean Wind Speed (mph)	Corresponding peak wind with 1.30 gust factor (mph)	Wind pressure (pounds/square foot)
20.0	26.0	1.6
30.0	39.0	3.6
40.0	52.0	6.4
50.0	65.0	10.0
60.0	78.0	14.4
70.0	91.0	19.6
80.0	104.0	25.6
86.6	113.0	30.0
100.0	130.0	40.0
112.0	145.6	50.0
115.0	149.5	52.9
125.0	162.5	62.5

TABLE 2

Calculate the worst combinations of conditions in your area for winter and non-winter conditions to evaluate existing design. Numbers shown are for my QTH.

Season	Radial ice	Mean wind	Peak wind	Pressure level
Winter	0.25 inch	40.0 mph	52 mph	6.4 pounds/square foot
Non-winter	0 inch	86.6 mph	113 mph	30 pounds/square foot

TABLE 3

Dimensions for half of a 36-foot Yagi element with four sections as in *fig. 2*.

Section	L (inch)	D (inch)	T (inch)
1	48.0	0.500	0.058
2	60.0	0.625	0.058
3	72.0	0.750	0.058
4	36.0	0.875	0.058

TABLE 4

Winter conditions

Section	Wi (pounds)	Wa (pounds)	Fw (pounds)	Ft (pounds)
1	0.92	0.39	1.45	2.76
2	1.34	0.61	2.04	3.99
3	1.83	0.90	2.71	5.44
4	1.04	0.53	1.49	3.06

TABLE 5

Non-winter conditions

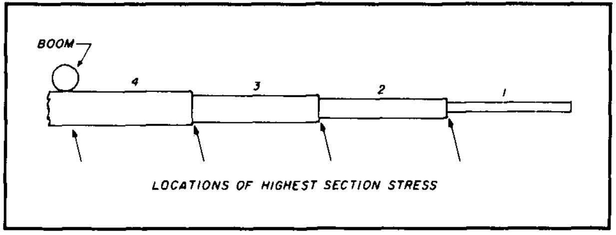
Section	Wi (pounds)	Wa (pounds)	Fw (pounds)	Ft (pounds)
1	0	0.39	3.38	3.77
2	0	0.61	5.29	5.90
3	0	0.90	7.61	8.51
4	0	0.53	4.44	4.97

standard by which to evaluate existing designs. Judge the expected amount of radial ice and, more importantly, the combination of wind and ice for your own area and make your evaluations based on these sets of conditions. Here in northern Texas, our highest winds occur in the spring and early summer. We often have ice storms in the winter, but the winds are not very high. At my location I use the two sets of conditions in **table 2**; yours may be quite different.

Loading example

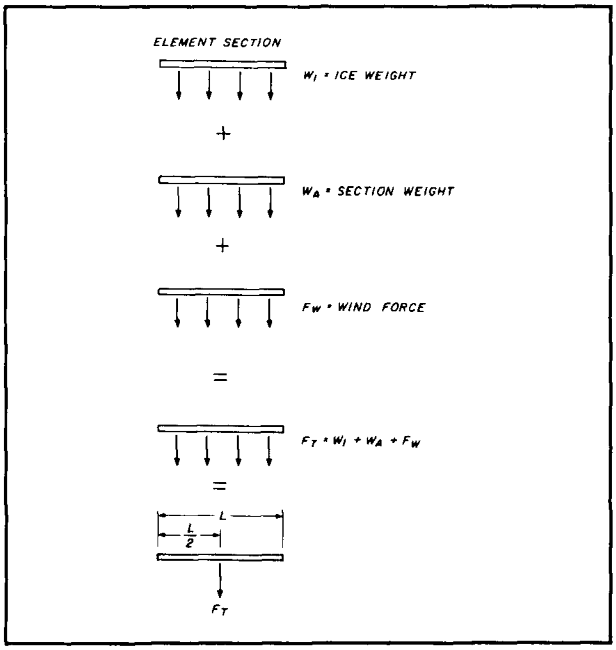
Table 3 gives the dimensions for half of a 36-foot Yagi

FIGURE 4



The joints where progressive sections of an element telescope together are typically the high stress points along the element.

FIGURE 5



Shown here are the three individual distributed forces, the total distributed force, and the total force applied at the element's "center of action."

element with four sections like those in **fig. 2. Tables 4** and **5** show the loads Wi, Wa, Fw, and Ft for the winter and non-winter conditions in **table 2**. Comparing the Fts for both cases shows the non-winter conditions to be much more severe than the winter ones. Because the non-winter conditions are the most severe, only they will be used in the last stages of the element analysis. When confronted with several sets of conditions, determine which are the most severe and use them in your analysis.

The stress in a section varies along the section length. The highest value occurs at the point where one section ends and another begins, as you approach the boom. In this analysis procedure, you'll calculate only the highest stress value in each section. **Figure 4** shows the locations under the greatest stress in a four-section element.

The forces resulting from wind, ice weight, and element weight of each section are evenly distributed over the section's length. The three evenly distributed forces can be replaced by a point force (Ft) applied at a unique location. The location is at the "center of action" — the section's midpoint. **Figure 5** shows the three individual distributed forces, the total distributed force, and the total force applied at its center of action. You need Fts and their points of application to find the maximum stress in the sections.

Fts cause the element to bend; this results in bending stresses in the tube sections. These stresses are calculated from the geometry of the tube and the amount of bending action. Use **eqn. 8** to find the bending stress when you know the section modulus of the tube and the bending moment at the point of interest. There is another stress at this point, but it's very small and will be ignored.

$$Sb = \frac{M}{Z} \qquad \textbf{(8)}$$

Sb = bending stress (pounds per square inch, psi)
M = bending moment (pound per inch)
Z = section modulus (inch^3)

The section modulus for a round tube (Z) can be found using **eqn. 9**.

$$Z = 0.098 \times \frac{D^4 - (D - 2T)^4}{D} \qquad \textbf{(9)}$$

Z = section modulus (inch^3)
D = tube outer diameter (inch)
T = tube wall thickness (inch)

The section modulus describes the geometry of the tube. If you consider tubes of the same material, the one with the larger section modulus can take additional bending. To find the section modulus for two or more close-fitting telescoped tubes, make the combined wall thickness T and the largest outer diameter D. **Table 6** gives the section moduli for a number of tube sizes. **Table 7** gives the section moduli for various telescoped combinations.

In **table 7**, the combined wall thickness of 0.116 inch is for two walls of 0.058 inch; the combined wall thickness of 0.174 inch is for three walls of 0.058 inch. The values shown are for standard telescoping combinations. For example, an 0.875 inch outer diameter tube with a combined wall thickness of 0.174 inch is made of three telescoped tubes. It has 0.875, 0.750, and 0.500-inch diameter tubes, each with a wall thickness of 0.058 inch.

To find the bending moment you must know the forces causing the bending and the distances to their points of application. The forces are the Fts found for each section; the distances are taken from the location of the section midpoints. **Figure 6A** shows the situation for section 1. Find the moment at the point of maximum stress in section 1 with **eqn. 10**.

$$M1 = Ft1 \times \frac{L1}{2} \qquad \textbf{(10)}$$

TABLE 6

Section moduli and weights for a number of tube sizes.

Tube outer diameter (inch)	Wall thickness (inch)	Weight per foot (lbs/ft)	Section modulus (inch³)
0.25	0.035	0.03	0.0011
0.25	0.049	0.04	0.0013
0.25	0.058	0.04	0.0014
0.375	0.049	0.06	0.0036
0.375	0.058	0.07	0.0040
0.50	0.058	0.01	0.0080
0.50	0.125	0.17	0.0115
0.625	0.058	0.12	0.0134
0.625	0.125	0.23	0.0208
0.75	0.058	0.15	0.0202
0.75	0.125	0.	0.0332
0.875	0.058	0.18	0.0285
0.875	0.120	0.34	0.0474
1.00	0.058	0.20	0.0382
1.00	0.125	0.40	0.0670
1.125	0.058	0.23	0.0492
1.125	0.125	0.46	0.0885
1.25	0.058	0.26	0.0618
1.25	0.125	0.52	0.1130

TABLE 7

Section moduli for various telescoped combinations.

Tube outer diameter (inch)	Combined wall thickness (inch)	Section Modulus (inch³)
0.375	0.116	0.0051
0.500	0.116	0.0112
0.500	0.174	0.0120
0.625	0.116	0.0202
0.625	0.174	0.0230
0.750	0.116	0.0319
0.750	0.174	0.0379
0.875	0.116	0.0465
0.875	0.174	0.0570
1.000	0.116	0.0639
1.000	0.174	0.0803
1.125	0.116	0.0841
1.125	0.174	0.1078
1.250	0.116	0.1072
1.250	0.174	0.1395

M1 = moment in section 1 (pound-inch)
Ft1 = total load on section 1 (pounds)
L1 = length of section 1 (inch)

Using the non-winter conditions of **table 5**, calculate the bending moment and bending stress for section 1 as follows:

From **table 5**, Ft1 = 3.77 pounds
From **table 3**:
L1 = 48.0 inches
D1 = 0.500 inch
T1 = 0.058 inch
and then from **table 6**
Z1 = 0.0080 inch³
Using **eqn. 10**

$$M1 = 3.77\,pounds \times \frac{48.0}{2}\,inch = 90.5\,pound\text{-}inch$$

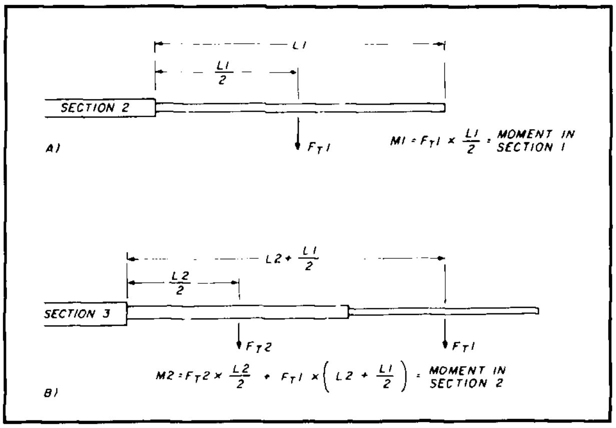
Using the bending moment and the section modulus (Z1) calculate the bending stress using **eqn. 8**.

$$Sb1 = \frac{90.5\,pound\text{-}inch}{0.0080\,inch^3} = \frac{11{,}312.5\,pounds}{inch^2}$$

$$Or\ 11{,}312.5\ psi$$

Sb1 = bending stress for section 1 (pounds per square inch)

FIGURE 6



(A) Determining the moment for section one of the element. (B) Determining the moment for section two, and showing how the moment of the previous section(s) are added together for each new section calculated.

To find the bending moment at the highest stress point in section 2, multiply the appropriate Fts by the distance from their centers of action to the highest stress point and then add them together. **Figure 6B** shows the forces and distances. M2 is the sum of the moments produced by Ft1 and Ft2.

$$M2 = Ft2 \times \frac{L2}{2} + Ft1 \times \left(L2 + \frac{L1}{2}\right) \quad \textbf{(11)}$$

M2 = bending moment at end of section 2 (pound-inch)
Ft2 = section 2 total load (pounds)
Ft1 = section 1 total load (pounds)
L1 = section 1 length (inch)
L2 = section 2 length (inch)

Find the stress in section 2 with **eqn. 8** using the moment at the point of highest stress and the section modulus at that point.

$$Sb2 = \frac{M2}{Z2}$$

Continuing with the values from **table 3** and the non-winter case from **table 5**, the variables are as listed:

L1 = 48.0 inches
L2 = 60.0 inches
Ft1 = 3.77 pounds
Ft2 = 5.91 pounds
D2 = 0.625 inch
T2 = 0.058 inch
Z2 = 0.0134 inch^3 (from **table 6**)

$$M2 = 5.91\,pounds \times \frac{60.0}{2}\,inch + 3.77\,pounds \times$$

$$(60.0\,inch + \frac{48.0}{2}\,inch)$$

M2 = 177.3 pound-inch + 316.7 pound-inch = 494.0 pound-inch

$$Sb2 = \frac{M2}{Z2} = \frac{494.0\,pound\text{-}inch}{0.0134\,inch^3} = 36{,}865.6\ PSI$$

If there are three sections, M3 is calculated from:

$$M3 = Ft3 \times \frac{L3}{2} + Ft2 \times \ L3 + \frac{L2}{2}$$

$$+ Ft3 \times \left(L3 + L2 + \frac{L1}{2}\right)$$

$$Sb3 = \frac{M3}{Z3}$$

If there are four sections, M4 is calculated from:

$$M4 = Ft4 \times \frac{L4}{2} + Ft3 \times \left(L4 + \frac{L3}{2}\right)$$

$$+ Ft2 \times \left(L4 + L3 + \frac{L2}{2}\right)$$

$$+ Ft1 \times \left(L4 + L3 + L2 + \frac{L1}{2}\right)$$

$$Sb4 = \frac{M4}{Z4}$$

If there are more than four sections, the method is expanded following the same pattern. Use what follows as a guide.

The highest stress in a section is determined by finding the bending moment at the point of highest stress and dividing it by the section modulus of the tube at that point. The bending moment is found by multiplying the forces (Fts) causing the bending at the point of highest stress by the corresponding distance to their points of application and then summing.

At this point, it's easier to either write a program to do all the math, or do it by hand in tabular form. **Table 8** shows the complete solution set for the example being used.

The maximum stress in each section has been calculated and must be compared to the allowable maximum. There are three popular aluminum alloys used in commercial Yagis and by Amateur builders. The maximum allowable stress for each is shown in **table 9**. The most commonly used alloy, 6061-T6, is found in most commercial Yagis; it can be obtained from supply houses and mail-order outlets.

The maximum allowable stress is usually called the "yield stress." Exceed this stress level and the part may break or be permanently bent. If you go beyond this level only slightly, you may not notice the bend because of the existing element droop. But if you greatly exceed the stress level, your element may incur a large, permanent bend or break. In this situation, a hidden safety factor

TABLE 8

Complete solution set.

Sec	OD (in)	T (in)	L (in)	Ft (lbs)	Z (in^3)	M (lbs-in)	Sb (psi)
1	0.500	0.058	48.0	3.77	0.0081	90.5	11,300
2	0.625	0.058	60.0	5.90	0.0134	494.0	36,860
3	0.750	0.058	72.0	8.51	0.0202	1496.3	74,070
4	0.875	0.058	36.0	4.97	0.0285	2240.2	78,600

TABLE 9

Maximum allowable stress for the three popular aluminum alloys used in commercial Yagis and by Amateur builders.

Aluminum Alloy	Maximum allowable stress (psi) (4)
6061-T6	35,000
6063-T6	25,000
6063-T83	30,000

TABLE 10

Element with section lengths altered to obtain maximum allowable stress.

Sec	OD (in)	T (in)	L (in)	Ft (lbs)	Z (in^3)	M (lbs-in)	Sb (psi)
1	0.500	0.058	84.0	6.59	0.0081	276.7	34,580
2	0.625	0.058	24.0	2.36	0.0134	463.2	34,500
3	0.750	0.058	24.0	2.84	0.0202	712.0	35,130
4	0.875	0.058	84.0	11.69	0.0285	2189.0	76,720

TABLE 11

Element with section 4 a telescoped combination 1.00 and 0.875-inch diameter tube.

Sec	OD (in)	T (in)	L (in)	Ft (lbs)	Z (in^3)	M (lbs-in)	Sb (psi)
1	0.500	0.058	84.0	6.59	0.0081	276.7	34,580
2	0.625	0.058	24.0	2.36	0.0134	463.2	34,500
3	0.750	0.058	24.0	2.84	0.0202	712.0	35,130
4	1.000	0.116	84.0	14.51	0.0640	2311.5	36,110

may come into play. If the maximum allowable stress is just slightly surpassed, you may not have a failure resulting in element breakage. The only result may be a slight permanent bend, which may not be observable or cause any harm. This safety factor would come into play if the peak wind conditions were exceeded.

The example in **table 8** shows that, regardless of the alloy used, this design is over stressed in two areas. In addition, it's marginal in one area and acceptable in another. Using 6061-T6 aluminum throughout this example, the maximum allowable stress is 35,000 psi. Any section stress below this value indicates a section which is not fully utilized; any section stress above the maximum value indicates a section which is overloaded. An overloaded section must be changed to bring the stress level down to an acceptable level. You'll have equal strength when all section stresses have the same value. There are good reasons to have some sections stronger than others, but this is an economic decision to be discussed later.

What can be done to improve the example element in **table 8**? Make the 0.500 diameter tube longer to take more load and reduce the length of others while keeping the total length the same. Lengthening the 0.500 diameter tube to allow it to take more load also reduces the total wind load put into the element because the smaller diameter tubing is replacing the larger. **Table 10** shows the same element with altered section lengths. Starting at the outer section and working towards the boom, the section lengths were changed to obtain the maximum allowable stress.

Sections 1, 2, and 3 are acceptable; 4 is still unacceptable. There will be slight improvement if you use more of the lighter, less expensive tubing. Section 4 still has a problem, but has improved somewhat. With the smaller sections optimized, improvement in section 4 is impossible without a change in its geometry. **Table 11** shows the same element, with section 4 as a telescoped combination of 1.00 and 0.875-inch diameter tubes.

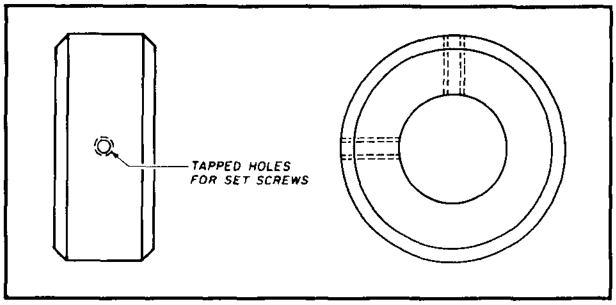
Section 4 has a stress slightly over the maximum. This

TABLE 12

Example of section 4 shown as a single tube with marginal strength.

Sec	OD (in)	T (in)	L (in)	Ft (lbs)	Z (in^3)	M (lbs-in)	Sb (psi)
1	0.500	0.058	84.0	6.59	0.0081	276.7	34,580
2	0.625	0.058	24.0	2.36	0.0134	463.2	34,500
3	0.750	0.058	24.0	2.84	0.0202	712.0	35,130
4	1.250	0.058	84.0	16.60	0.0619	2399.4	38,780

FIGURE 7



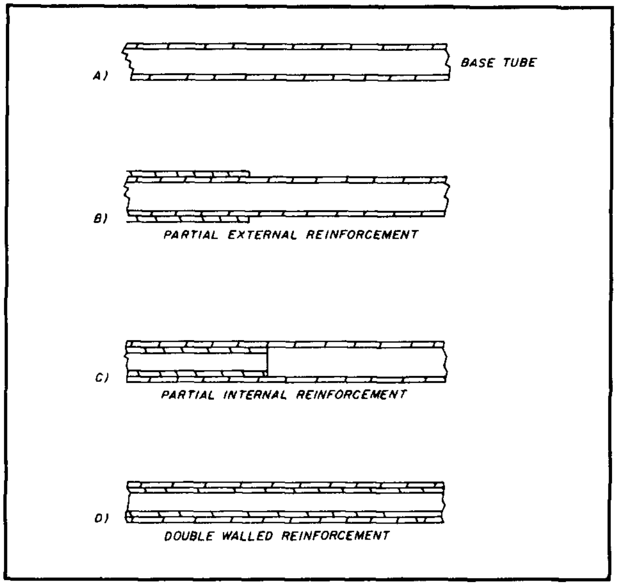
Description of a spacer which can be used when making a large decrease in tubing sizes on an element; i.e., two sizes that will not telescope together and allow a compression joint.

design is totally acceptable given the conservative nature of the rigid element model. There are several things to note. As the element gets longer, the strength requirements rapidly increase. This can be seen by the very short lengths of sections 2 and 3. In addition, section 4 had to be drastically reinforced. **Table 12** shows the same example, where section 4 is a single tube with marginal strength. Section 4 is a 1.250-inch diameter tube of 0.058-inch wall thickness. This large tube has about the same section modulus as the composite of the 1.000 and 0.875-inch tubes, but has a larger wind load due to its larger diameter. This offsets some of its greater load bearing capacity.

You'll encounter a problem when making a large jump in tubing size. Because the jump from 0.750 to 1.250 isn't a telescoping fit, you need to fabricate a spacer or "donut." **Figure 7** shows a spacer used by N5RM to build his 40-meter flame thrower.[1] Several manufacturers swage the end of a larger tube to a smaller size. The result is a large diameter reduction allowing a telescoping fit with a smaller tube. This method is not practical for the individual builder.

There are several ways to achieve a significant increase in section strength. One is to try increasingly larger diameter tubes in your calculations, until you find an outcome with an acceptable stress. This could lead to a fabrication problem due to non-telescoping tubing sections. You can also increase the strength of a section by externally or internally reinforcing the tube along part or all of its length. **Figure 8** shows three reinforcement methods. In doing the analysis, you will create a new section when there is a change in the tube geometry.

FIGURE 8



Several methods for reinforcing element tubing are shown: At (A) the base tube with no reinforcing, at (B) the base tube with partial external reinforcement, at (C) the base tube with partial internal reinforcement, and at (D) the base tube as used in a double walled reinforcement.

Figures 8A and **8D** are one section while **figs. 8B** and **8C** are two sections. The method you select should be based on cost, ease of construction, availability of materials, total element weight, and total element wind area. There are a large number of possible combinations of tubing sizes which can be successfully used in a design. The final configuration depends on your resources and ingenuity.

It's desirable to have a design with no weak links, but having links of differents strengths can be good and bad. It depends on what you want the design to accomplish. If you want the absolutely lightest element, design sections with the same maximum allowable stress. This design may not provide an economical use of tubing; it's usually purchased in finite lengths, and sections may be wasted. Zero waste may not be possible unless you make it a design consideration from the beginning. You could try to put together an element without cutting tubing which could be used for another project. In this case the section stresses might be quite different. This is totally acceptable provided none exceed the maxi-

TABLE 13

Tubing sizes of a 36-foot element with poor design.

EWT = 8.4 pounds EWL = 68.4 pounds

Section	D (inch)	T (inch)	L (inch)	Sb (psi)
1	1.000	0.058	48.00	4,760
2	1.125	0.058	96.00	35,050
3	1.250	0.058	72.00	64,910

TABLE 14

36-foot element with improved design.

EWT = 8.0 pounds EWL = 66.4 pounds

Section	D (inch)	T (inch)	L (inch)	Sb (psi)
1	1.000	0.058	131.00	35,450
2	1.125	0.058	13.00	33,220
3	1.250	0.058	18.00	33,700
4	1.250	0.116	54.00	35,830

TABLE 15

Comparison of materials used in *Tables 13* and *14*.

	Case 1 (Table 13)		Case 2 (Table 14)	
Tube Diameter size (0.058 wall)	**12-foot lengths needed**	**waste**	**12-foot lengths needed**	**waste**
1.000	1	38 inches	2	16 inches
1.125	2	86 inches	1	0 inches
1.250	1	0 inches	1	0 inches

mum allowable stress. You can use different alloys of tubing as long as you don't exceed the maximum allowable stress level for each type.

The section nearest the boom will be the most expensive and minimum waste is a goal. Make section 1 from the least costly tubing. It can give you the largest span for the least money. Look closest at the intermediate sections for waste. Several other considerations mentioned earlier come into play when making tradeoffs between tubing sizes and reinforcement methods. Consider the overall element weight and area. If there is choice between several options, the lighter, smaller area element offers some advantages. If two designs for a four-element, 20-meter beam were found to have acceptable stress levels, choose between them on basis of the amount of wind load they put into the tower and rotator. Because using REM requires finding the weight and wind load of each section, it would be easy to sum the total section weights and wind loads to obtain two other parameters for comparing element designs. Multiply these by 2 to obtain the total for both element halves.

EWT = 2 × (sum of all section Was) **(12)**
= total element weight (pounds) ignoring overlap

EWL = 2 × (sum of all section Fws) **(13)**
= total wind load on element (pounds) at maximum wind speed

I found the element design in **table 13** in an Amateur publication. The tubing sizes for this 36-foot element show that it is a very strong one. Or is it? With the analysis done at 86.6 mph and no ice, this element was found to be poor and the end of section 3 to be very weak. Section 1 could be made a lot longer. I found an acceptable configuration after I made several attempts to improve this design using the same tube sizes. **Table 14** shows the improved design.

Section 1 was greatly lengthened, while section 2 was greatly reduced. Section 3 was changed to a shorter section. The new section 4 is the remainder of the old section 3, reinforced on the inside with some of the same material used in section 2. Not only has the strength of the element improved, but there has been a slight drop in element weight and wind load. Was this an efficient use of the material? **Table 15** shows the materials used and the waste for the two cases. This was done assuming a 5-inch overlap at each joint and stock tubing lengths of 12 feet. You can make several conclusions when comparing the published design and improved version by looking at

TABLE 16

Revised element for improved design.

EWT = 7.3 pounds EWL = 42.8 pounds

Section	D (inch)	T (inch)	L (inch)	Sb (psi)
1	0.500	0.058	84.00	34,580
2	0.625	0.058	24.00	34,500
3	0.750	0.058	23.00	34,550
4	0.750	0.116	30.00	34,640
5	1.00	0.116	55.00	34,730

TABLE 17

Summary of features of element designs in *Tables 16, 13,* and *14.*

	Table 16	Table 13	Table 14
Survival mean wind speed (peak) (mph)	86.6 (112.5)	64.0 (83.2)	86.6 (112.50)
Element weight (pounds)	7.3	8.4	8.0
Element wind load at 86.6 mph (pounds)	42.8	68.4	66.4

tables 13, 14, and **15**. The improved version is lighter, less expensive to build, places less wind load on the tower, and is significantly stronger.

Take care not to generate a design with a hidden problem. The example in **table 11** is a buildable design, but has a construction problem. Section 4 is 84 inches long. This is not half of a 12-foot piece where 6 feet are used on each side of the boom. Using the 84-inch section results in a lot of waste, and requires special efforts for mounting and joining at the boom. A design revision uses a piece of section 2 material for internal reinforcement. Two 12-foot telescoped pieces are cut to a length of 110.0 inches with half on each side of the boom. **Table 16** shows the improved design.

Table 17 summarizes the features for the element designs in **tables 16, 13,** and **table 13**'s improved version in **table 14**. This improvement costs less and is slightly lower in weight and wind load. The element in **table 16** will withstand the same wind, but have about 35 percent less wind load. You can build Yagis which minimize the loads placed on towers, booms, and rotators, while still surviving very high winds.

Before using this method of element design, determine your constraints, limitations, and objectives. The procedure allows you to generate designs to minimize weight and wind loading, and make optimal use of materials. It can be used to evaluate any existing design.

Summary

This analysis procedure provides a simple and sound method to evaluate the structural integrity of existing element designs and assist in the process of designing an element. I have presented several methods of reinforcing element sections and various criteria by which to judge them. To implement the procedure, you'll need to determine the *worst set of survival conditions for your geographical location*, your objectives, and restrictions.

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3. C.J. Richards, et al., "Mechanical Engineering in Radar and Communications," D. Van Nostrand Reinhold Company, 1969, page 150.
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