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Deflections and guy tensions of guyed masts subjected to direct and torsional loads.

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DEFLECTIONS AND GUY TENSIONS OF GUYED MASTS SUBJECTED TO DIRECT AND TORSIONAL LOADS

Submitted in partial fulfilment of the requirements for the degree of Master of Applied Science from the University of Windsor.

By

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NOTATION

T	Tension in a guy cable.
H	Horizontal component of guy tension.
V	Vertical component of guy tension.
ds	Element of guy length.
w	Weight per unit length of guy cable.
w^1	Weight per unit length of horizontal projection.
h	Horizontal distance from guy anchorage to guy attachment.
v	Vertical height from guy anchorage to guy attachment.
C	Chord length of guy cable.
S	Length of guy cable.
θ	Angle between the guy chord and the horizontal.
w_n	Weight of the cable acting normal to the chord.
Δ	Elongation of the cable.
A	The metalic area of the guy cable.
E	The elastic modulus of the guy cable.
Δc	Change in chord length due to a change in load in the cable.
Δh	Horizontal deflection of guy attachment point.
w_1	Load acting normal to the chord of the cable for the initial condition.
w_2	Load acting normal to the chord of the cable for the final condition.
Δx	Deflection in the x-direction.
Δy	Deflection in the y-direction.

Δm Deflection due to applied torque.

Δh Horizontal deflection of guy attachment point.

b Distance from centre of mast to guy attachment point on the outrigger.

γ Horizontal angle between the guy and the nominal guy line.

A_{nn} Coefficient used in the matrix.

V_n Constants used in the column matrix.

VR_n Constants used in the column matrix.

1.0 INTRODUCTION

Guyed masts have been used for over 40 years in the communication field. Radio towers were the first uses, either to support antennas or as the radiating element itself. As television became popular, guyed masts were used to achieve the ever increasing heights demanded by this industry, until today these towers are the tallest man made structures. Another very important use is for the support of microwave dishes serving the telecommunication industry.

With the increased use of guyed masts and especially with the ever increasing heights, better and more accurate methods of analysis have been required. To satisfy these requirements numerous papers have been written (5, 6, 7, 8, 9, 11)*. However all of these papers have ignored or only briefly alluded to torsional loads. This is understandable in that they have been primarily concerned with the "tall guyed masts" associated with television or radio towers and these towers by their nature are subjected to little or no torsional loads. It is only in the microwave tower with its paraboloidal dishes that torsional loads become significant and must be given consideration.

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*Numbers in parentheses refer to items in the list of references.

1.1 The Microwave Tower

Microwave systems for the long distance transmission of telephone, television and telex signals have become the main carriers of our modern telecommunications industry. These systems require that the microwave antennas be supported at an elevation so that a "line of sight" signal can be beamed from one antenna to the other. Due to the curvature of the earth and for electronic reasons these antennas are usually located 20 or 30 miles apart. When longer distances must be traversed, a series of repeater stations are used, which pick up the signal, strengthen it and then beam it on to the next station.

Microwave antennas are paraboloidal in shape with a horn located at the focal point to transmit or receive the signal. The antenna size can vary from four feet to over 120 feet in diameter. The larger size antennas are self supporting structures in themselves, while antennas up to 30 feet in diameter have been supported on free-standing towers. The maximum size of antenna used on a guyed tower has been 12 feet in diameter.

The size and shape of these antennas are such that they impose large direct and torsional loads on the tower. The calculation of the magnitude of these loads are a study in themselves and outside the scope of this paper.* For the purposes of this study, it is assumed that the magnitude and

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*References 6, 9, 11, deal with the calculation of loads and reactions in multilevel guyed towers.

direction of the loads at the guy level are known.

Because the signal being transmitted is directed to the receiving antenna, deflections must be limited to specified tolerances or else the signal will fade below an acceptable level and therefore be unuseable. The amount of deflection or tilt (deviation from the vertical) and rotation (deviation in the horizontal plane) allowed will vary from system to system, depending on the frequency of the signal, equipment used, and local conditions. One system might specify the deflections be limited to $\pm$ one degree; another system may specify $\pm$ 0.5 degrees of twist and $\pm$ 0.25 degrees of tilt.

1.2 Deflections and Guy Tensions

The deflection of the shaft is dependant upon the deflection of the guys, which is in turn related to the initial and final tensions of the guys. To resist the applied torque extra guys must be introduced, beyond that required for stability. Since the deflection of the guys are non-linear in nature a trial and error method is usually required. All of these factors present a lengthy and complicated problem for the designer.

This paper first developes the basic equations relating to guy cables used for microwave towers and then presents a method for finding the tensions and deflections resulting from a known direct and torsional load. Because of the magnitude of these calculations, a Fortran programme for an IBM 1620 Computer was written to perform the necessary calculations.

In order to varify the results of the theoretical analysis, experiments were carried out on an 80 ft. prototype guyed mast to determine the guy tensions and the resulting deflections. These deflections are limited to the deflections resulting from the action of the guy cables and guy outrigger. The deflection of the shaft is usually quite small in comparison with those of the guys and can usually be determined by conventional analysis.

2.0 GENERAL CABLE EQUATIONS

The general equations for cables as they relate to guys will be developed as an introduction to the action and behavior of the system as a whole. The basic assumption in developing these equations is that the cable is perfectly flexible and inextensible.*

Consider first a small element Δs of the cable as shown in Figure 2-1. w is the weight per unit length of the cable.

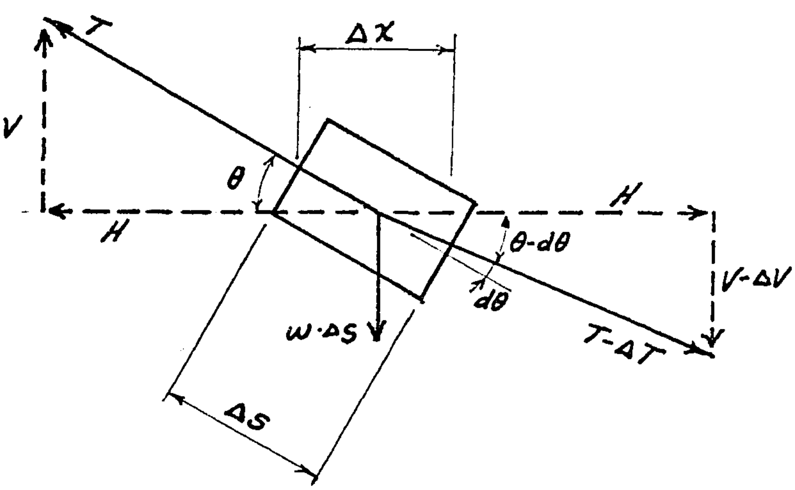

Figure 2.1 Element of a Guy.

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*Both assumptions are in error for the material used.

Writing the equations of equilibrium in the vertical direction:

$$V - \omega \cdot \Delta S = V - \Delta V$$

or

$$\Delta V = \omega \cdot \Delta S$$

Dividing by Δx yields, after proceeding to the limit,

$$\frac{dV}{dx} = \omega \frac{dS}{dx} \qquad (2\text{-}1)$$

We can also write

$$V = H \tan\theta = H \frac{dy}{dx} \qquad (2\text{-}2)$$

Differentiating with respect to x gives

$$\frac{dV}{dx} = H \frac{d^2y}{dx^2} \qquad (2\text{-}3)$$

Thus, from (2-1) and (2-3)

$$\frac{d^2y}{dx^2} = \frac{\omega}{H} \cdot \frac{ds}{dx} \qquad (2\text{-}4)$$

Equation (2-4) is the basic differential equation of a cable. The solution of equation (2-4) will determine the shape of the cable, depending on the assumptions made.

2.1 Catenary Equation

The general equation for an infinitesmal length of curve is given by

$$\frac{ds}{dx} = \left[1 + \left(\frac{dy}{dx}\right)^2 \right]^{\frac{1}{2}} \qquad (2\text{-}5)$$

substituting equation (2-5) into the general equation (2-4) gives the differential equation

$$\frac{d^2y}{dx^2} = \frac{\omega}{H} \left[1 + \left(\frac{dy}{dx}\right)^2 \right]^{\frac{1}{2}} \qquad (2\text{-}6)$$

Integrating equation (2-6) once gives

$$\frac{dy}{dx} = \sinh\left[\frac{\omega}{H} x + C_1\right] \qquad (2\text{-}7)$$

and integrating again yields

$$y = \frac{H}{w} \cosh\left[\frac{w}{H}x + C_1\right] + C_2 \tag{2-8}$$

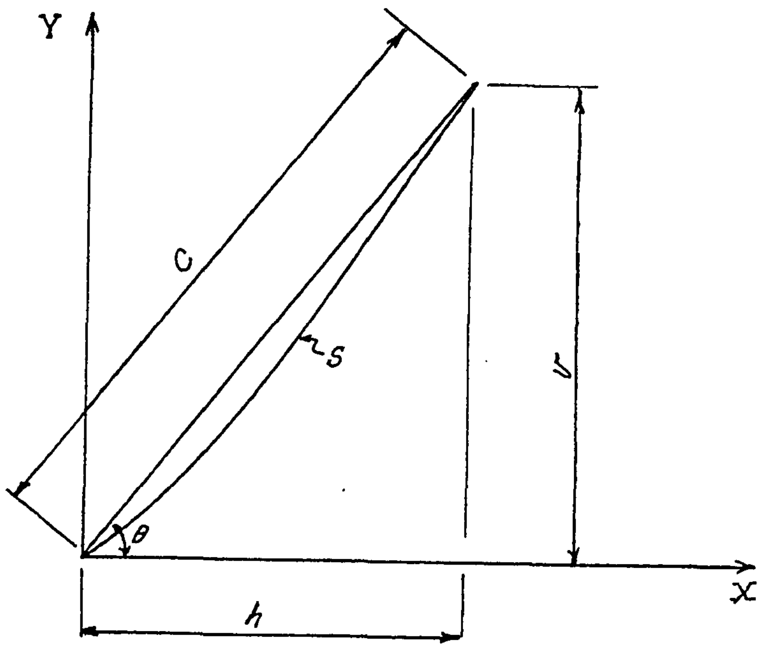


Figure 2-2 Elevation of Guy Cable (Catenary).

The constants C_1 and C_2 are obtained from the boundary conditions shown in Figure 2-2.

Whence,

$$C_2 = -\frac{H}{w} \cosh C_1$$

$$C_1 = \sinh^{-1}\left[\frac{wv}{2H \sinh(\frac{wh}{2H})}\right] - \frac{wh}{2H}$$

$$\therefore y = \frac{2H}{w} \sinh\left[\frac{wx}{2H} + C_1\right] \sinh \frac{wx}{2H} \tag{2-9}$$

This is the equation of a catenary.

The length of the cable is found using equations (2-7) and (2-5)

$$S = \int ds = \int_0^h \frac{ds}{dx} \cdot dx$$

$$S = \int_0^h \cosh\left(\frac{wx}{H} + C_1\right) dx$$

$$\therefore S = \left[v^2 + \frac{4H^2}{w^2} \sinh^2\left(\frac{wh}{2H}\right)\right]^{\frac{1}{2}} \quad (2\text{-}10)$$

or

$$\left[S^2 - v^2\right]^{\frac{1}{2}} = \frac{2H}{w} \sinh\left(\frac{wh}{2H}\right) \quad (2\text{-}11)$$

After expanding the hyperbolic sine term the above equation becomes

$$\left[S^2 - v^2\right]^{\frac{1}{2}} \approx h + \frac{w^2 h^3}{24 H^2}$$

$$S^2 = C^2 + \frac{w^2 h^4}{12 H^2} + \frac{w^4 h^6}{576 H^4} \quad (2\text{-}12)$$

For guy cables it has been found sufficiently accurate [4] to drop the last term. Using the binomial series to find the square root of equation (2-12) and neglecting the higher order terms yields

$$S = C + \frac{w^2 h^4}{24 H^2 C} \quad (2\text{-}13)$$

2.2 Parabolic Equation

If the weight of the cable w^1 is assumed constant along the horizontal projection of the cable, i.e. the x-axis rather than along the cable itself the basic equation (2-4) becomes

$$\frac{d^2 y}{dx^2} = \frac{w'}{H} \quad (2\text{-}14)$$

Integrating twice gives

$$\frac{dy}{dx} = \frac{w'}{H}x + C_1 \tag{2-15}$$

and

$$y = \frac{w'x^2}{2H} + C_1 x + C_2 \tag{2-16}$$

From the boundary conditions shown in Figure 2-3,

$$C_1 = C_2 = 0$$

Hence

$$y = \frac{w'x^2}{2H} \tag{2-17}$$

This is the equation of a parabolic cable. The length of the cable is found by equations (2-15) and (2-5)

$$S = \int_0^h ds = \int_0^h \left[1 + \left(\frac{w'x}{H}\right)^2\right]^{\frac{1}{2}} dx \tag{2-18}$$

Expansion in a binomial series and integrating yields

$$S = h + \frac{(w')^2 h^3}{6 H^2} - \frac{(w')^4 C^5}{640 H^4}$$

For a taut cable the last term is negligible and therefore

$$S = h + \frac{(w')^2 h^3}{6 H^2} \tag{2-19}$$

If we consider a horizontal cable with the origin at the centre of the span as shown in figure 2-3, then

$$S = 2\left[\frac{C}{2} + \frac{(w')^2 (C/2)^3}{6H^2}\right]$$

$$S = C + \frac{(w')^2 C^3}{24 H^2} \tag{2-20}$$

for the horizontal condition shown $w^1 = w$

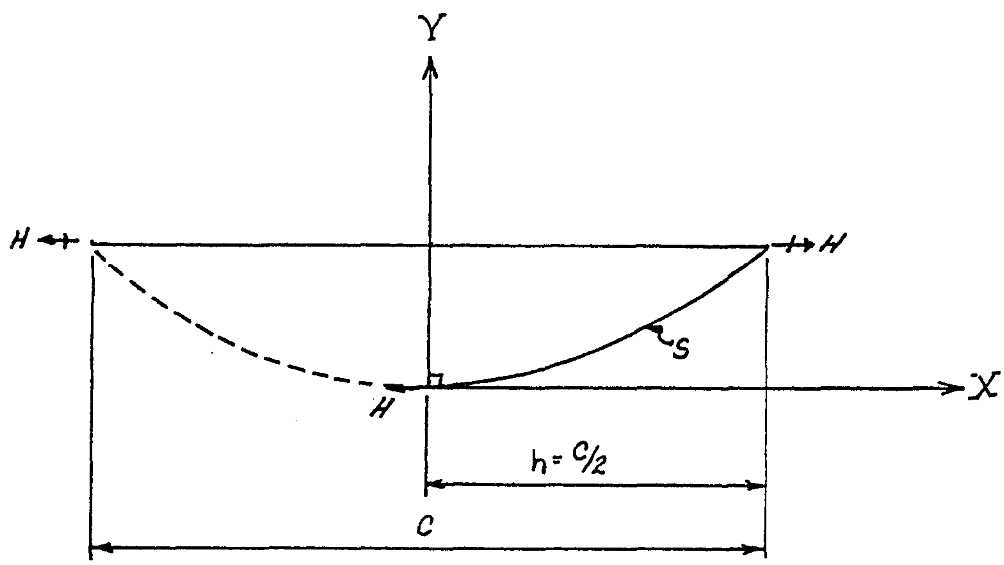


Figure 2-3 Horizontal Cable

2.3 Inclined Guys

Equation (2-20) applies to a horizontal parabolic cable. In practice guys are not horizontal but inclined. However for guy cables it is sufficiently accurate to assume that such guys, when rotated as shown in Figure 2-4, maintain a symmetrical parabolic shape.

The constant horizontal tension H of equation (2-19) becomes the average tension T acting at the mid-point and parallel to the chord. Thus equation (2-20) can be written as

$$S = C + \frac{w_n^2 C^3}{24 T^2} \qquad (2\text{-}21)$$

Where w_n is the load acting normal to the chord, as

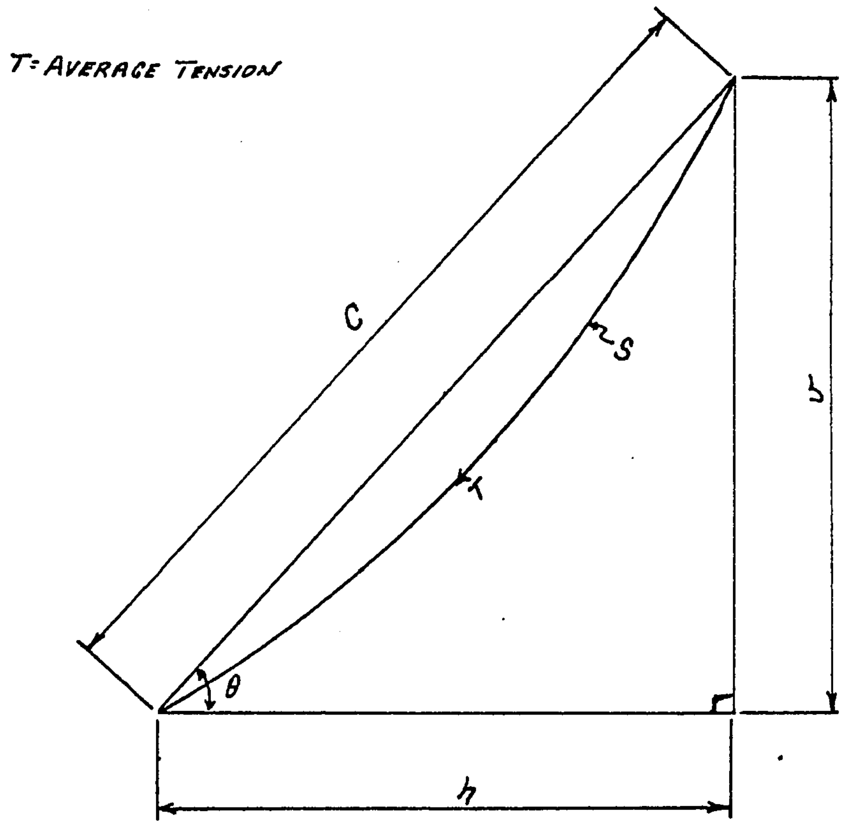
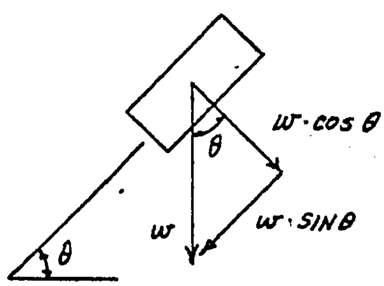


Figure 2-4 Elevation of Guy Cable (Parabolic)

shown in Figure 2-5.



$$w_n = w \cdot \cos\theta$$

$$\therefore\ w_n = w\,\frac{h}{c}$$

Figure 2-5 Load Components

Hence substituting for w_n in Equation (2-21):

$$S = C + \frac{w^2 h^2 C}{24\ T^2} \tag{2-22}$$

The horizontal component of the average tension T is

$$H = T\frac{h}{c} \qquad \text{or} \qquad T = H\frac{c}{h}$$

$$S = C + \frac{w^2 h^4}{24 H^2 C} \tag{2-23}$$

Comparing equation (2-23) with equation (2-13) shows, that for the taut cable condition, they are identical.

2.4 Maximum and Minimum Guy Tensions

The equations developed have employed the average tensions. Often it is required to know the maximum and minimum tensions. The maximum tension occurs at the upper end of the guy and is the resultant of the force composed of the average tension plus the component of weight acting parallel to the chord and the force composed of the component of weight normal to the chord.

Thus

$$T_{MAX.} = \left[\left(T + \frac{C}{2} w \sin\theta\right)^2 + \left(\frac{C}{2} w \cos\theta\right)^2\right]^{\frac{1}{2}} \tag{2-24}$$

The min. tension occurs at the lower or anchorage end and is given by

$$T_{MIN.} = \left[\left(T - \frac{C}{2} w \sin\theta\right)^2 + \left(\frac{C}{2} w. \cos\theta\right)^2\right]^{\frac{1}{2}} \tag{2-25}$$

2.5 Elastic Stretch

In the derivation of the basic equations it was assumed that the guy material was inextensible. Since this property is not realized in practice some modification is required. Using the average tension at the mid-point, the elastic stretch is given by Hooke's law as

$$\Delta = \frac{TS}{AE}$$

Where Δ = Elongation

T = The Average Tension

S = The Length of the Cable

A = The Metalic Area of the Cable

E = The Elastic Modulus.

This value of Δ contributes to the value for the total length of the cable, together with the effect of sag and hence an exact value for S is not possible. Therefore it is not unreasonable to use the chord length C instead of the exact value S for the length. Thus the elongation becomes

$$\Delta = \frac{TC}{AE} \qquad (2\text{-}26)$$

2.6 Final Cable Equation

From the foregoing derivations the equation for the length of a guy cable can be written as:

$$S = C + \frac{w^2 h^2 C}{24\,T^2} + \frac{TC}{AE}$$

or

$$S = C + \frac{w_n^2\, C^3}{24\,T^2} + \frac{TC}{AE} \qquad (2\text{-}27)$$

It should be remembered that, because of the assumptions made in developing this equation it is only valid for taut cables (i.e. where the sag is less than 10% of the chord length) as encountered in guy cables used in tower construction.

THEORETICAL BEHAVIOR OF THE CABLE SYSTEM

The cables of a guyed mast are connected to a fixed support at the anchorage and to a movable support--the mast. The amount of movement will depend on the resistance of the guys to change in geometry and the tensile resistance of the guys to the movement of the mast. This interdependent relationship will now be examined.

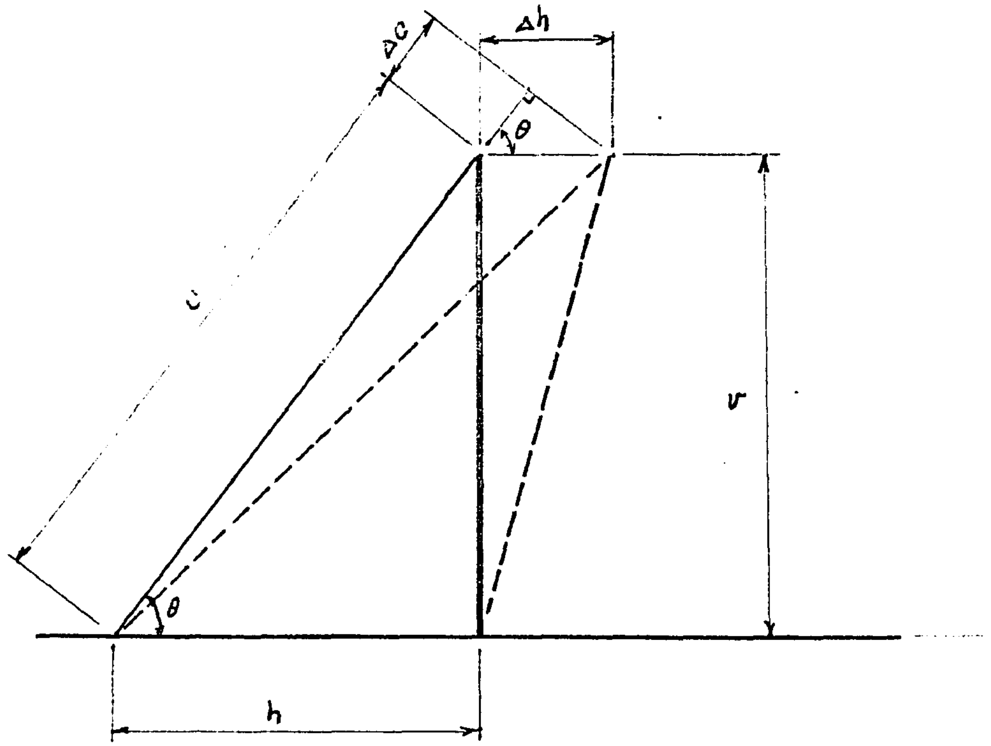


Figure 3-1 Displacement of Cable

It is assumed that the mast is erected in still air, plumb, and that the guys have a known initial tension. The change in length of the cable from the initial to the final condition is due to the elastic stretch of the cable. The variables are denoted by a subscript 1 for the initial condition and by a subscript 2 for the final condition.

$$\Delta S = \frac{T_2(C_1 + \Delta C)}{AE} - \frac{T_1 C_1}{AE}$$

$$\Delta S = \frac{C_1}{AE}(T_2 - T_1) + \frac{T_2 \Delta C}{AE}$$

Also

$$S_2 = S_1 + \Delta S$$

$$C_2 = C_1 + \Delta C$$

$$S_1 = C_1 + \frac{w_1^2 C_1^3}{24 T_1^2}$$

$$S_2 = C_2 + \frac{w_2^2 C_2^3}{24 T_2^2}$$

$$C_1 + \Delta C + \frac{w_2^2 (C_1 + \Delta C)^3}{24 T_2^2} = C_1 + \frac{w_1^2 C_1^3}{24 T_1^2} + \frac{C_1}{AE}(T_2 - T_1) + \frac{T_2 \cdot \Delta C}{AE}$$

Since ΔC is small when compared to C_1, terms in the expansion of $(C_1 + \Delta C)^3$ containing ΔC, as well as the term $\frac{T_2 \cdot \Delta C}{AE}$, can be neglected [7] . Thus.

$$\Delta C = \frac{w_1^2 C_1^3}{24 T_1^2} - \frac{w_2^2 C_1^3}{24 T_2^2} + \frac{C_1}{AE}(T_2 - T_1) \qquad (3\text{-}1)$$

In determining w_2, for the actual field conditions the effect of wind on the cable must be considered. This can be evaluated using the method outlined in Appendix 'A'.

Since ΔC is small compared to C the horizontal deflection of the mast can be found by the tangent offset method as shown in

Figure 3-1. Meyers [9] has shown that this assumption and the small change in the inclination of θ have negligible effect on the analysis. Hence

$$\Delta h = \Delta c \cdot \frac{c}{h} \qquad (3-2)$$

3.1 Guy Arrangement

Guyed masts usually are of triangular cross section with the guys attached to the legs of the mast at the corners of the triangle, and arranged 120° apart, as shown in Figure 3-2,

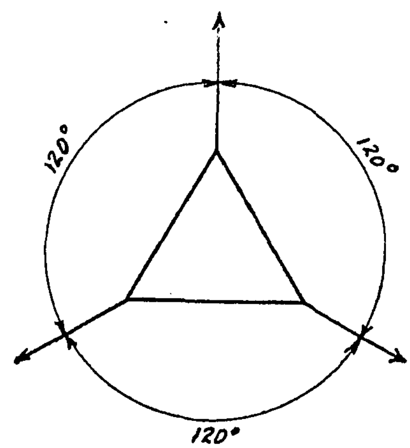


Figure 3-2 Standard Guy Configuration

This arrangement offers no resistance to torsional loads until the deflections become excessively large. For most masts such as AM radiators, TV Masts, antenna array support masts etc, torsional loads are non-existent or so small that the resulting deflections do not effect the performance of the mast or it's equipment. However microwave masts with relatively lar antennas, are subjected to large torsional moments.

Moreover, for these antennas to function properly deflections must be limited to very close tolerances. To resist these torsional loads six instead of three guys are employed, the guys being attached either to the legs or to special outriggers as shown in Figure 3-3.

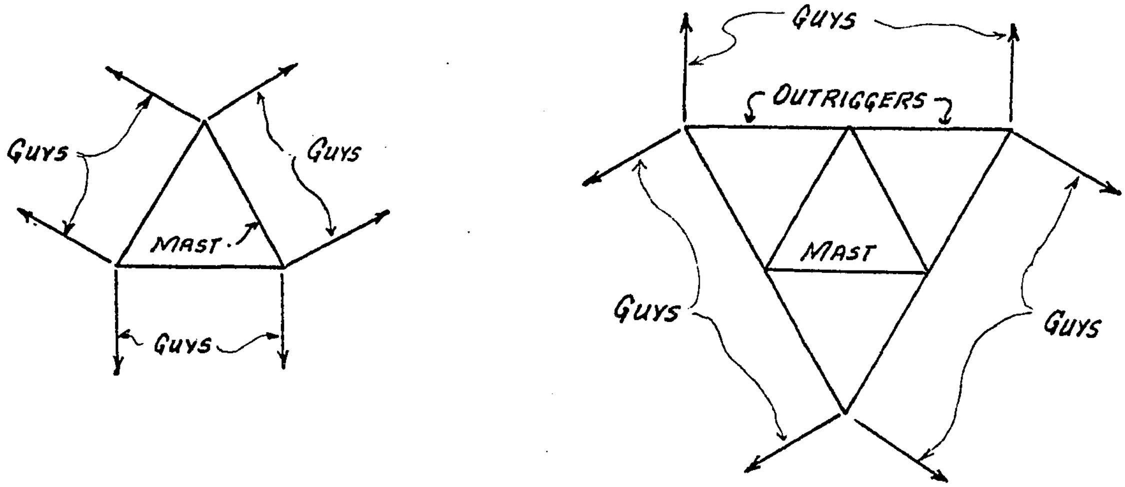


Figure 3-3 Double Guy Configuration

3.2 Deflections

A mast subjected to direct and torsional loads deflects in two modes: translational due to the direct load, and rotational due to the torsional load. It is convenient to resolve the translational deflections into components in the x and y directions. Figure 3-4 shows the segmental effect of the displacements at the upper end of the guys of a mast with outriggers, and subjected to both direct and torsional loads.

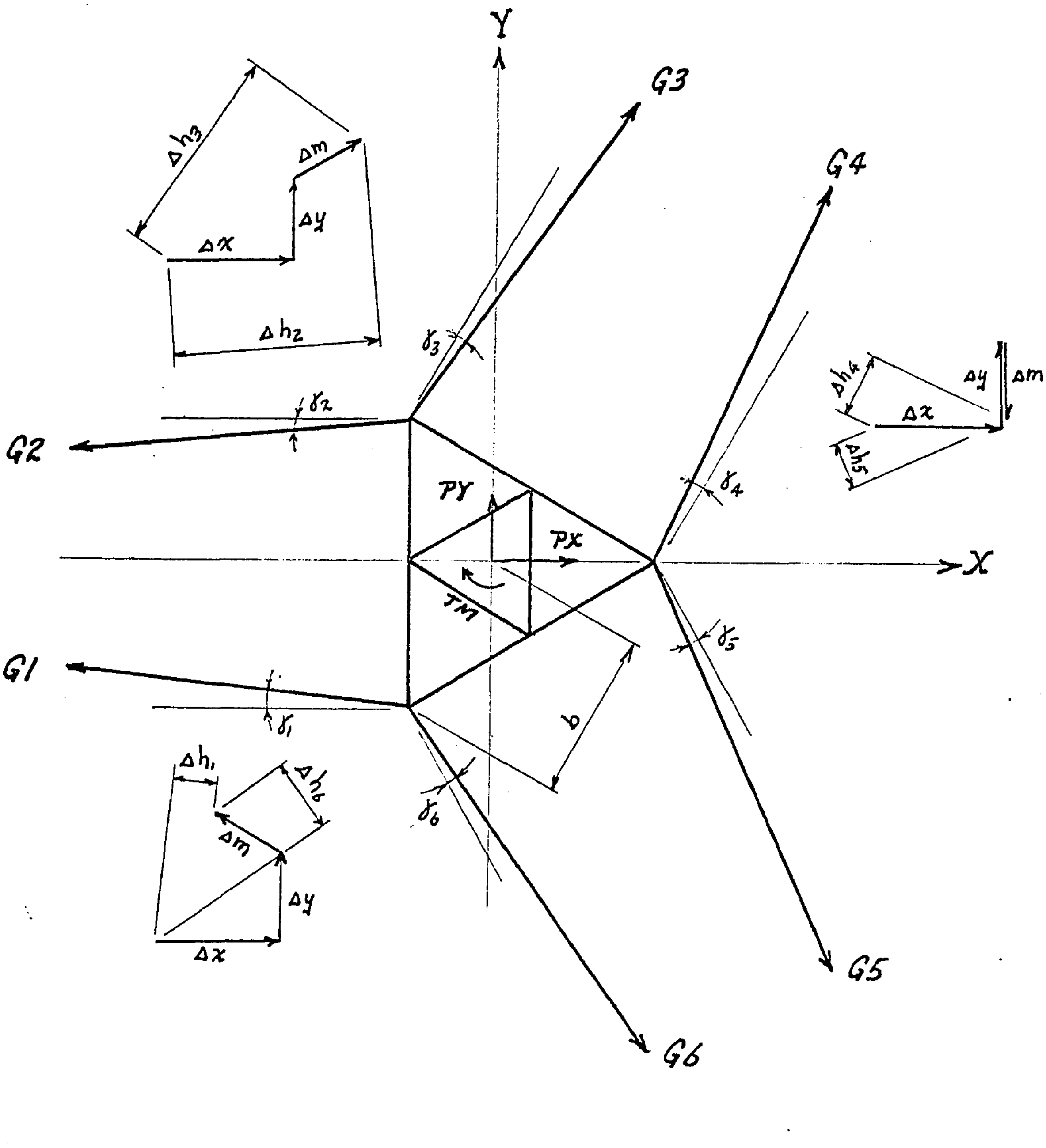


Figure 3-4 Mast and Guy Displacements

To solve the present problem it is necessary to establish force and moment equilibrium between the applied loads Px, Py and Tm and the guy tensions G1, G2 . . ., G6, while meeting the geometric compatibility of displacements Δx, Δy and Δm.

3.3 Cable Equations for the System

From Equations (3-1) and (3-2) the deflection equations for the six guys can be written as follows:

$$\Delta h_1 = \frac{C_1}{h_1}\left[-\frac{w_{12}^2 C_1^3}{24 T_{12}^2} + \frac{w_{11}^2 C_1^3}{24 T_{11}^2} + \frac{C_1}{AE}(T_{12} - T_{11})\right] \quad (3\text{-}3)$$

$$\Delta h_2 = \frac{C_2}{h_2}\left[-\frac{w_{22}^2 C_2^3}{24 T_{22}^2} + \frac{w_{21}^2 C_2^3}{24 T_{21}^2} + \frac{C_2}{AE}(T_{22} - T_{21})\right] \quad (3\text{-}4)$$

$$\Delta h_3 = \frac{C_3}{h_3}\left[-\frac{w_{32}^2 C_3^3}{24 T_{32}^2} + \frac{w_{31}^2 C_3^3}{24 T_{31}^2} + \frac{C_3}{AE}(T_{32} - T_{31})\right] \quad (3\text{-}5)$$

$$\Delta h_4 = \frac{C_4}{h_4}\left[-\frac{w_{42}^2 C_4^3}{24 T_{42}^2} + \frac{w_{41}^2 C_4^3}{24 T_{41}^2} + \frac{C_4}{AE}(T_{42} - T_{41})\right] \quad (3\text{-}6)$$

$$\Delta h_5 = \frac{C_5}{h_5}\left[-\frac{w_{52}^2 C_5^3}{24 T_{52}^2} + \frac{w_{51}^2 C_5^3}{24 T_{51}^2} + \frac{C_5}{AE}(T_{52} - T_{51})\right] \quad (3\text{-}7)$$

$$\Delta h_6 = \frac{C_6}{h_6}\left[-\frac{w_{62}^2 C_6^3}{24 T_{62}^2} + \frac{w_{61}^2 C_6^3}{24 T_{61}^2} + \frac{C_6}{AE}(T_{62} - T_{61})\right] \quad (3\text{-}8)$$

Where the first subscript refers to the guy number, and the second subscript refers to the condition of loading or tension, i.e. whether initial or final. The values for the Δh's can be written in terms of Δx, Δy and Δm. It should also be noted that each pair of guys are connected to a common anchorage, so that a guy makes a small angle γ with the normal to the mast face as shown in Figure 3-4. Moreover the direction of the loads and deflections must be carefully considered. For example when Px is positive Δh_1 and Δh_2 are in a positive direction and are positive because the right hand side of equations (3-3) and (3-4) are positive, but Δh_3, Δh_4, Δh_5, and Δh_6 while in a positive direction must be negative because the right hand side of equations (3-5) to (3-8) will be negative due to the decrease in the guy tensions from the initial to the final condition.

Therefore

$$\Delta h_1 = \Delta x \cdot \cos\gamma_1 - \Delta y \cdot \sin\gamma_1 - \Delta m \cdot \cos(30-\gamma_1) \qquad (3\text{-}9)$$

$$\Delta h_2 = \Delta x \cdot \cos\gamma_2 + \Delta y \cdot \sin\gamma_2 + \Delta m \cdot \cos(30-\gamma_2) \qquad (3\text{-}10)$$

$$-\Delta h_3 = -\Delta x \cdot \sin(30+\gamma_3) - \Delta y \cdot \cos(30+\gamma_3) - \Delta m \cdot \cos(30-\gamma_3) \qquad (3\text{-}11)$$

$$-\Delta h_4 = -\Delta x \cdot \sin(30-\gamma_4) - \Delta y \cdot \cos(30-\gamma_4) + \Delta m \cdot \cos(30-\gamma_4) \qquad (3\text{-}12)$$

$$-\Delta h_5 = -\Delta x \cdot \sin(30-\gamma_5) + \Delta y \cdot \cos(30-\gamma_5) - \Delta m \cdot \cos(30-\gamma_5) \qquad (3\text{-}13)$$

$$-\Delta h_6 = -\Delta x \cdot \sin(30-\gamma_6) + \Delta y \cdot \cos(30+\gamma_6) + \Delta m \cdot \cos(30-\gamma_6) \qquad (3\text{-}14)$$

Equations (3-9) to (3-14) are now substituted into equations (3-3) to (3-6). The resulting six equations together with the three equilibrium equations for forces in the x and y directions and for twisting moments will contain the nine unknowns: T_{12}, T_{22}, T_{32}, T_{42}, T_{52}, T_{62}, Δx, Δy, and Δm.

These nine equations for the cable system have the following form:

$$-\frac{w_{12}^2 C_1^4}{24 h_1 T_{12}^2} + \frac{w_{11}^2 C_1^4}{24 h_1 T_{11}^2} + \frac{C_1^2}{AEh_1}(T_{12}-T_{11}) - \Delta x \cdot \cos\gamma_1$$

$$+ \Delta y \cdot \sin\gamma_1 + \Delta m \cdot \cos(30-\gamma_1) = 0 \qquad (3\text{-}15)$$

$$-\frac{w_{22}^2 C_2^4}{24 h_2 T_{22}^2} + \frac{w_{21}^2 C_2^4}{24 h_2 T_{21}^2} + \frac{C_2^2}{AEh_2}(T_{22}-T_{21}) - \Delta x \cdot \cos\gamma_2$$

$$- \Delta y \cdot \sin\gamma_2 - \Delta m \cdot \cos(30-\gamma_2) = 0 \qquad (3\text{-}16)$$

$$-\frac{w_{32}^2 C_3^4}{24 h_3 T_{32}^2} + \frac{w_{31}^2 C_3^4}{24 h_3 T_{31}^2} + \frac{C_3^2}{AEh_3}(T_{32}-T_{31}) + \Delta x \cdot \sin(30+\gamma_3)$$

$$+ \Delta y \cdot \cos(30+\gamma_3) + \Delta m \cdot \cos(30-\gamma_3) = 0 \qquad (3\text{-}17)$$

$$-\frac{w_{42}^2 C_4^4}{24 h_4 T_{42}^2} + \frac{w_{41}^2 C_4^4}{24 h_4 T_{41}^2} + \frac{C_4^2}{AEh_4}(T_{42}-T_{41}) + \Delta x \cdot \sin(30-\gamma_4)$$

$$+ \Delta y \cdot \cos(30-\gamma_4) - \Delta m \cdot \cos(30-\gamma_4) = 0 \qquad (3\text{-}18)$$

$$-\frac{w_{52}^2 C_5^4}{24 h_5 T_{52}^2} + \frac{w_{51}^2 C_5^4}{24 h_5 T_{51}^2} + \frac{C_5^2}{AEh_5}(T_{52}-T_{51}) + \Delta x \cdot \sin(30-\gamma_5)$$

$$- \Delta y \cdot \cos(30-\gamma_5) + \Delta m \cdot \cos(30-\gamma_5) = 0 \qquad (3\text{-}19)$$

$$-\frac{w_{62}^2 C_6^4}{24 h_6 T_{62}^2} + \frac{w_{61}^2 C_6^4}{24 h_6 T_{61}^2} + \frac{C_6^2}{AEh_6}(T_{62}-T_{61}) + \Delta x \cdot \sin(30+\gamma_6)$$

$$- \Delta y \cdot \cos(30+\gamma_6) - \Delta m \cdot \cos(30-\gamma_6) = 0 \qquad (3\text{-}20)$$

$$-\cos\gamma_1 \cdot \frac{h_1}{C_1} T_{12} - \cos\gamma_2 \frac{h_2}{C_2} T_{22} + \sin(30+\gamma_3) \cdot \frac{h_3}{C_3} T_{32}$$

$$+ \sin(30-\gamma_4) \frac{h_4}{C_4} T_{42} + \sin(30-\gamma_5) \frac{h_5}{C_5} \cdot T_{52}$$

$$+ \sin(30+\gamma_6) \cdot \frac{h_6}{C_6} \cdot T_{62} + PX = 0 \qquad (3\text{-}21)$$

$$\sin\gamma_1 \cdot \frac{h_1}{C_1} \cdot T_{12} - \sin\gamma_2 \cdot \frac{h_2}{C_2} \cdot T_{22} + \cos(30+\gamma_3) \frac{h_3}{C_3} \cdot T_{32}$$

$$+ \cos(30-\gamma_4) \frac{h_4}{C_4} \cdot T_{42} - \cos(30-\gamma_5) T_{52} \cdot \frac{h_5}{C_5}$$

$$- \cos(30+\gamma_6) \cdot \frac{h_6}{C_6} \cdot T_{62} + PY = 0 \qquad (3\text{-}22)$$

$$\cos(30-\gamma_1) \frac{h_1}{C_1} \cdot T_{12} \cdot b - \cos(30-\gamma_2) \frac{h_2}{C_2} \cdot T_{22} \cdot b$$

$$+ \cos(30-\gamma_3) \frac{h_3}{C_3} \cdot T_{32} \cdot b - \cos(30-\gamma_4) \frac{h_4}{C_4} \cdot T_{42} \cdot b$$

$$+ \cos(30-\gamma_5) \frac{h_5}{C_5} \cdot T_{52}\, b + \cos(30-\gamma_6) \cdot \frac{h_6}{C_6} \cdot T_{62} \cdot b + TM = 0 \qquad (3\text{-}23)$$

3.4 Solution of Equations

The solution of equations (3-15) to (3-23) is complicated by the fact that six of the equations are non-linear. Newton's Method was used to solve these equations by successive iterations. The form of Newton's Method employed is outlined in Appendix 'B'. A general solution programme was written in Fortran for the IBM 1620 Computer, and employed standard subroutines for the matrix inversion.

For convenience equations (3-15) to (3-23) are written in the following modified form:

$$-\frac{\omega_{12}^2 C_1^4}{24 h_1 T_{12}^2} + \frac{C_1^2 T_{12}}{AE\, h_1} - \Delta x \cos\gamma_1 + \Delta y . \sin\gamma_1 + \Delta m . \cos(30-\gamma_1) = -\frac{\omega_{11}^2 C_1^4}{24 h_1 T_{11}^2} + \frac{C_1^2 T_{11}}{AE\, h_1} \tag{3-24}$$

$$-\frac{\omega_{22}^2 C_2^4}{24 h_2 T_{22}^2} + \frac{C_2^2 T_{22}}{AE\, h_2} - \Delta x \cdot \cos\gamma_2 - \Delta y \cdot \sin\gamma_2 - \Delta m \cdot \cos(30-\gamma_2) = -\frac{\omega_{21}^2 C_2^4}{24 h_2 T_{21}^2} + \frac{C_2^2 T_{21}}{AE\, h_2} \tag{3-25}$$

$$-\frac{\omega_{32}^2 C_3^4}{24 h_3 T_{32}^2} + \frac{C_3^2 T_{32}}{AE\, h_3} + \Delta x \cdot \sin(30+\gamma_3) + \Delta y \cos(30+\gamma_3) + \Delta m \cdot \cos(30-\gamma_3) = -\frac{\omega_{31}^2 C_3^4}{24 h_3 T_{31}^2} + \frac{C_3^2 T_{31}}{AE\, h_3} \tag{3-26}$$

$$-\frac{w_{42}^2 C_4^4}{24 h_4 T_{42}^2} + \frac{C_4^2 T_{42}}{AE h_4} + \Delta x \cdot SIN(30-\delta_4) + \Delta y \cdot COS(30-\delta_4) + \Delta m \cdot COS(30-\delta_4) =$$

$$-\frac{w_{41}^2 C_4^4}{24 h_4 T_{41}^2} + \frac{C_4^2 T_{41}}{AE h_4} \tag{3-27}$$

$$-\frac{w_{52}^2 C_5^4}{24 h_5 T_{52}^2} + \frac{C_5^2 T_{52}}{AE h_5} + \Delta x \cdot SIN(30-\delta_5) - \Delta y \cdot COS(30-\delta_5) + \Delta m \cdot COS(30-\delta_5) =$$

$$-\frac{w_{51}^2 C_5^4}{24 h_5 T_{51}^2} + \frac{C_5^2 T_{51}}{AE h_5} \tag{3-28}$$

$$-\frac{w_{62}^2 C_6^4}{24 h_6 T_{62}^2} + \frac{C_6^2 T_{62}}{AE h_6} + \Delta x \cdot SIN(30+\delta_6) - \Delta y \cdot COS(30+\delta_6) + \Delta m \cdot COS(30-\delta_6) =$$

$$-\frac{w_{61}^2 C_6^4}{24 h_6 T_{61}^2} + \frac{C_6^2 T_{61}}{AE h_6} \tag{3-29}$$

$$-COS\,\delta_1 \cdot \frac{h_1}{C_1} \cdot T_{12} - COS\,\delta_2 \cdot \frac{h_2}{C_2} \cdot T_{22} + SIN(30+\delta_3)\frac{h_3}{C_3} + SIN(30-\delta_4)\frac{h_4}{C_4} \cdot T_{42}$$

$$+ SIN(30-\delta_5) \cdot \frac{h_5}{C_5} \cdot T_{52} + SIN(30+\delta_6)\frac{h_6}{C_6} \cdot T_{62} = -PX \tag{3-30}$$

$$SIN\,\delta_1 \cdot \frac{h_1}{C_1} \cdot T_{12} - SIN\,\delta_2 \cdot \frac{h_2}{C_2} \cdot T_{22} + COS(30+\delta_3)\frac{h_3}{C_3} \cdot T_{32} + COS(30-\delta_4)\frac{h_4}{C_4} \cdot T_{42}$$

$$- COS(30-\delta_5)\, T_{52} - COS(30+\delta_6)\, T_{62} = -PY \tag{3-31}$$

$$COS(30-\delta_1)\frac{h_1}{C_1} \cdot b \cdot T_{12} - COS(30-\delta_2)\frac{h_2}{C_2} \cdot b \cdot T_{22} + COS(30-\delta_3)\frac{h_3}{C_3} \cdot b \cdot T_{32}$$

$$- COS(30-\delta_4)\frac{h_4}{C_4} \cdot b \cdot T_{42} + COS(30-\delta_5)\frac{h_5}{C_5} \cdot b \cdot T_{52}$$

$$+ COS(30-\delta_6) \cdot \frac{h_6}{C_6} \cdot b \cdot T_{62} = -TM. \tag{3-32}$$

In symbolic form, the above equations become:

$$\frac{A_{10}}{T_{12}^2} + A_{11}T_{12} + A_{17}\Delta x + A_{18}\Delta y + A_{19}\Delta m = V_1 \qquad (3\text{-}33)$$

$$\frac{A_{20}}{T_{22}^2} + A_{22}T_{22} + A_{27}\Delta x + A_{28}\Delta y + A_{29}\Delta m = V_2 \qquad (3\text{-}34)$$

$$\frac{A_{30}}{T_{32}^2} + A_{33}T_{32} + A_{37}\Delta x + A_{38}\Delta y + A_{39}\Delta m = V_3 \qquad (3\text{-}35)$$

$$\frac{A_{40}}{T_{42}^2} + A_{44}T_{42} + A_{47}\Delta x + A_{48}\Delta y + A_{49}\Delta m = V_4 \qquad (3\text{-}36)$$

$$\frac{A_{50}}{T_{52}^2} + A_{55}T_{52} + A_{57}\Delta x + A_{58}\Delta y + A_{59}\Delta m = V_5 \qquad (3\text{-}37)$$

$$\frac{A_{60}}{T_{62}^2} + A_{66}T_{62} + A_{67}\Delta x + A_{68}\Delta y + A_{69}\Delta m = V_6 \qquad (3\text{-}38)$$

$$A_{71}T_{12} + A_{72}T_{22} + A_{73}T_{32} + A_{74}T_{42} + A_{75}T_{52} + A_{76}T_{62} = V_7 \qquad (3\text{-}39)$$

$$A_{81}T_{12} + A_{82}T_{22} + A_{83}T_{32} + A_{84}T_{42} + A_{85}T_{52} + A_{86}T_{62} = V_8 \qquad (3\text{-}40)$$

$$A_{91}T_{12} + A_{92}T_{22} + A_{93}T_{32} + A_{94}T_{42} + A_{95}T_{52} + A_{96}T_{62} = V_9 \qquad (3\text{-}41)$$

To start Newton's Method initial values for variables are required. These values are obtained by dropping the first term of equations (3-33) to (3-38) and solving the resulting linear set of equations, shown in matrix form as equation (3-42).

$$\begin{bmatrix} A_{11} & 0 & 0 & 0 & 0 & 0 & A_{17} & A_{18} & A_{19} \\ 0 & A_{22} & 0 & 0 & 0 & 0 & A_{27} & A_{28} & A_{29} \\ 0 & 0 & A_{33} & 0 & 0 & 0 & A_{37} & A_{38} & A_{39} \\ 0 & 0 & 0 & A_{44} & 0 & 0 & A_{47} & A_{48} & A_{49} \\ 0 & 0 & 0 & 0 & A_{55} & 0 & A_{57} & A_{58} & A_{59} \\ 0 & 0 & 0 & 0 & 0 & A_{66} & A_{67} & A_{68} & A_{69} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & 0 & 0 & 0 \\ A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & 0 & 0 & 0 \\ A_{91} & A_{92} & A_{93} & A_{94} & A_{95} & A_{96} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_{12} \\ T_{22} \\ T_{32} \\ T_{42} \\ T_{52} \\ T_{62} \\ \Delta x \\ \Delta y \\ \Delta m \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \\ V_9 \end{bmatrix} \qquad (3\text{-}42)$$

Applying Newton's Method (Appendix 'B') to equations (3-33) to (3-41) yields the following set of simultaneous equations in matrix form [equation (3-43)] where the dT_{12}, dT_{22} . . . dT_{62} $d(\Delta x)$, $d(\Delta y)$ and $d(\Delta m)$ are small changes in the unknowns:

$$
\begin{bmatrix}
\left[A_{11}-\frac{2A_{10}}{T_{12}^3}\right] & 0 & 0 & 0 & 0 & 0 & A_{17} & A_{18} & A_{19} \\
0 & \left[A_{22}-\frac{2A_{20}}{T_{22}^3}\right] & 0 & 0 & 0 & 0 & A_{27} & A_{28} & A_{29} \\
0 & 0 & \left[A_{33}-\frac{2A_{30}}{T_{32}^3}\right] & 0 & 0 & 0 & A_{37} & A_{38} & A_{39} \\
0 & 0 & 0 & \left[A_{44}-\frac{2A_{40}}{T_{42}^3}\right] & 0 & 0 & A_{47} & A_{48} & A_{49} \\
0 & 0 & 0 & 0 & \left[A_{55}-\frac{2A_{50}}{T_{52}^3}\right] & 0 & A_{57} & A_{58} & A_{59} \\
0 & 0 & 0 & 0 & 0 & \left[A_{66}-\frac{2A_{60}}{T_{62}^3}\right] & A_{67} & A_{68} & A_{69} \\
A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & 0 & 0 & 0 \\
A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & 0 & 0 & 0 \\
A_{91} & A_{92} & A_{93} & A_{94} & A_{95} & A_{96} & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
d\,T_{12} \\ d\,T_{22} \\ d\,T_{32} \\ d\,T_{42} \\ d\,T_{52} \\ d\,T_{62} \\ d\,\Delta x \\ d\,\Delta y \\ d\,\Delta m
\end{bmatrix}
=
\begin{bmatrix}
VR_1 \\ VR_2 \\ VR_3 \\ VR_4 \\ VR_5 \\ VR_6 \\ VR_7 \\ VR_8 \\ VR_9
\end{bmatrix}
\qquad (3\text{-}43
$$

The solution of equations (3-43) will provide new approximations to the unknowns. These are

$$T_{12} = T_{12} + d\,T_{12}$$

$$T_{22} = T_{22} + d\,T_{22}$$

$$T_{32} = T_{32} + dT_{32} \qquad \Delta x = \Delta x + d(\Delta x)$$

$$T_{42} = T_{42} + dT_{42} \qquad \Delta y = \Delta y + d(\Delta y)$$

$$T_{52} = T_{52} + dT_{52} \qquad \Delta m = \Delta m + d(\Delta m)$$

$$T_{62} = T_{62} + dT_{62}$$

Using these new approximations in equations (3-43) will after a number of iterations, give the required roots of equations (3-33) to (3-34)

It frequently occurred that upon solving equations (3-33) to (3-38), using their linearized form a sufficiently large negative deflection resulted, which gave rise to a negative value for a guy tension (indicating compression). This is illustrated in Figure 3-5. Since it is not possible for a guy to be in compression, this situation had to be corrected. This was accomplished by the following procedure.

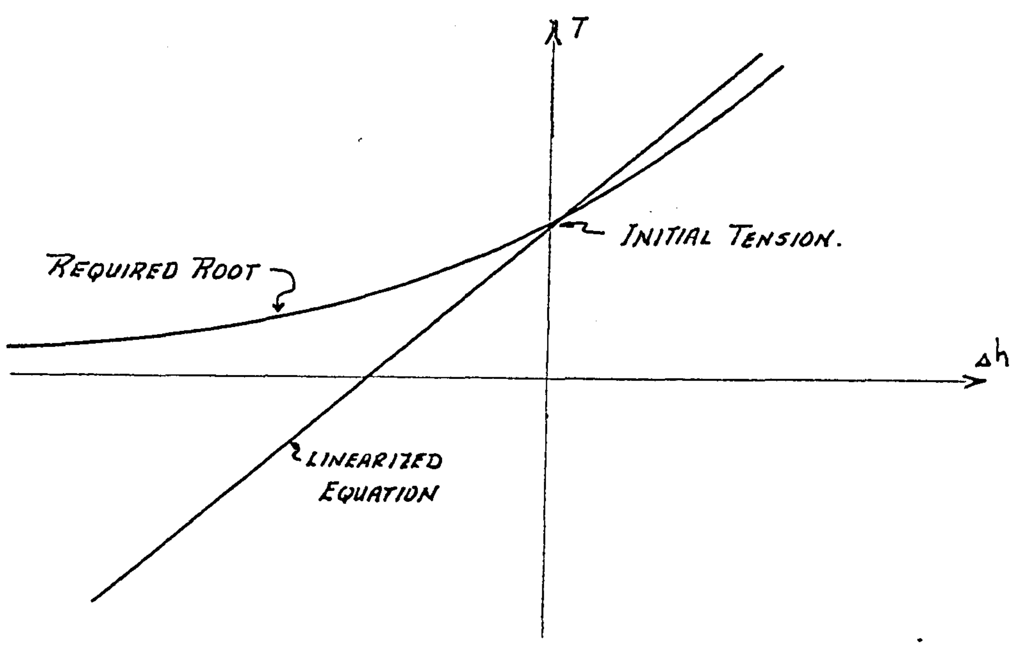


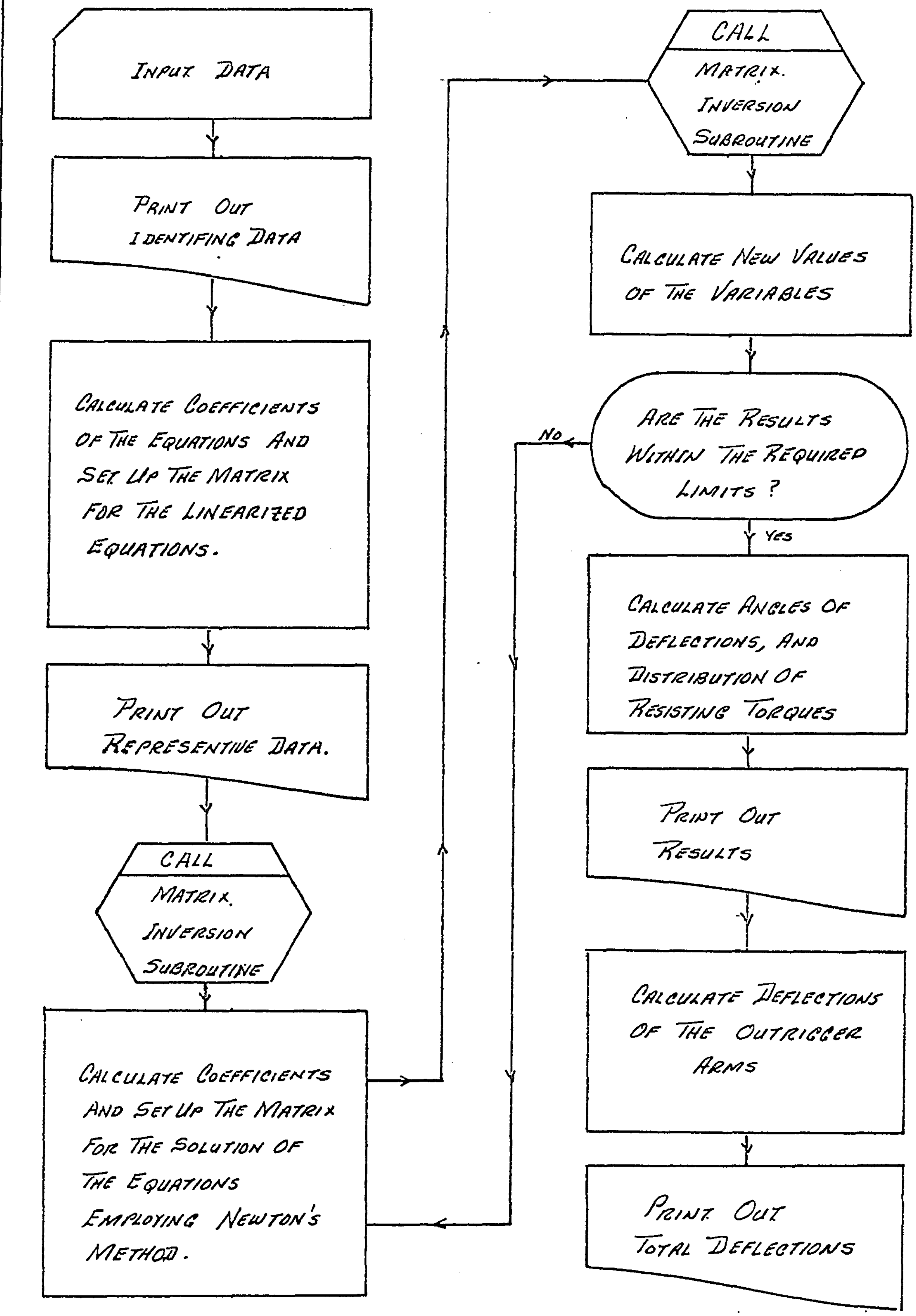
Figure 3-5 Tension-Deflection Curve

Examination of Figure 3-5 shows that this negative tension will always occur in the slack guys with the calculated tensions having a value less than the initial tension. When this occurred a positive tensile value was assigned to that particular guy. By trial and error, an assigned tensile value equal to 20% of the initial tension was found to be satisfactory for most cases examined. However in a few cases with a small initial tension and a large applied torque, an assigned value of 10% of the initial tension was necessary to circumvent the above mentioned situation.

3.5 The Computer Programme

A Fortran II programme was written for the IBM 1620 Computer, to perform the necessary calculations in solving the equations and obtaining the final results. A general flow diagram of the programme is given in Figure 3-6.

The programme takes about 5 minutes to compile and about 2 minutes of execution time for one set of data. The exact execution time depends on the number of iterations required, which is in turn dependant on the magnitude of the applied torque, the initial guy tensions and the height of the mast.



FLOW DIAGRAM FOR COMPUTER PROGRAMME FIGURE 3-6

4.0 EXPERIMENTAL WORK

To verify the theoretical work and to observe the action of a mast under applied twist loads, tests were performed on an 80 ft. prototype guyed mast. These tests were performed with the assistance of the Canadian Bridge Division of Dosco Industries at their tower testing facility in Walkerville, Ontario.

4.1 The Test Mast

The mast was of triangular cross-section 2'9 back to back of leg angles and 80 ft. in height. The legs were 3" x 3" x 3/16" angles closed to 60°, except for the top section where the legs were 3-1/2" x 3-1/2" x 3/16" angles to facilitate making connections. The web system consisted of 1-1/2" x 1-1/2" x 1/8" angle diagonals with angle struts located on one face for ease in climbing. The bottom 5 foot section was tapered to achieve a pin ended connection. Three outrigger arms and their knee braces were located at the 75 foot level. Also located at the 75 foot level was a frame for the support of the scales used to measure the deflections. At the top of the mast a pull-off angle was located with holes at 1'-3 centres for the application of the load.

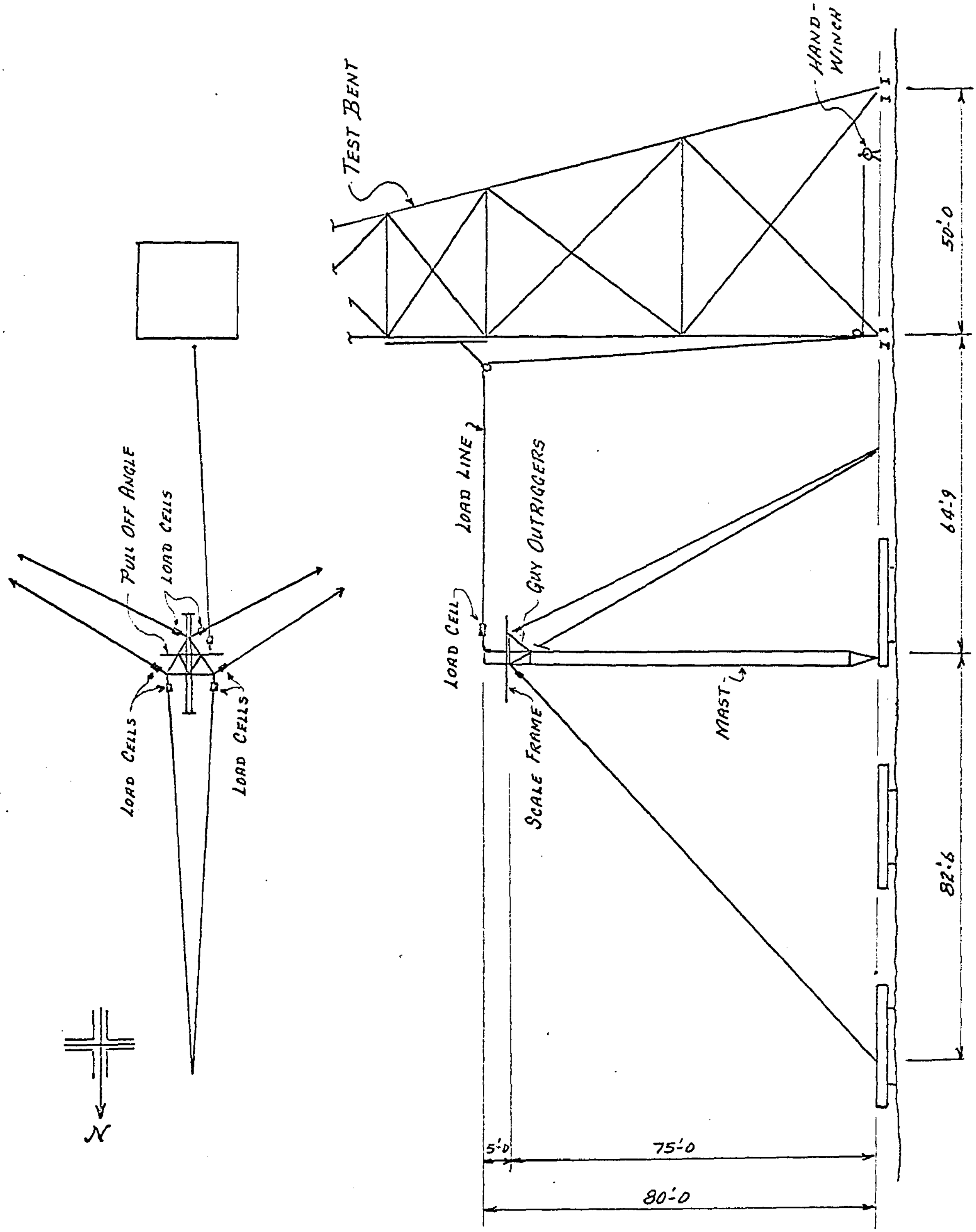
The guys were 3/8" diameter, 6 x 7 construction, improved plow steel wire rope with an independent wire rope centre. The guys were connected to a load cell, which was in turn connected to the outrigger arms by a series of anchor shackles and strain links. This linkage system was necessary to eliminate any bending on the load cell. The guys were connected to the anchorages through turnbuckles for adjusting the guy tension and plumbing the mast.

These features are illustrated in Photographs 1 to 8.

4.2 The Test Facility

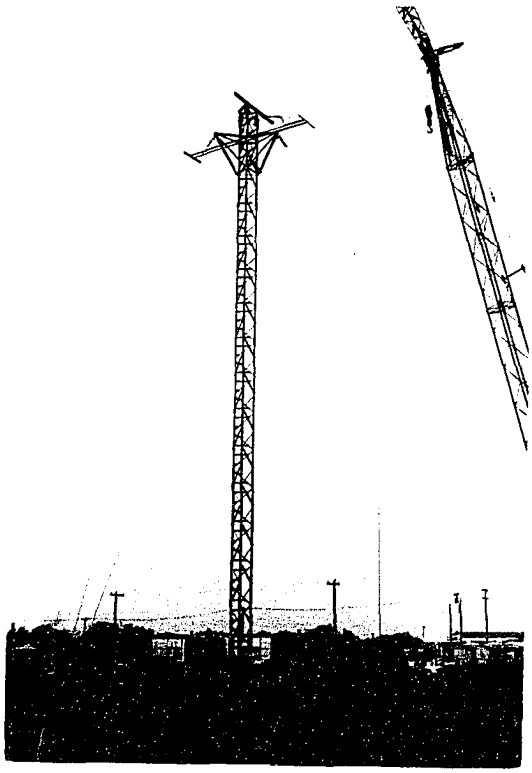
The Canadian Bridge test facility consists of a 160 foot test bent, a 120 foot test tower, three sets of beams connected to piles along the centre line, and numerous piles which have been used for anchorages. The arrangement used for this series of tests is illustrated in Figure 4-1. The mast was located on one set of beams, and the north anchorage on another set of beams. The south-west anchorage was a single pile cut off at the ground line. The south-east anchorage was on an extended pile structure, which was necessitated by a railway spur passing through one corner of the area and preventing the guy being carried down to the ground. This was not an undesirable feature inasmuch as guyed masts are frequently located on uneven ground with the anchorages at a different level than the tower base. Thus this raised anchorage enabled us to evaluate this effect on the action of the mast.

The loads were applied to the mast by connecting a line



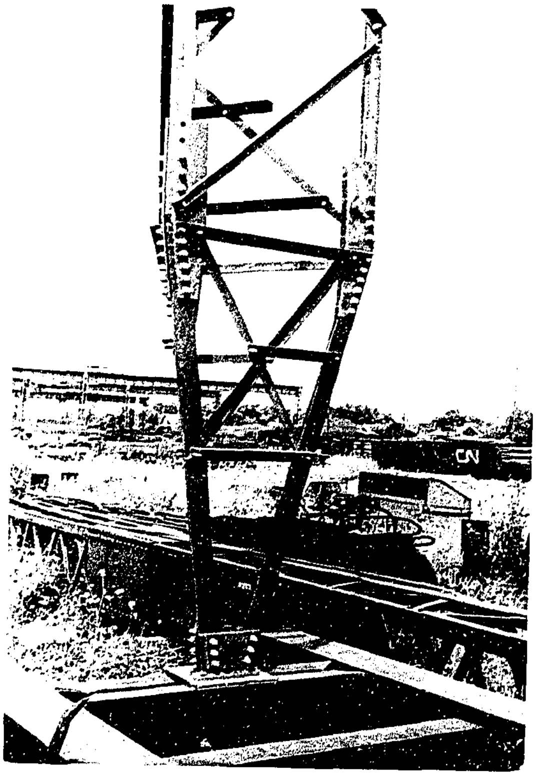
GENERAL ARRANGEMENT OF THE TOWER TEST

FIGURE 4-1



80 FT GUYED TEST MAST

PHOTOGRAPH 1

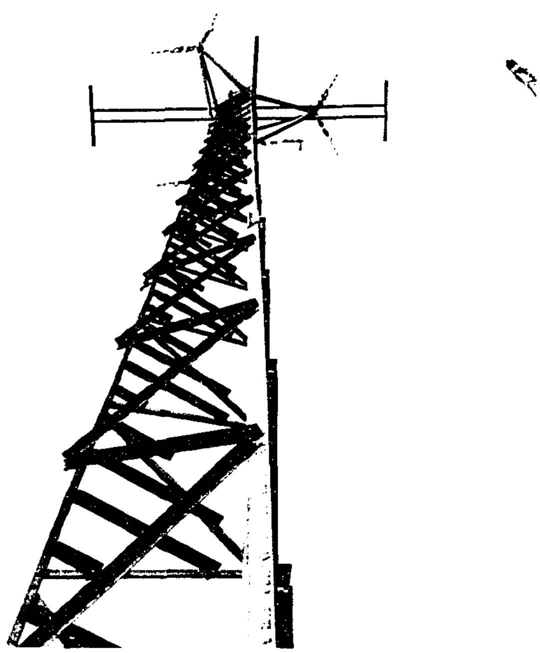


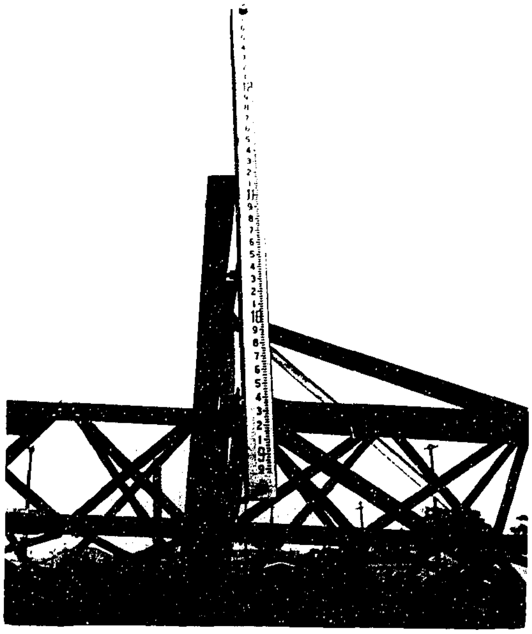
TAPERED BASE SECTION

PHOTOGRAPH 2

GUY OUTRIGGER & SCALE FRAME

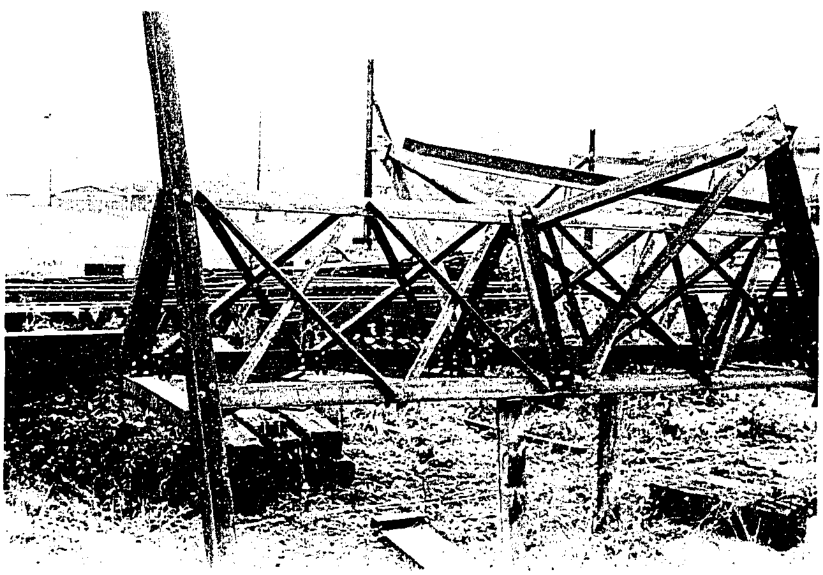
PHOTOGRAPH 3





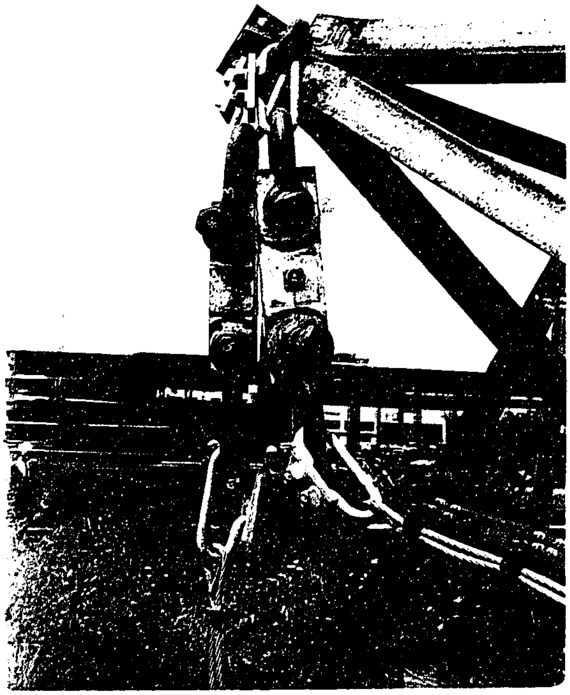
DEFLECTION SCALE

PHOTOGRAPH 4



PULL OFF ANGLE FOR APPLING LOADS

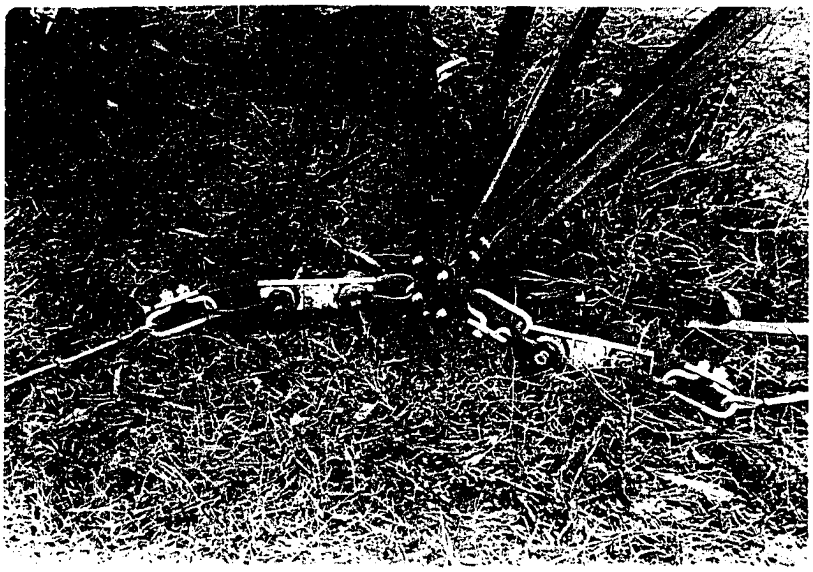
PHOTOGRAPH 5

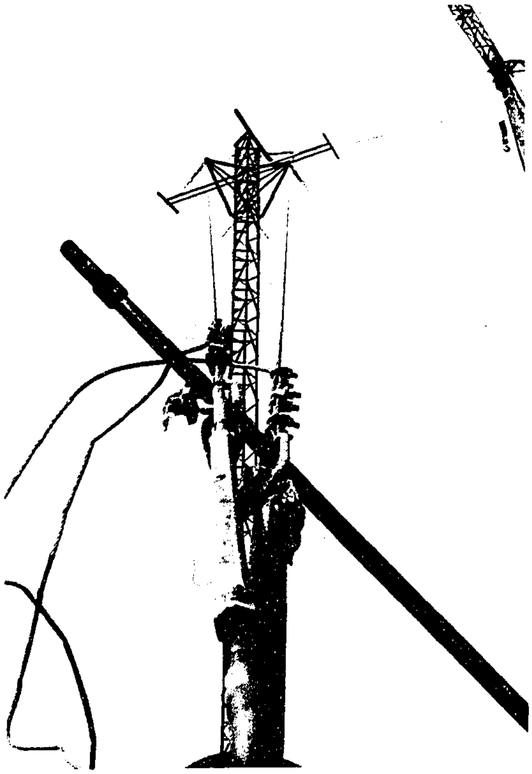


PHOTOGRAPH 6

LOAD CELLS FOR MEASURING GUY TENSIONS

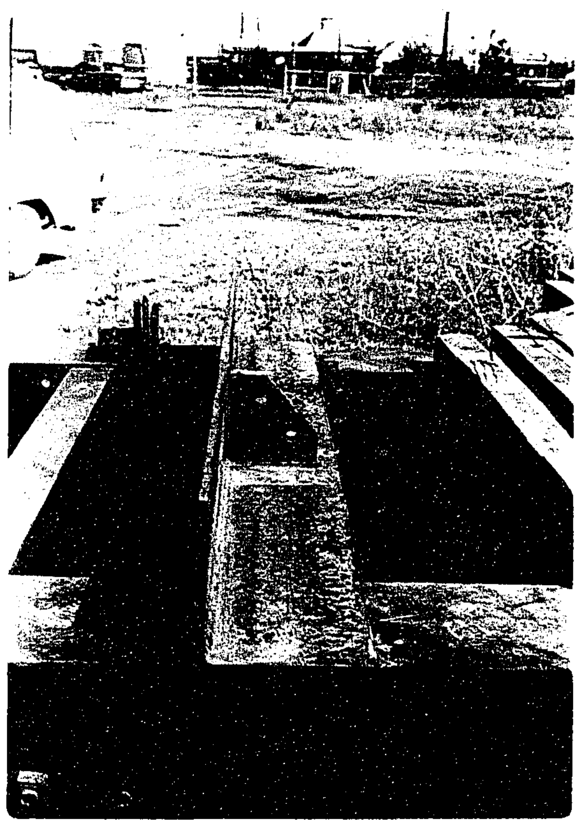
PHOTOGRAPH 7





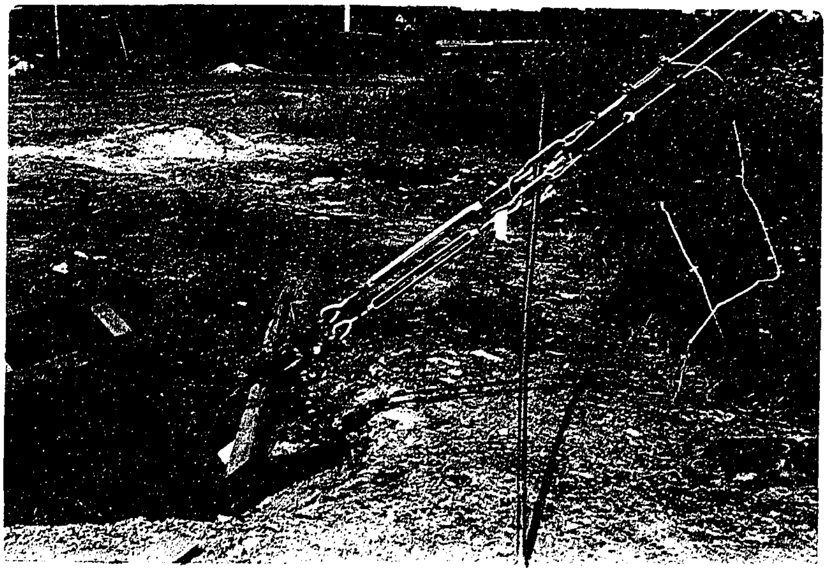
GUY SYSTEM

PHOTOGRAPH 8



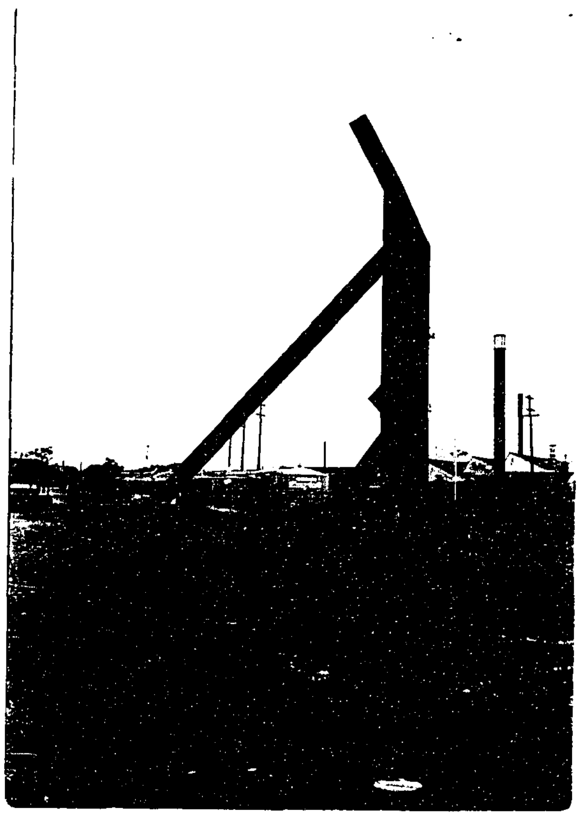
NORTH GUY ANCHORAGE

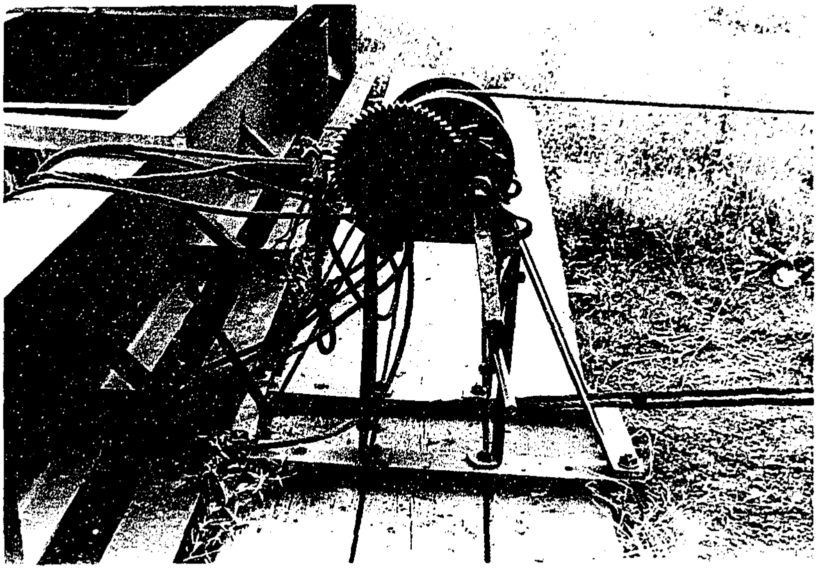
PHOTOGRAPH 9



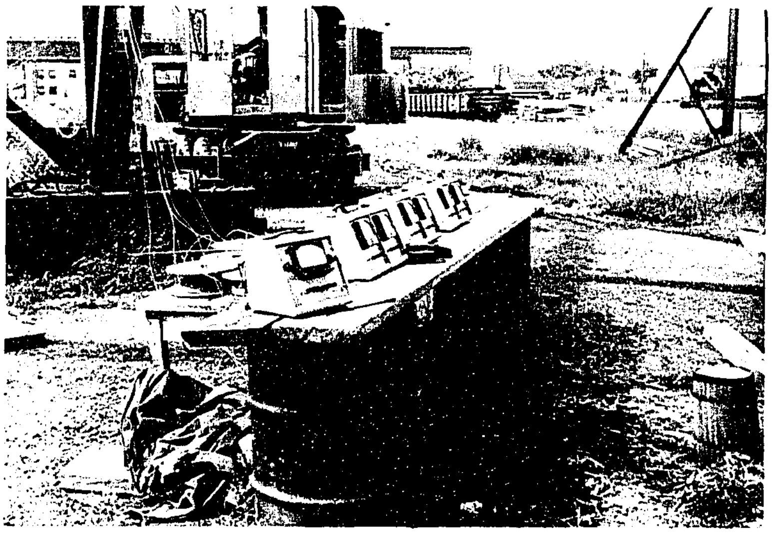
SOUTH-WEST GUY ANCHORAGE
PHOTOGRAPH 10

SOUTH-EAST GUY ANCHORAGE
PHOTOGRAPH 11





HANDWINCH FOR APPLING LOADS
PHOTOGRAPH 12



READ OUT METERS FOR THE LOAD CELLS
PHOTOGRAPH 13.

through a load cell, to the required position on the pull off angle. This line was carried back to a sheave located on the test bent, down the face, through another sheave to a five part line connected to a hand winch.

These features are illustrated in Photographs 9 to 12.

4.3 Load Cells

The load cells used to measure the applied load and the resulting guy tensions were of the strain gage type, and were part of the equipment supplied by Canadian Bridge. The strain gages are cemented in a hole in a steel bar, weather-proofed and connected to an outlet fitting.

Since these gages are for outside use, a dummy gage is included which corrects the readings for variations in temperature which occur during tests. The lead wire screws into the fitting on the load cell and runs to a read-out meter. Each load cell has its own meter which reads the load as a percentage of the rated capacity of the load cell. To provide greater accuracy at lower loads, a 30% button is provided which converts a 30% reading to a full scale reading. The rated accuracy of the meter is ±1%. The accuracy of the load cell decreases when the load drops below the 10% level.

The load cells are illustrated in Photographs 6 and 7 and the read out meters in Photograph 13.

4.4. Prestressing of the Guys

In order to remove the constructional stretch from the wire rope guys so as to obtain consistent deflections, and to obtain a value for the modulus of elasticity of the cable all of the guys were prestressed. The prestressing consisted of applying a load equal to 50% of the rated ultimate tensile strength of the cable and holding this load for one hour. During the first half hour the load was topped up as required.

During the application of the prestress load, length measurements were made to determine the amount of constructional stretch removed from the cable. After the load had been held for the required period, the load was removed and re-applied in increments and measurements taken at each increment. These values were used to establish the AxE value for the cables.

Figure 5-2 for guy G1 is typical of the load deflection diagram obtained. Table 4-1 gives the AxE values for all cables. Based on the catalogue value of the area of the cable, the modulus of elasticity is also obtained.

GUY	AxE	E
G1	1,270,000	20,150,000
G2	1,280,000	20,300,000
G3	1,270,000	20,150,000
G4	1,280,000	20,300,000
G5	1,291,000	20,500,000
G6	1,262,000	20,000,000
Average	1,275,500	20,200,000

Table 4-1 Elastic Modulus of Guy Cables

4.5 Measurement of Deflections

To provide the necessary scales for measuring deflections, strips of leveling rod tape were located on the four sides of the frame located at the outrigger level. Three theodolites and a transit were located along the principle axis of the bent, 90° apart and about 100 feet away from the mast. By using double scales symmetrically located about the centerline, the rotational effects could be averaged out of the tilt deflections. Since the rotational deflections were quite small in many instances, it was desirable to locate two of the scales as far as possible from the centre to obtain as large a deflection reading as possible. For comparison with the theoretical results these deflections were converted to angle rotations in degrees.

4.6 Tests Performed

Holes were provided at the centre point of the pull-off angle, spaced 1'-3 on either side. By selecting different pull-off positions various combinations of direct and torsional moments were obtained.

In order to evaluate the effect of initial guy tensions on the deflections, three different tensions were used. A slack condition where the initial tensions were about 5% of the rated ultimate tensile strength of the cable, a medium condition where the initial tensions were about 10% of the rated ultimate tensile strength, and a tight condition where the initial tensions were about 15% of the rated ultimate tensile strength. For a given pull off position and initial guy tension, the initial scale readings and load cell readings were taken; the load was then applied in a series of increments until the maximum allowable tension was reached in one of the guys. The applied load was then released in a series of decrements. At each increment and decrement of load, scale readings and load cell meter readings were taken. A final no-load reading was also taken.

Tests 1, 2 and 3 were performed with the load attachment point located at the centre point, so that no torque was applied to the mast. For tests 4, 5, 6 and 7 the load attachment point had an eccentricity of 1.25 feet. The attachment point was located on the west side for tests 4, 5 and 7 and on the east side for test 6. Tests 8, 9, 10 and 11 were performed with an eccentricity of 2.50 feet, and the attachment point located on the east side except for test 10 which was on the west side. Such alternate pull-off positions provided a check on the effect of the reversed direction of the moment.

During test 5 the load at each increment was held for 3 minutes, with scale readings and load cell meter readings taken at the beginning and end of this interval. This procedure was carried out to check and see if these readings showed any change with time. As there was no appreciable change in this time period, it was not felt necessary to repeat this check on the other tests.

The weather, during the tests, was warm with temperatures in the high 70's to low 80's. The sky was slightly overcase and a slight breeze was blowing from the south-west. While the odd gust caused some concern, the wind did not reach an intensity which warranted suspending the tests.

5.0 RESULTS AND DISCUSSION

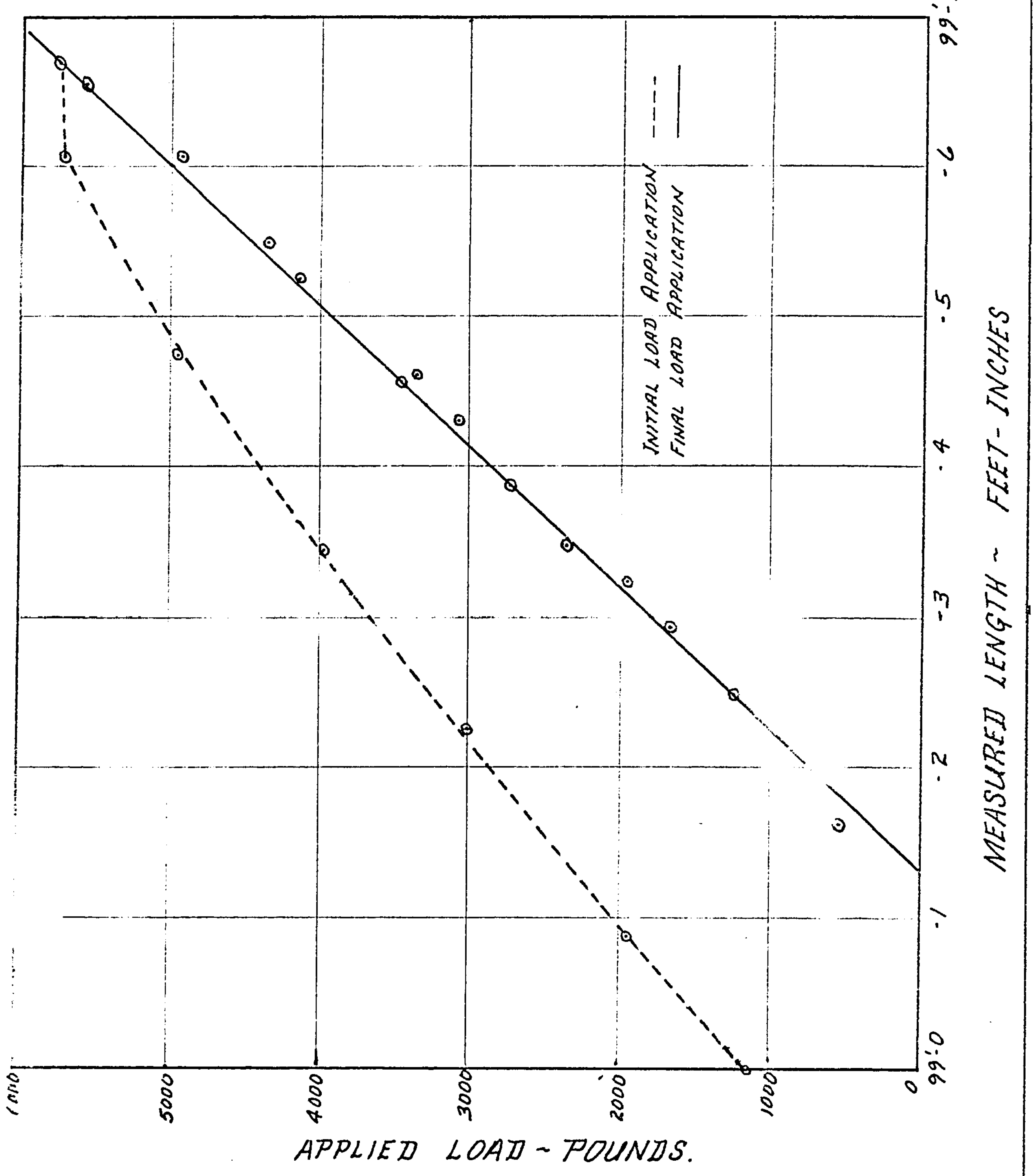
The experimental and theoretical results are compared in Figures 5-2 to 5-34.

5.1 Prestressing of the Guys

Figure 5-2 shows the load-elongation diagram for cable G1 during prestressing of the guy. The diagrams for the other cables are similar and therefore not shown.

The elongation of the cable during the application of the prestressing load is indicated by the dotted line shown in the above figure. The curvature of this line is caused by the constructional stretch of the cable. The horizontal line, at the prestressing load, indicates additional constructional stretch during the period this load was held. The solid straight line represents the elongation of the cable, after prestressing, as the load is released and reapplied. The slope of this line is used to establish the elastic modulus of the cable. The discrepancy between the solid and dotted lines represents the amount of constructional stretch removed from the guy.

Normally, if the guys have not been prestressed, it is necessary to re-tension them at some period, say one year, after they have been in service, to take up this constructional



LOAD - ELONGATION DIAGRAM - CABLE G1

FIGURE 5-2

stretch, and hence the establishment of a constant value for the elastic modulus.

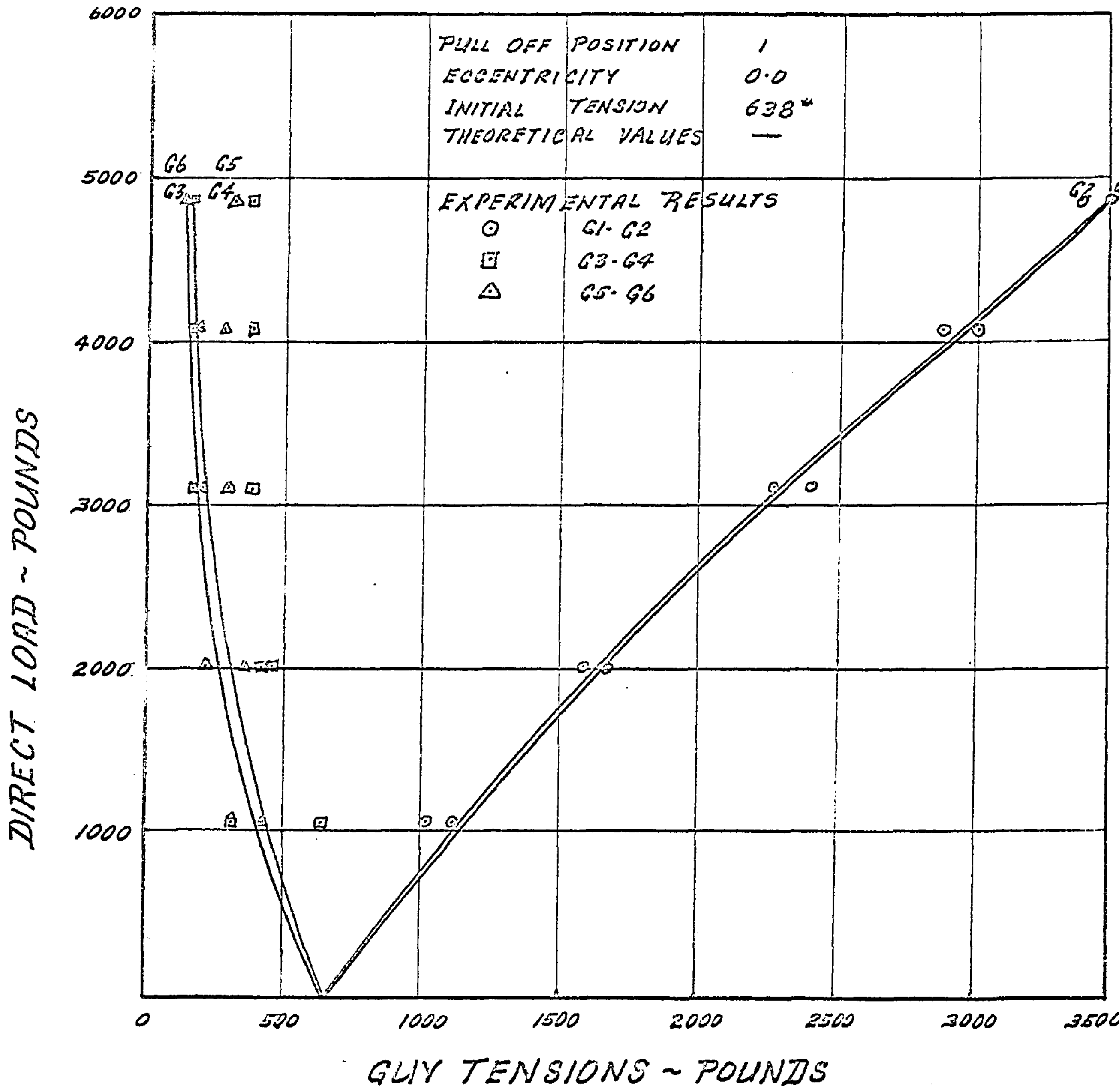
5.2 Guy Tensions

Figures 5-3 to 5-13 show the variation of the guy tensions with the direct load for the various tests performed.

Generally, the theoretical results for guys G1 and G2 are in close agreement with the experimental values. However similar comparisons for guys G3 to G6 exhibit more variance. This greater variance is attributed to the fact that guys G3 to G6 were slack, with tension values falling below the 10% level of the load cells. As noted earlier results obtained from readings below this level were not reliable. Furthermore since the initial tensions were obtained from load cell readings near or below this 10% level it is quite possible that such values were not as accurate and uniform as one might have desired.

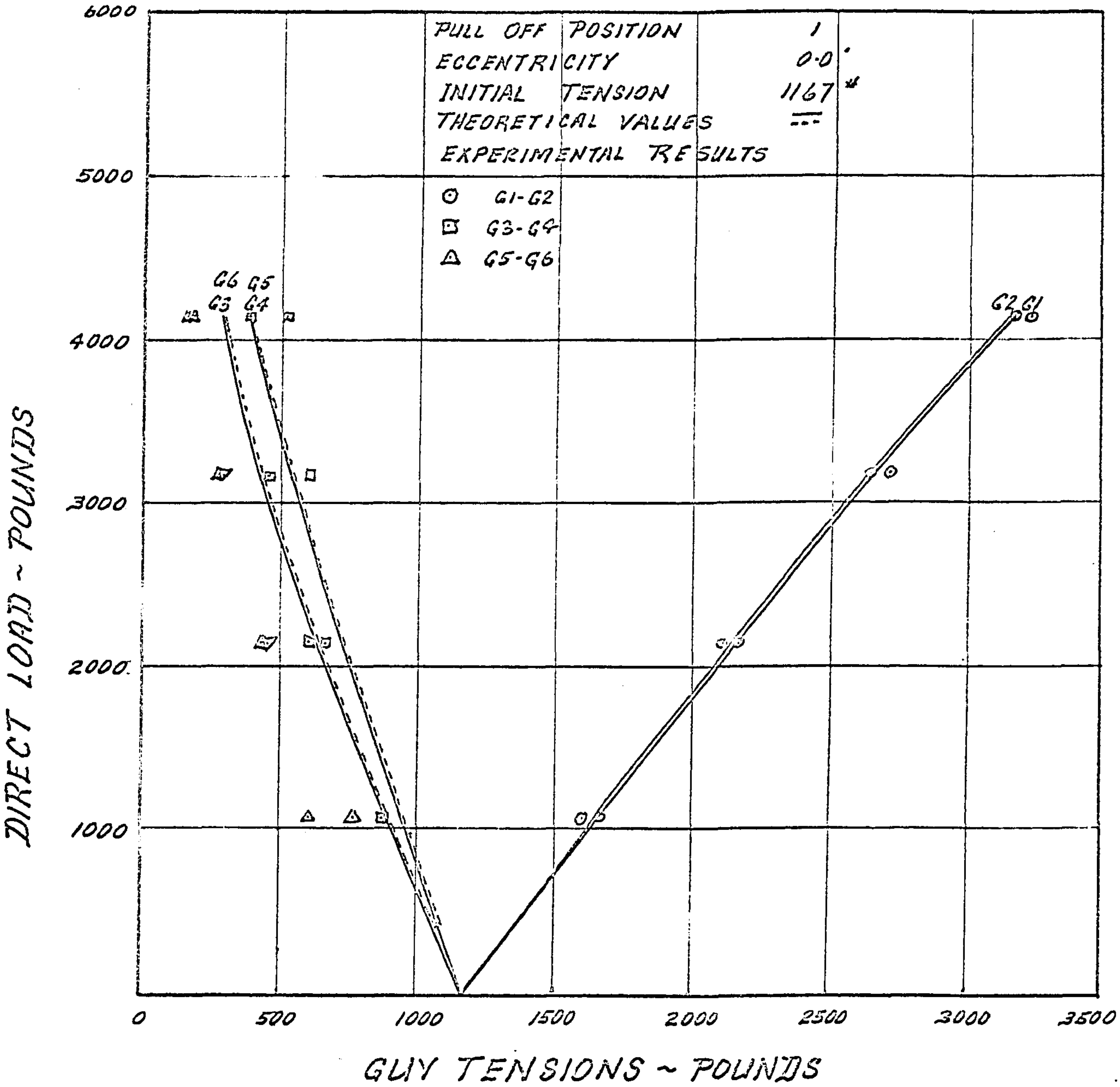
It can be observed that for low initial tensions the relationship between the guy tensions and the applied load is non-linear. However with increased initial tensions this relationship becomes more linear. This can be expected since a guy with a low initial tension has a greater sag which must be removed, before the linear elastic stretch becomes effective. Because the tensions are related to the sag of the cable, this sag relation is reflected in the guy tensions.

A comparison of the guy tensions for the cases of no applied moment with those with applied moment indicate that



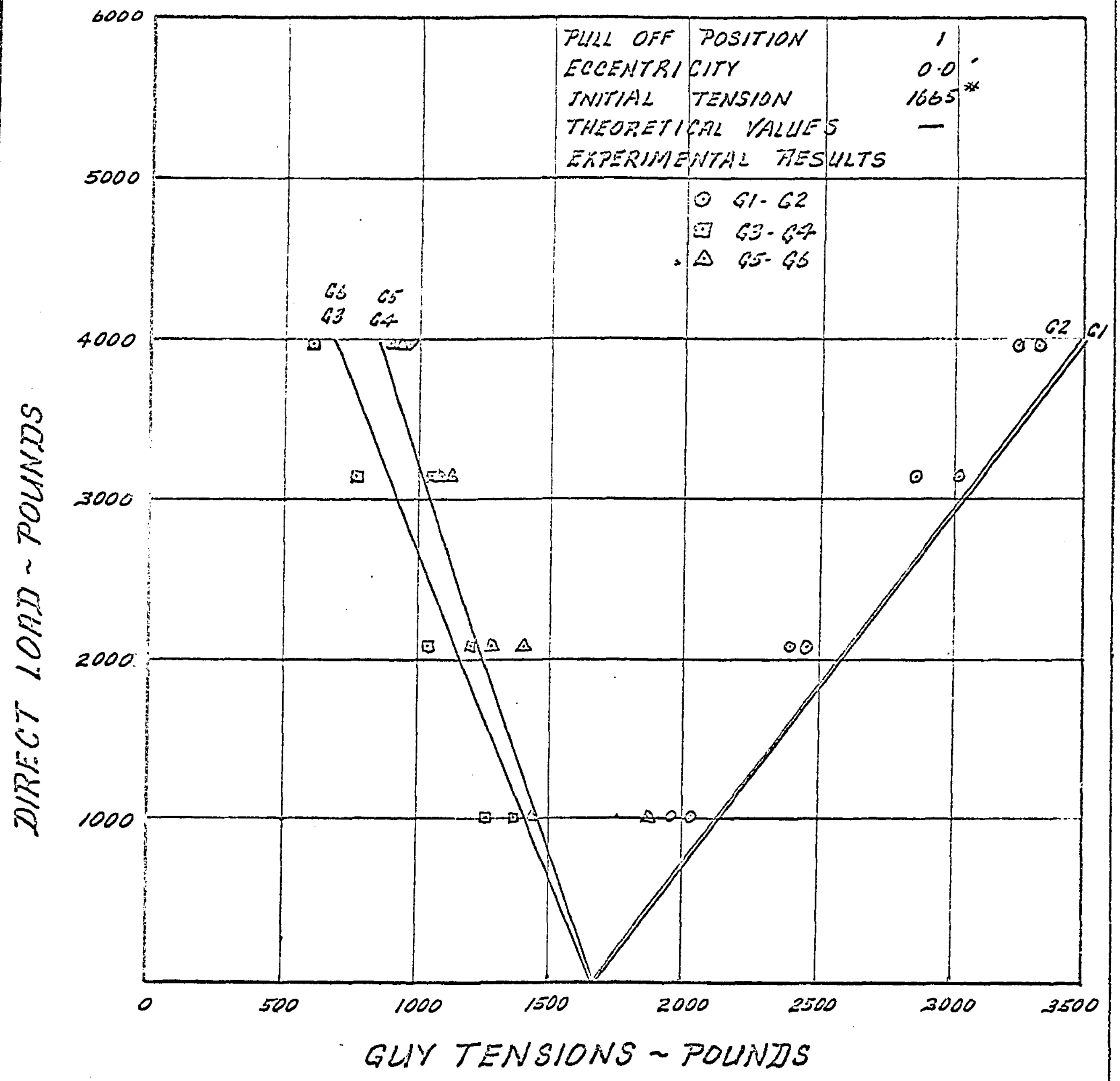
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST I

FIGURE 5-3



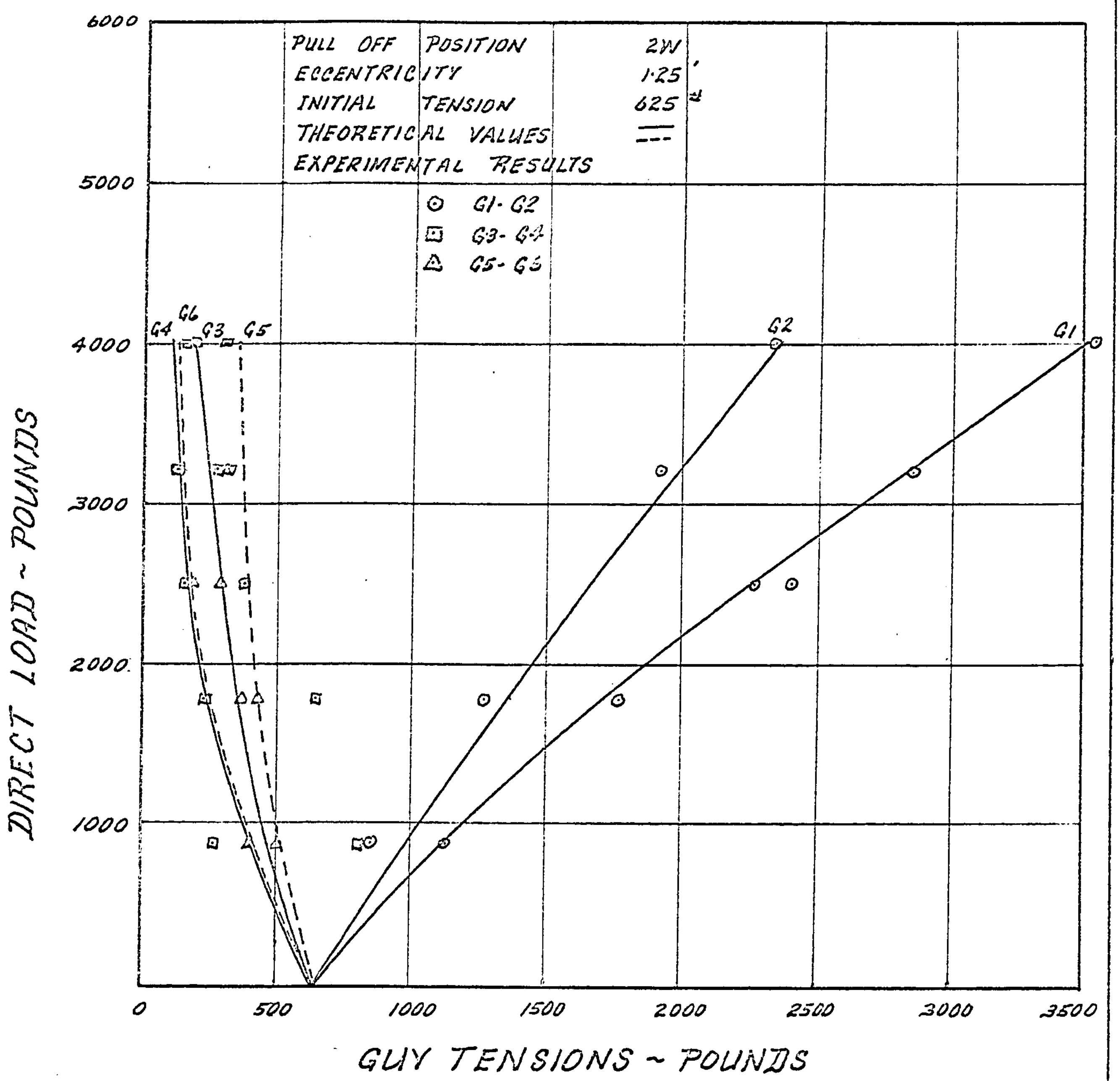
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 2

FIGURE 5-4



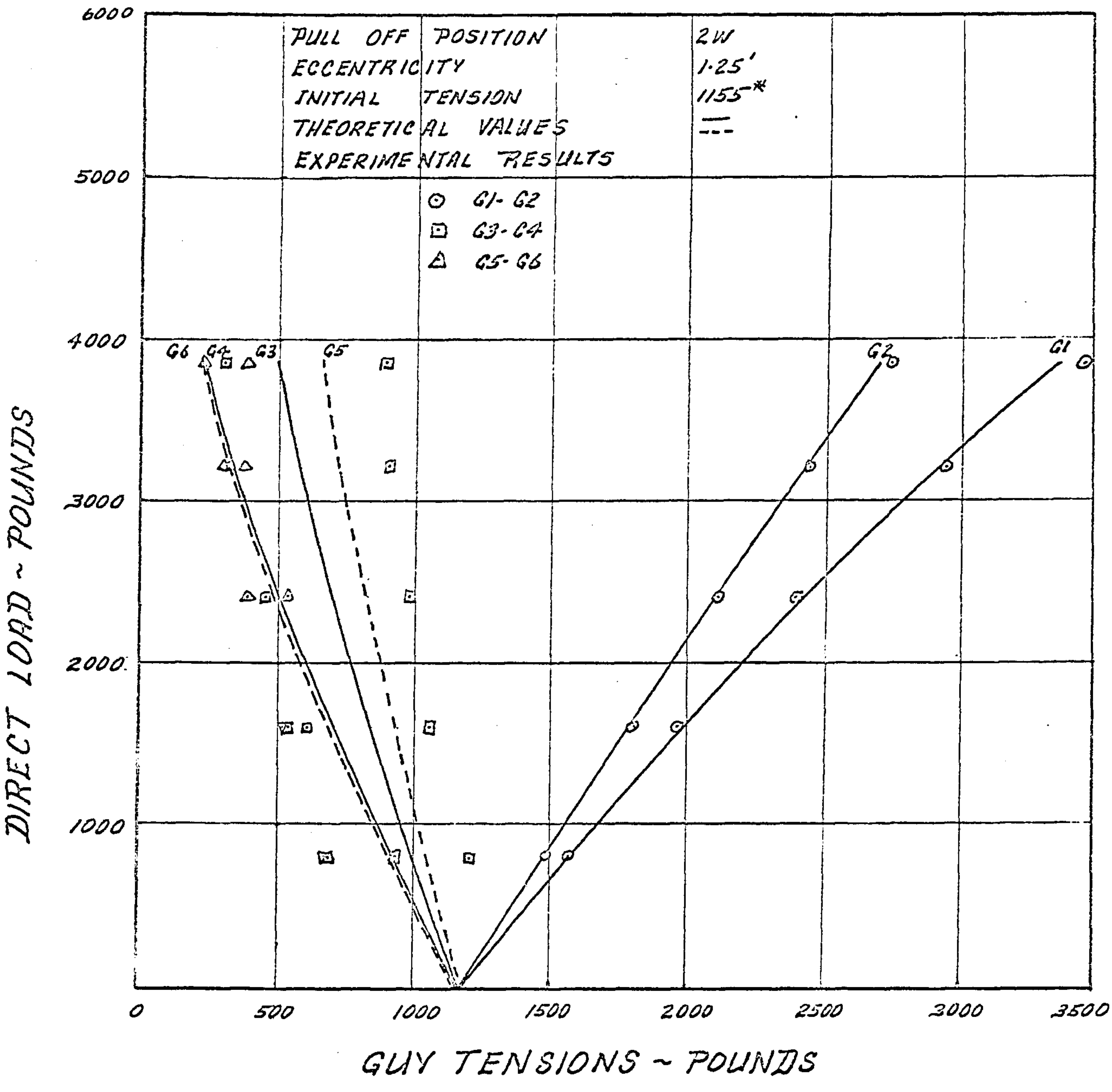
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 3

FIGURE 5-5



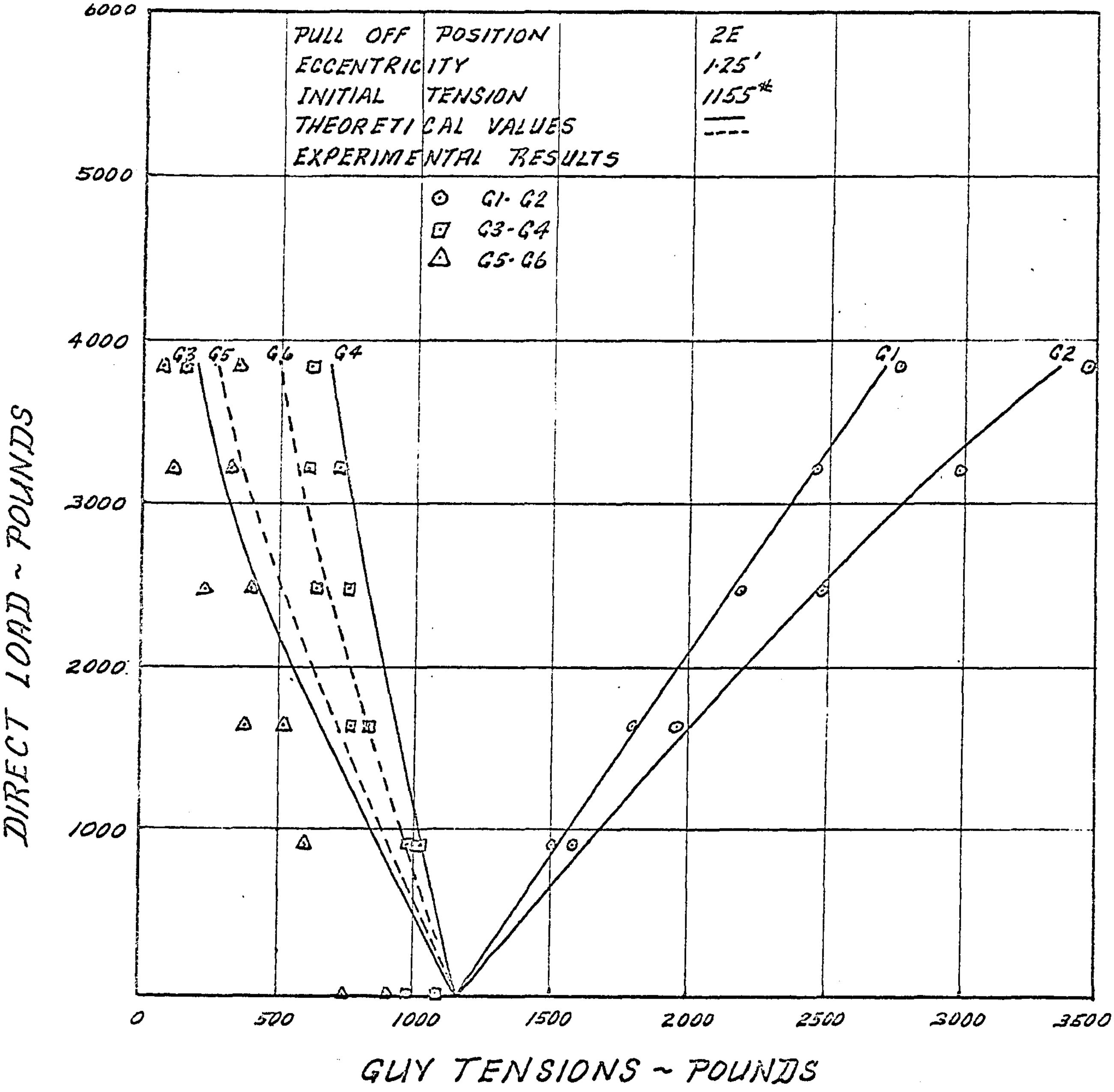
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 4

FIGURE 5-6



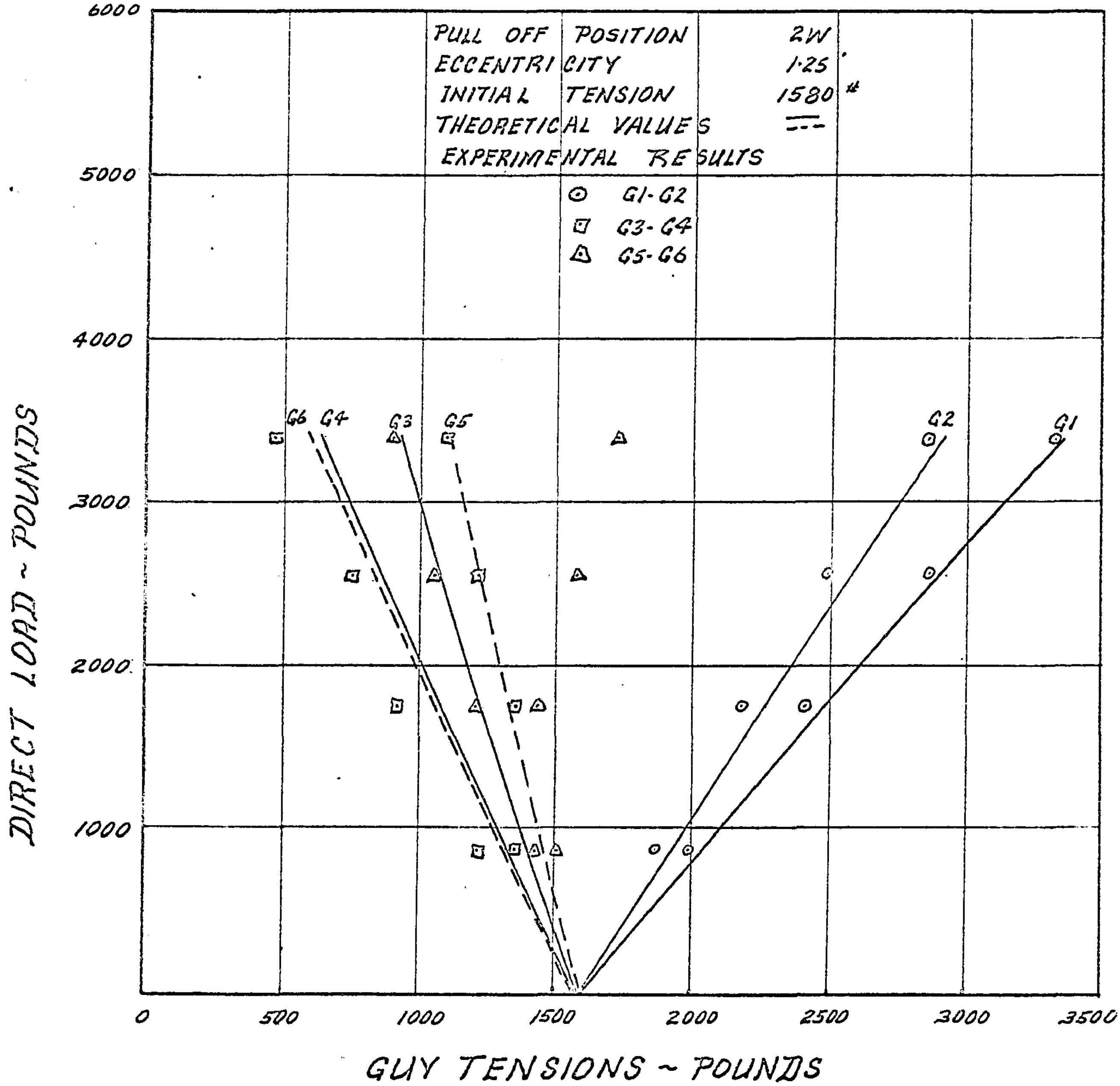
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 5

FIGURE 5-7



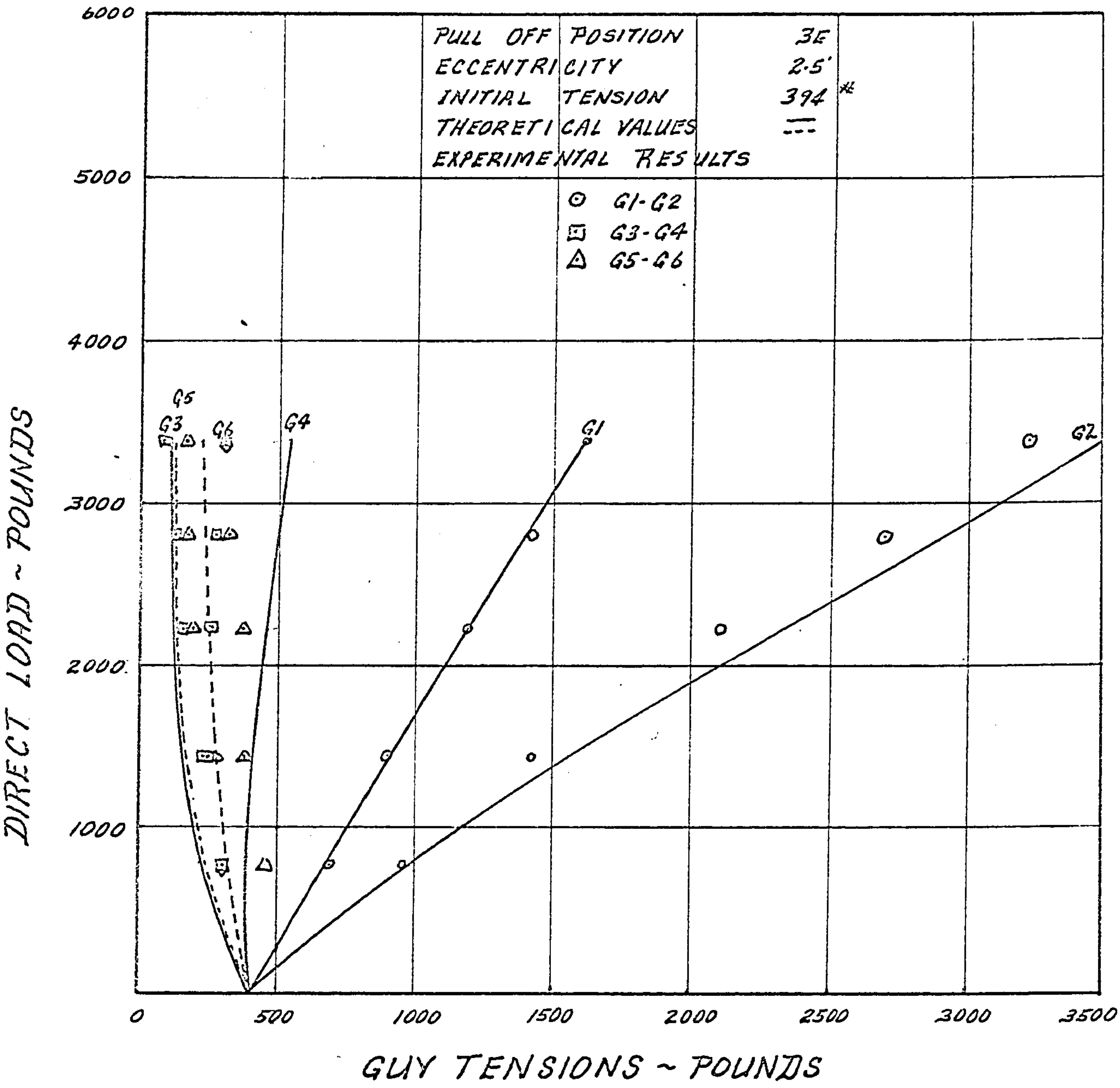
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 6

FIGURE 5-8



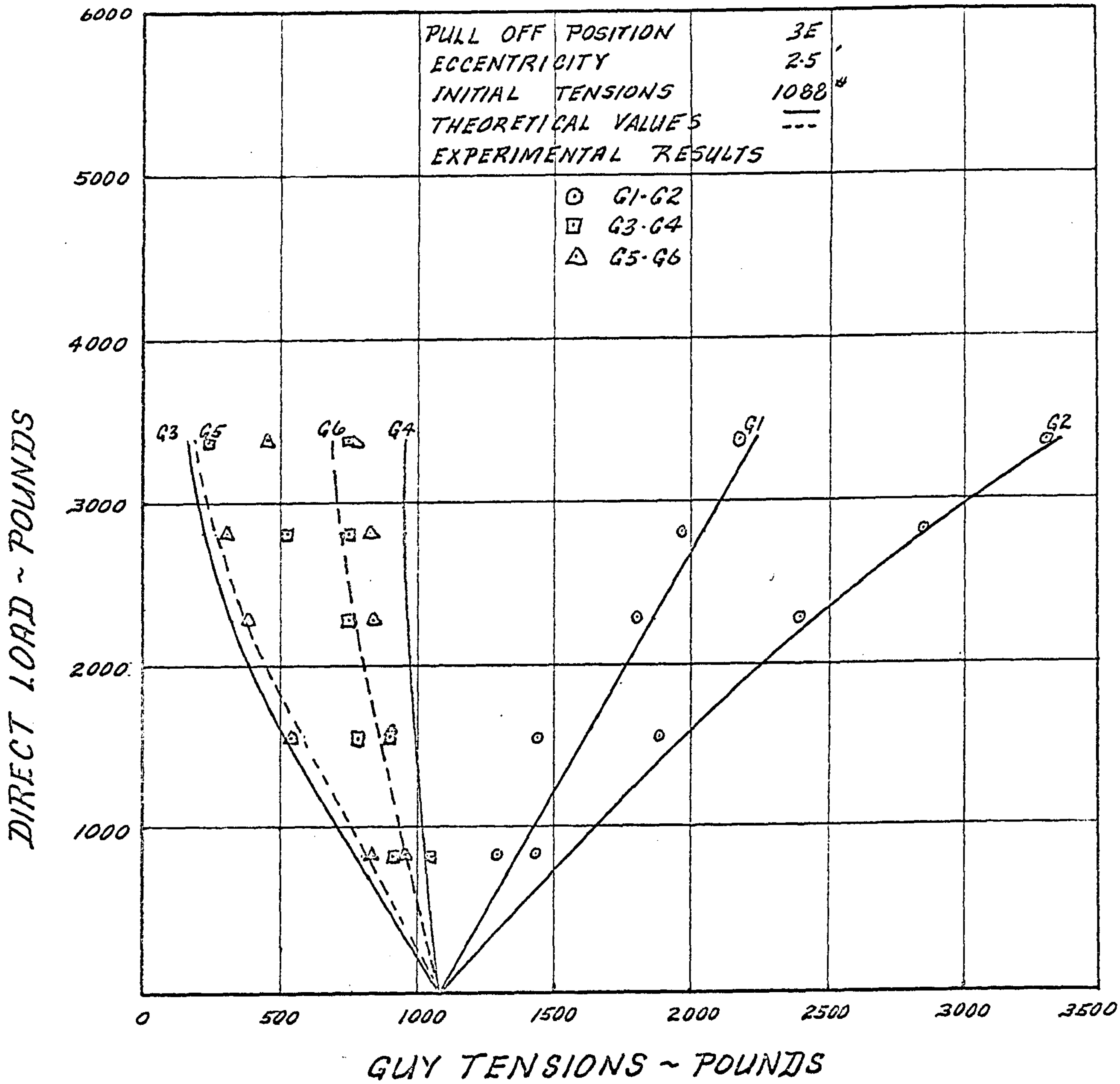
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 7

FIGURE 5-9



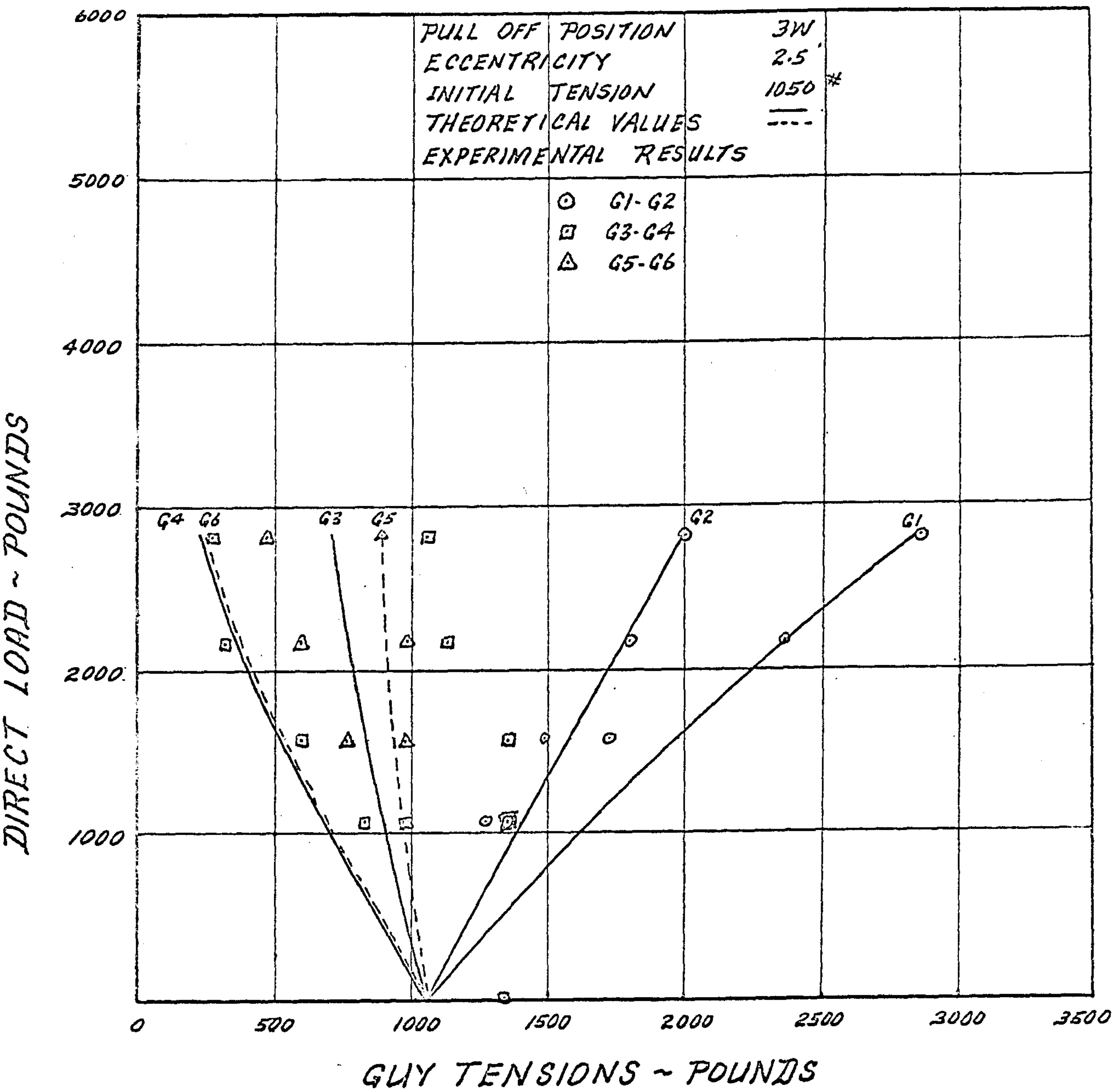
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 8

FIGURE 5-10



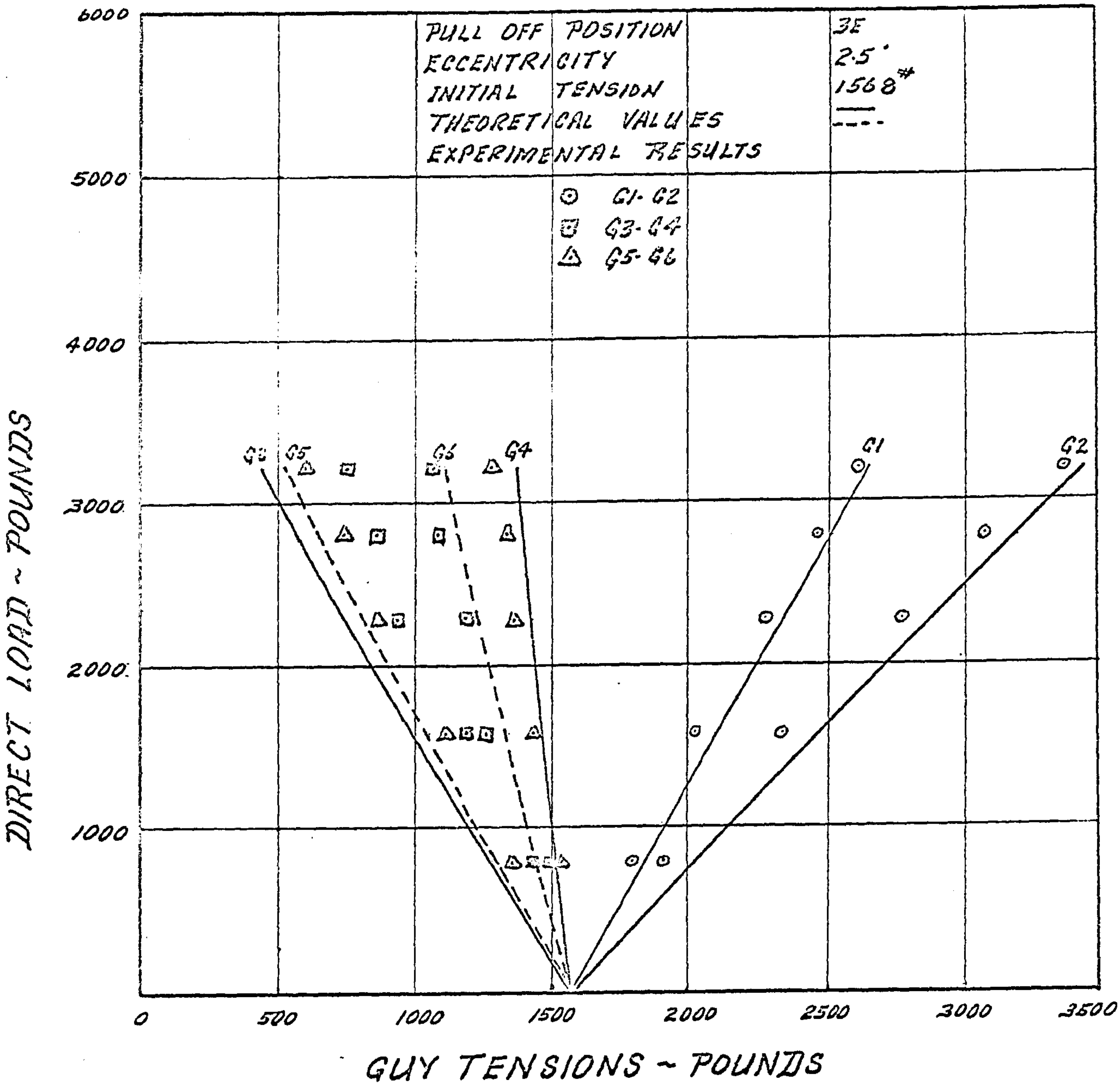
VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 9

FIGURE 5-11



VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 10

FIGURE 5-12



VARIATION OF GUY TENSION WITH DIRECT LOAD
TEST 11

FIGURE 5-13

the pairs of guys resist the applied moment by the one guy increasing in tension while the tension in the other guy decreases a nearly equal amount.

In almost all the cases considered, the theoretical results are conservative for the guys carrying the largest tensions. This is important since it is the largest tension that governs in the design.

5.3 Twist Deflections

Figures 5-14 to 5-21 show the variation of twist deflection (in degrees) with applied twist moment for tests 4 to 11.

The experimental values show fair agreement with the theoretical results, particularly for the slack and tight initial guy tension conditions. Results for the medium initial tension condition show more variance. A possible explanation of this is given in the section on tilt deflections 5.4.

It can be noted from the above figures that results from the loading stage differ from those for the unloading stage. The deflections are related to the elongations of the guys, which in turn are made up of decreased cable sag and elastic stretch. When the load is reduced, the cable shortens due to the decreased elastic stretch, but not all of the sag returns to the guys. Hence some residual deflection remains.

The twist deflections decrease as the initial guy tensions are increased. However no substantial decrease in the twist deflection is observed during the transition from the medium to the tight condition when compared to the decrease in

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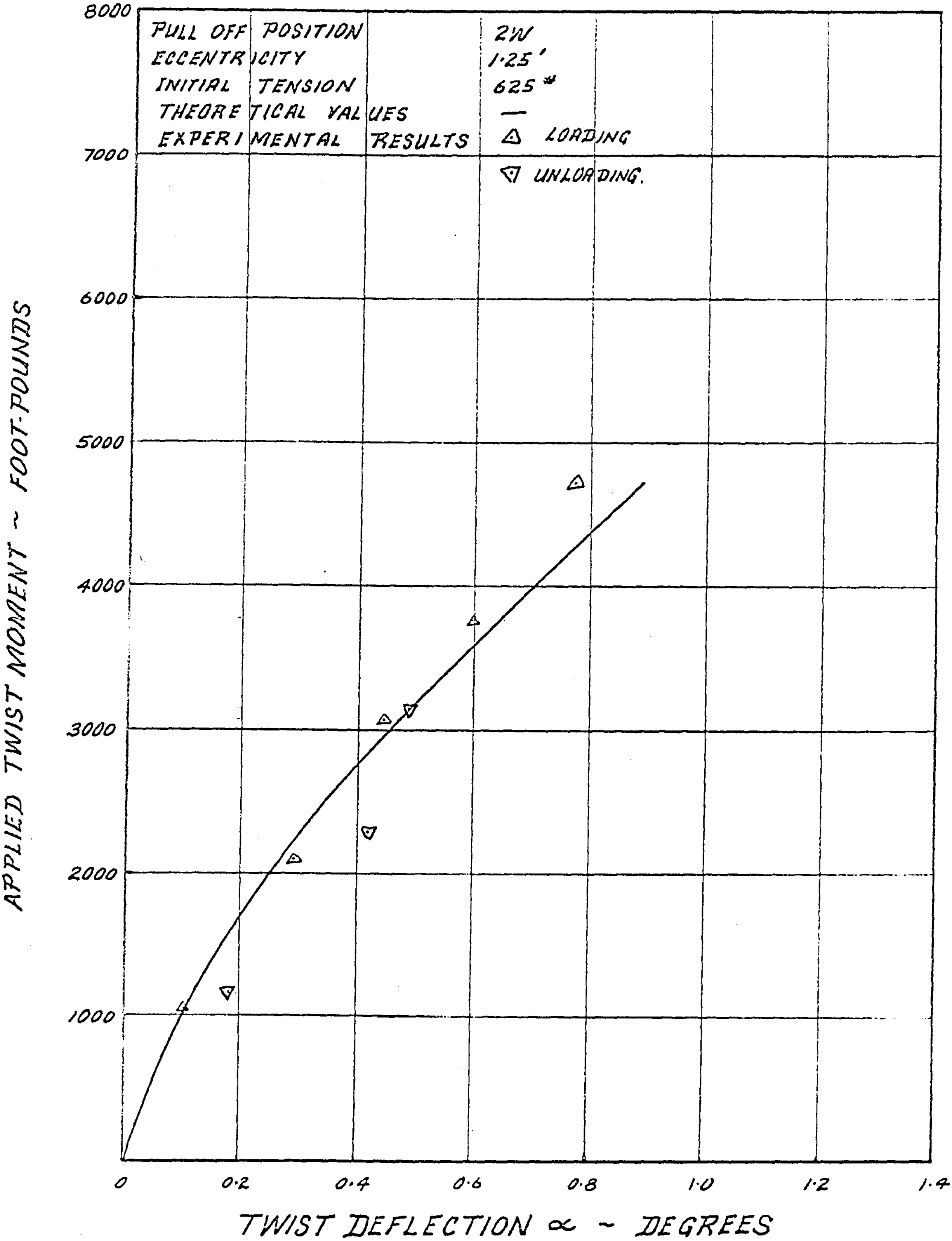
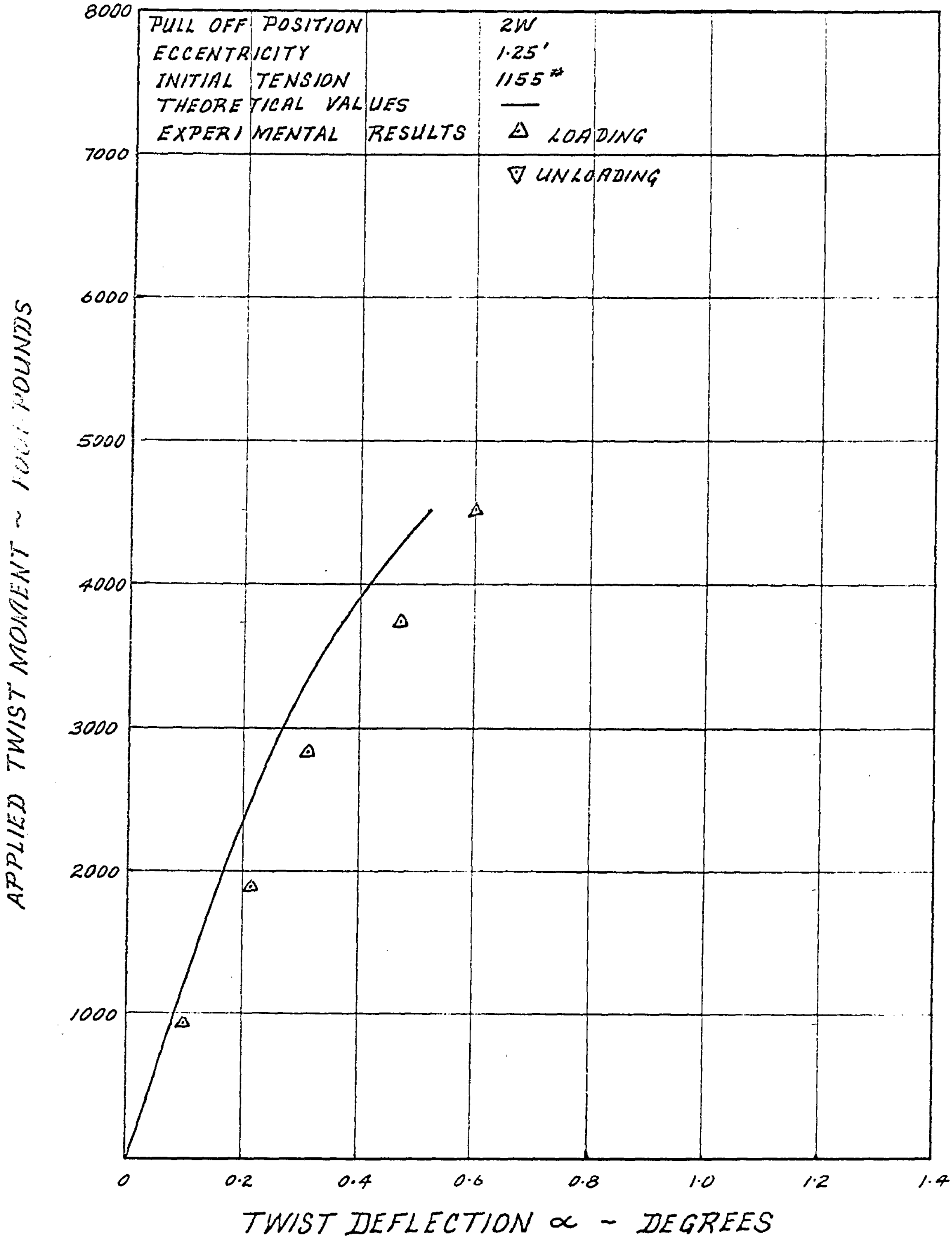
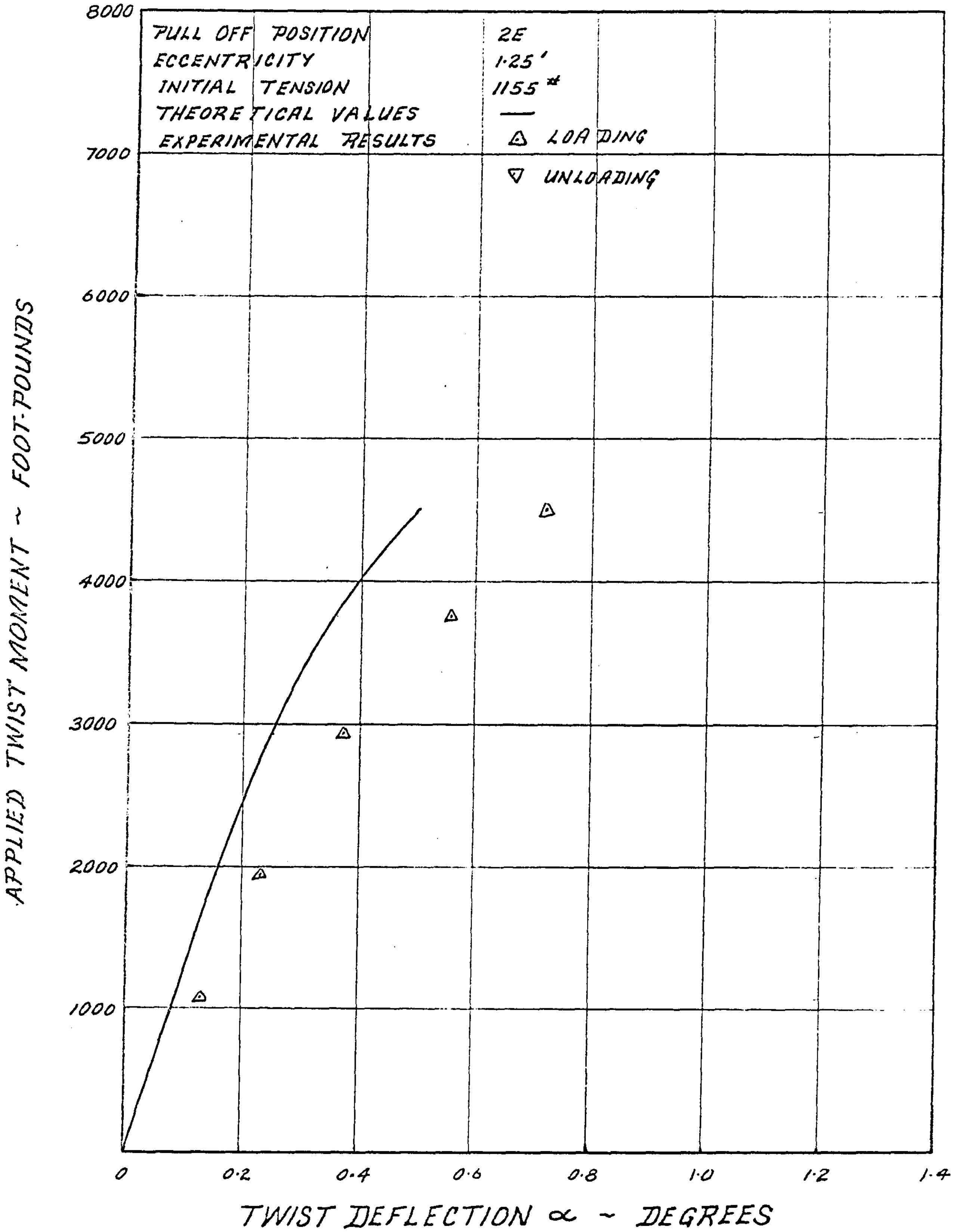


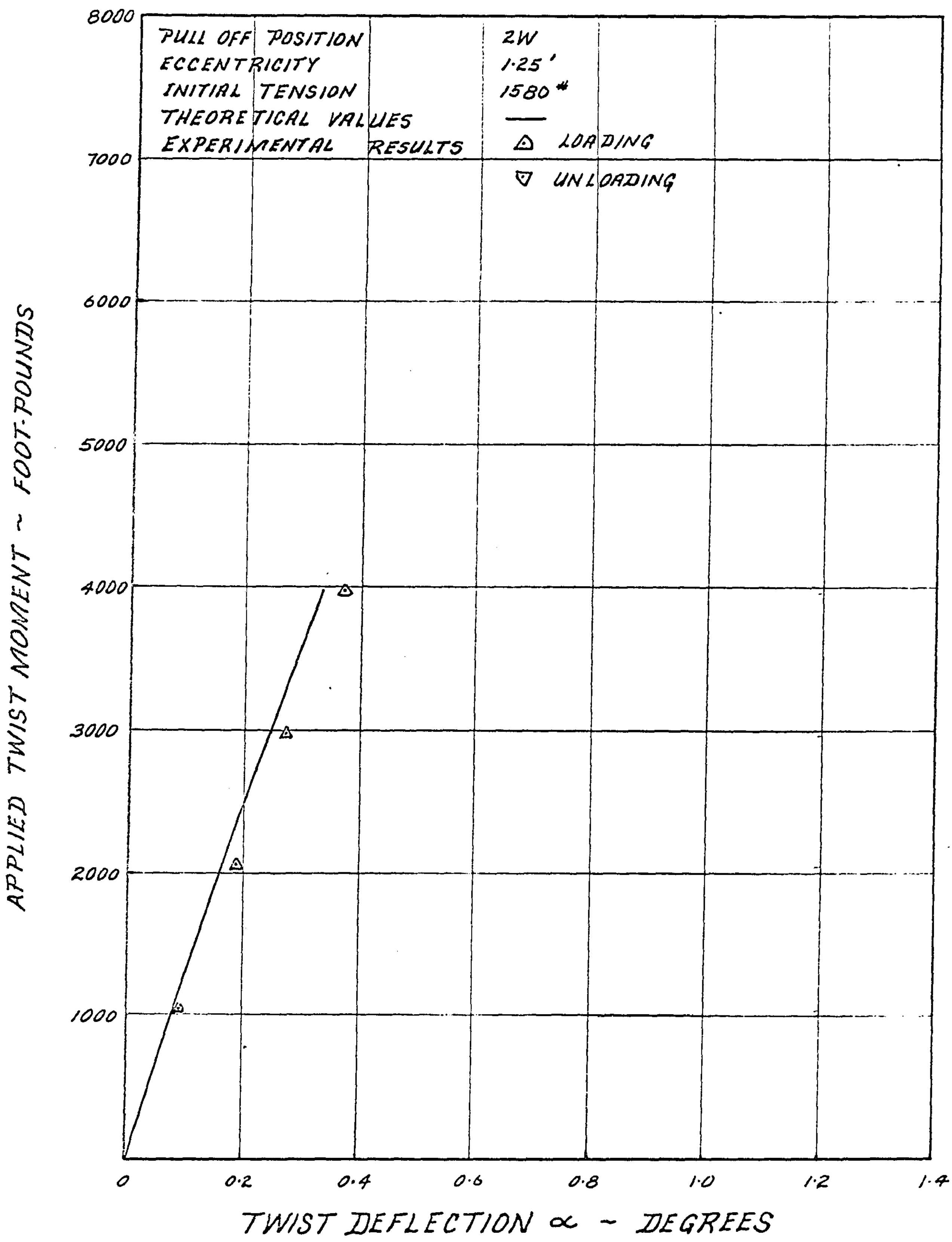
VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 4
FIGURE 5-14



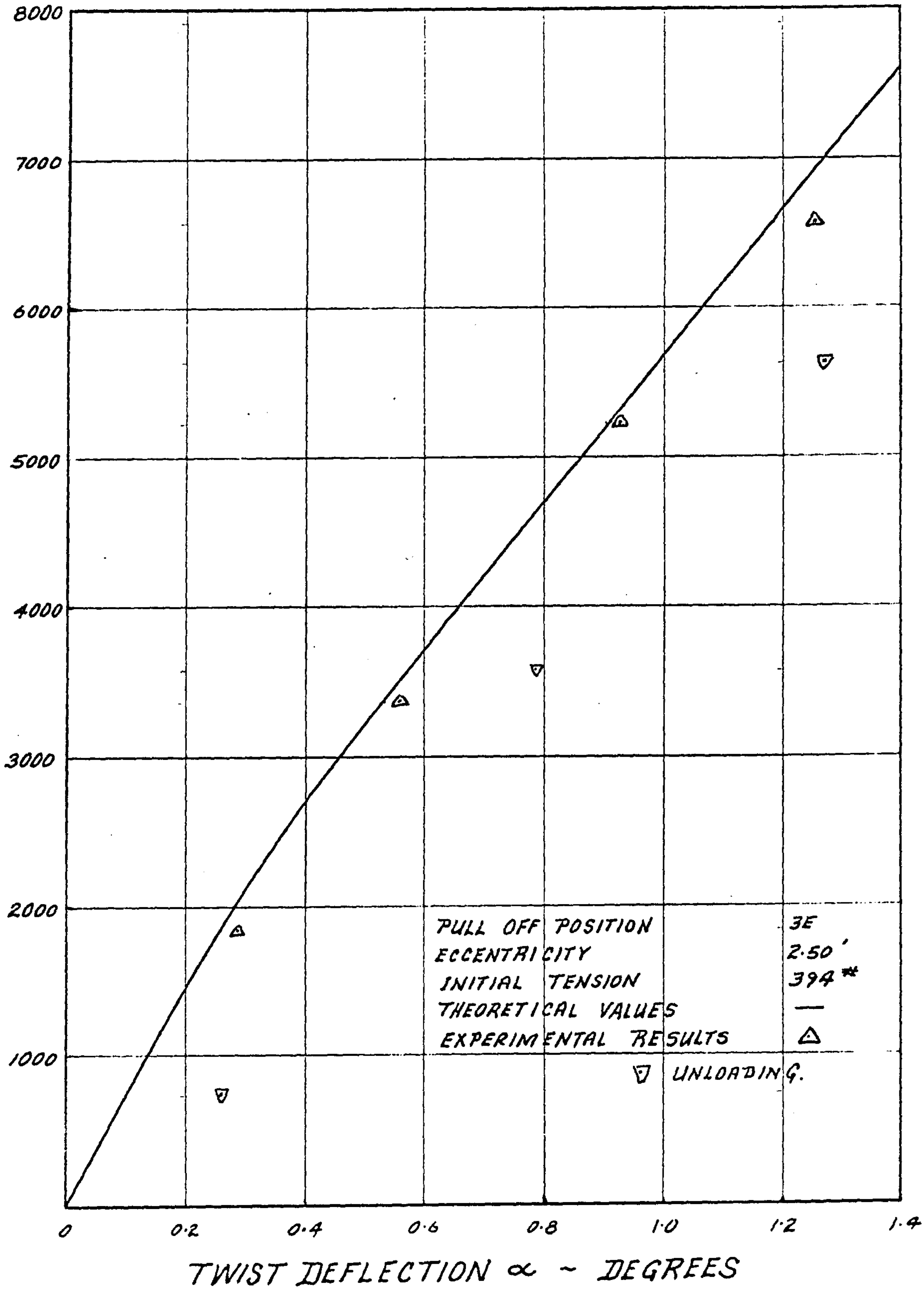
VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 5
FIGURE 5-15



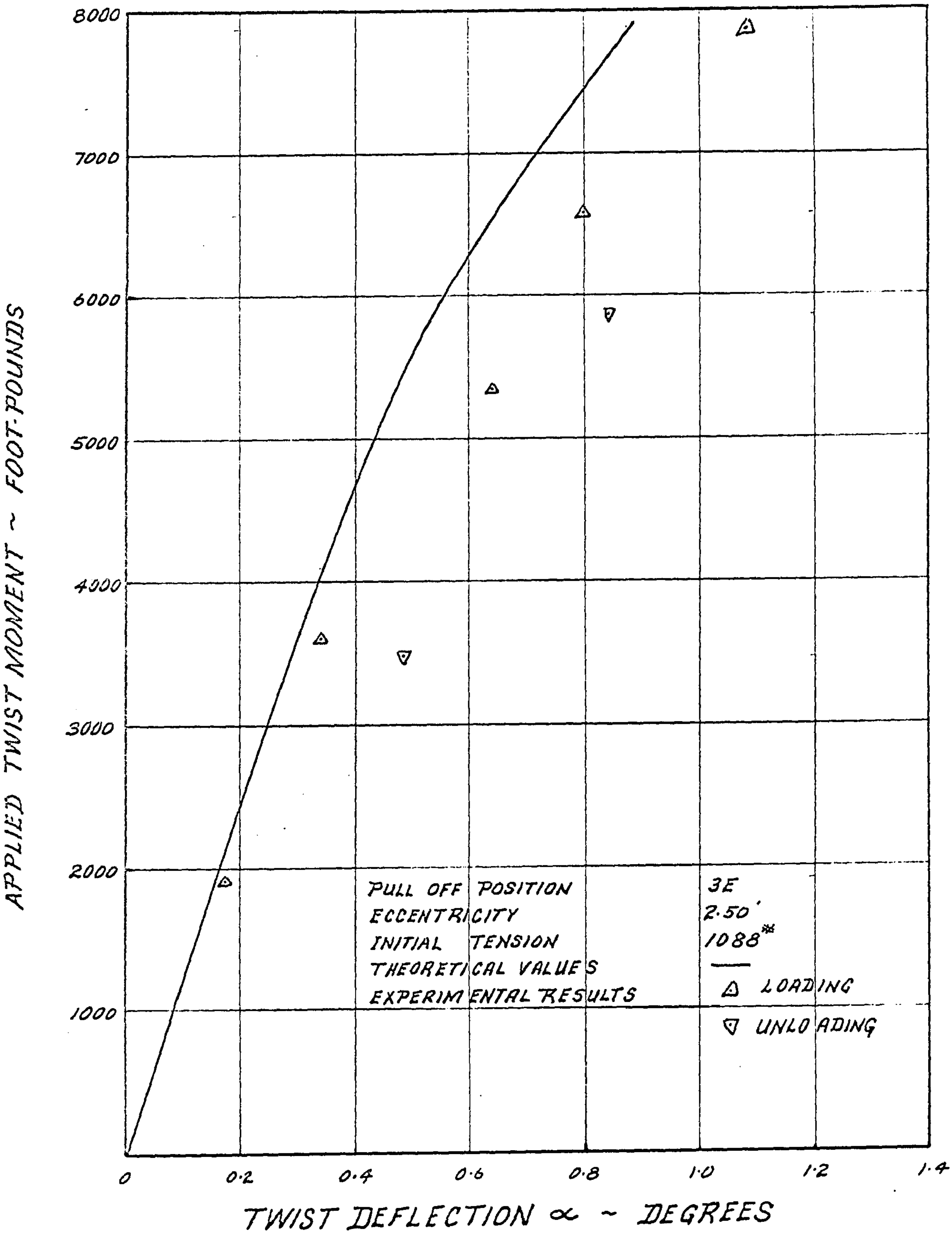
VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 6
FIGURE 5-16



VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 7
FIGURE 5-17



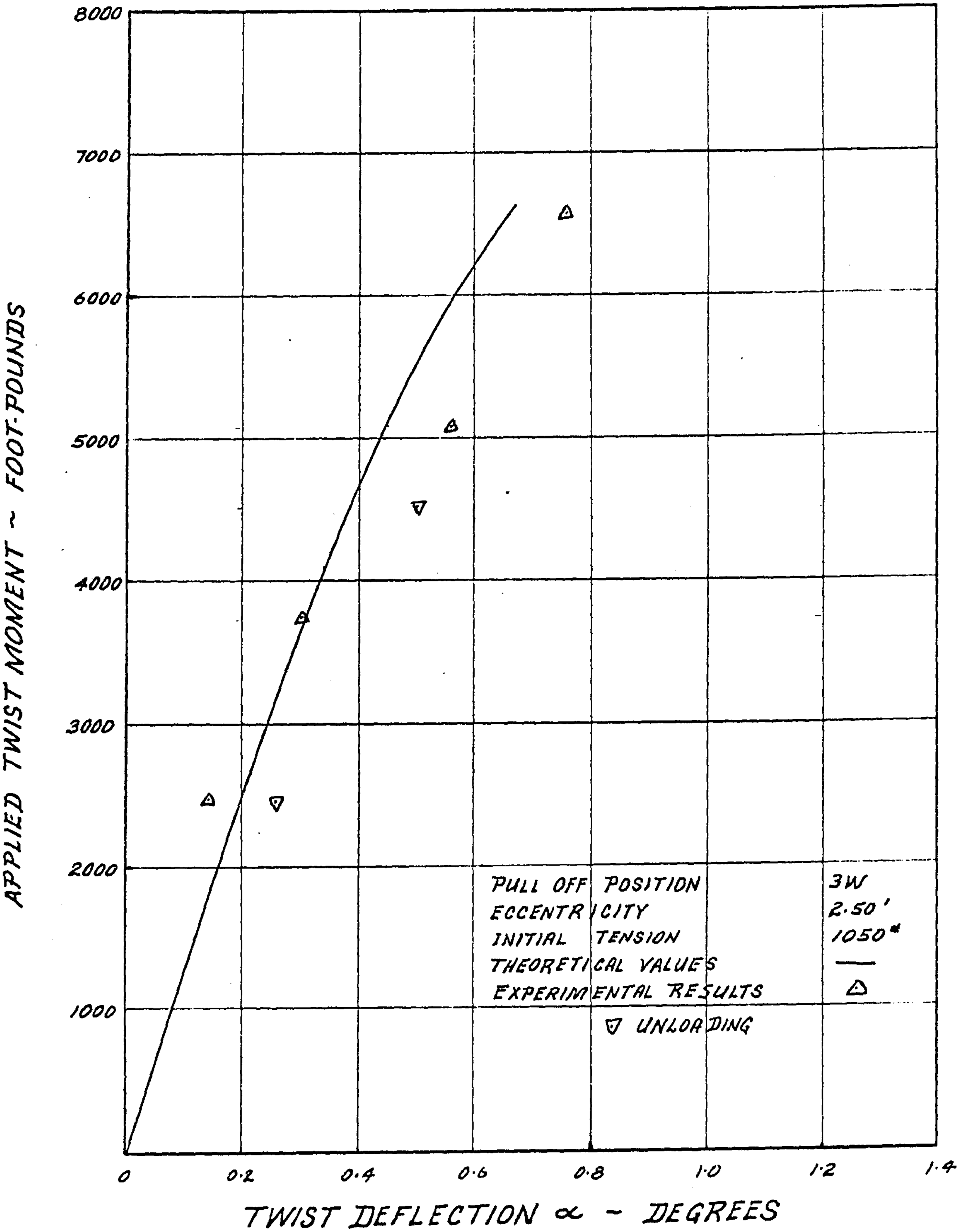
VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 8
FIGURE 5-18



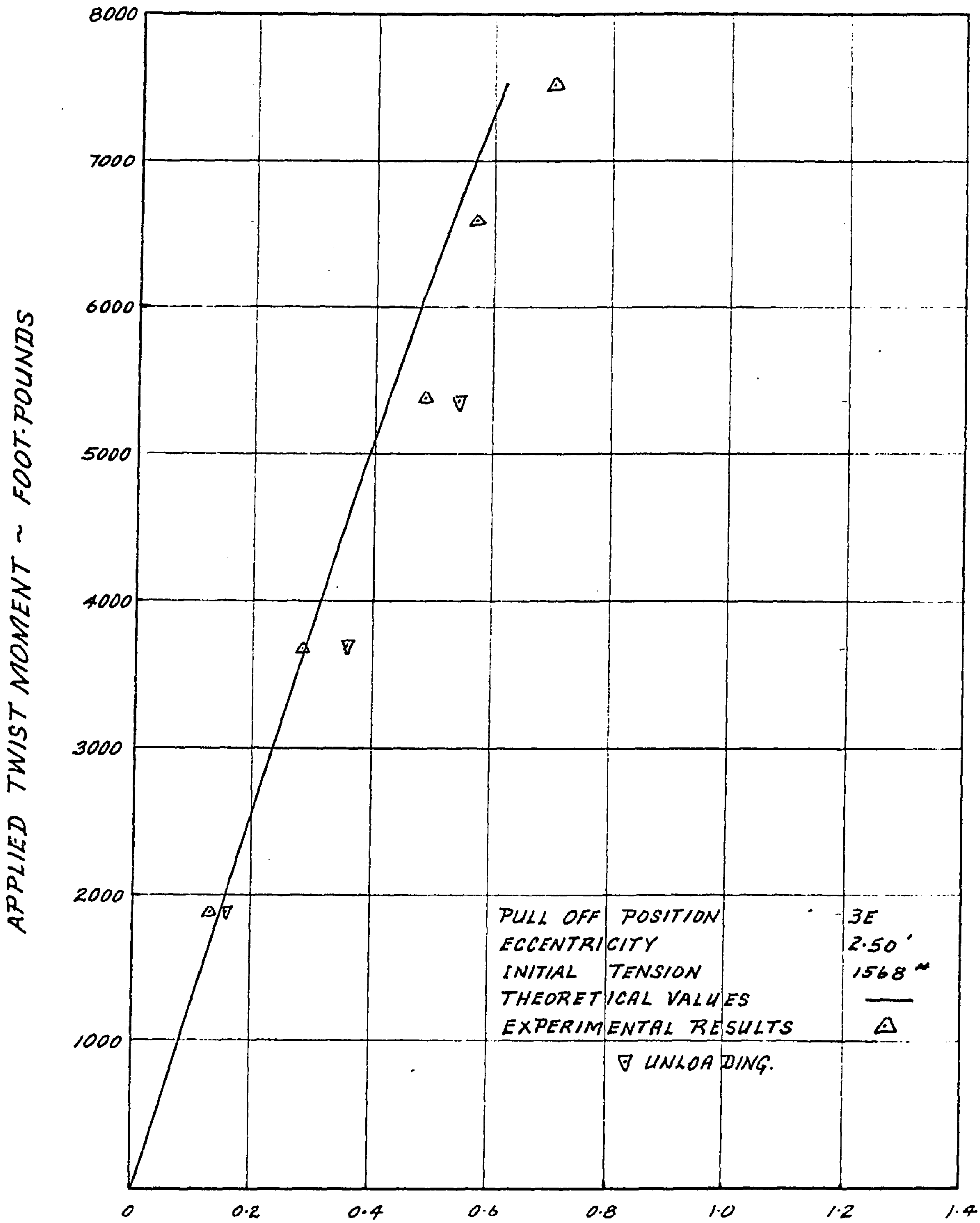
VARIATION OF TWIST DEFLECTION WITH MOMENT

TEST 9

FIGURE 5-19



VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 10
FIGURE 5-20



VARIATION OF TWIST DEFLECTION WITH MOMENT
TEST 11
FIGURE 5-21

deflection during the transition from the slack to the medium condition. This non-linear relationship is illustrated further in Chapter 6.

Here again the moment deflection relation is non-linear in form for the low initial tensions and tends to a linear form with increased initial tensions. This is explained in the same way as in section 5.2.

When the experimental values of the twist deflections for tests 5 and 6 (Figures 5-15 and 5-16) and tests 9 and 10 (Figures 5-19 and 5-20) are compared, some variations are observed, particularly at the higher moments. Tests 5 and 9 where the attachment point was on the east side, indicate slightly smaller deflection values than the corresponding values from tests 5 and 10, where the connection point was on the west side. It may be recalled that the east anchorage was the one which was connected to the raised pile. Since this anchorage was located closer to the mast, the angle γ which the guy makes with the normal to the tower was slightly greater than its west side counterpart and therefore provided greater resistance to the applied moment. The method of loading was such that the component of load in the Y direction increased the tension in the pair of guys on the side where the load was applied, and hence they supplied greater resistance to the torque. Therefore when the load pull-off point was on the east side, the system had slightly more resistance to the applied moment and hence the smaller deflection results.

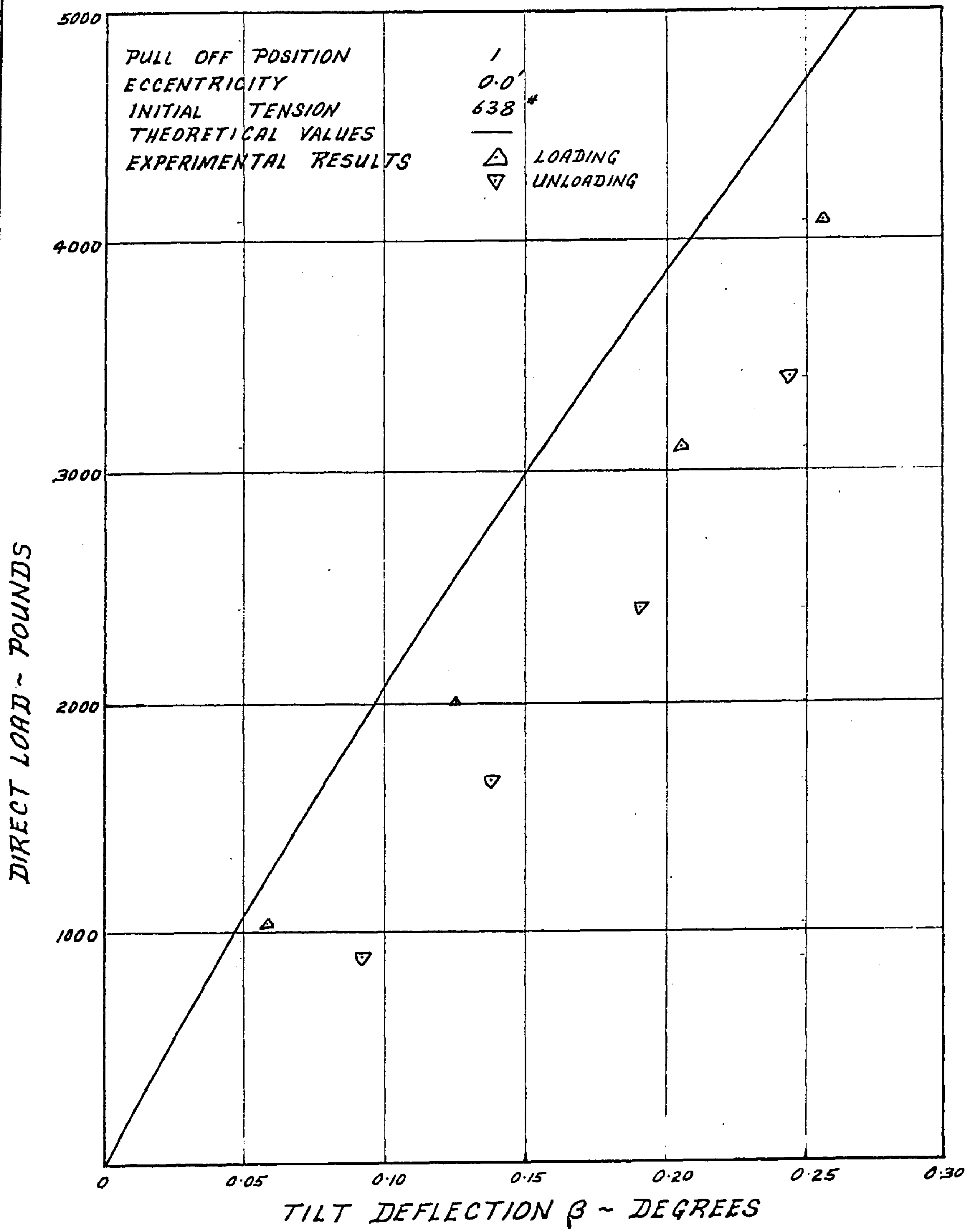
5.4 Tilt Deflections

Figures 5-22 to 5-32 exhibit the variation of the tilt deflections (in degrees) with the direct load for tests 1 to 11.

Comparison between the experimental values and the theoretical results show a varying degree of correlation. The experimental deflections for the slack initial tension conditions are invariably greater than the theoretical values; whereas the medium initial tension condition shows better correlation and the tight initial tension condition very close agreement. It should be noted that the load cells and their fittings, inserted in the guy system to measure the tensions, weighed considerably more than the equivalent length of guy which they replaced. This increased weight caused increased sag in the guys which would not have been present otherwise, particularly for the low initial tension values. It is suspected that such a situation would create the discrepancy between the theoretical and experimental results noted for the lower initial tensions.

The difference in experimental values during the loadings and unloading stages can also be observed here.

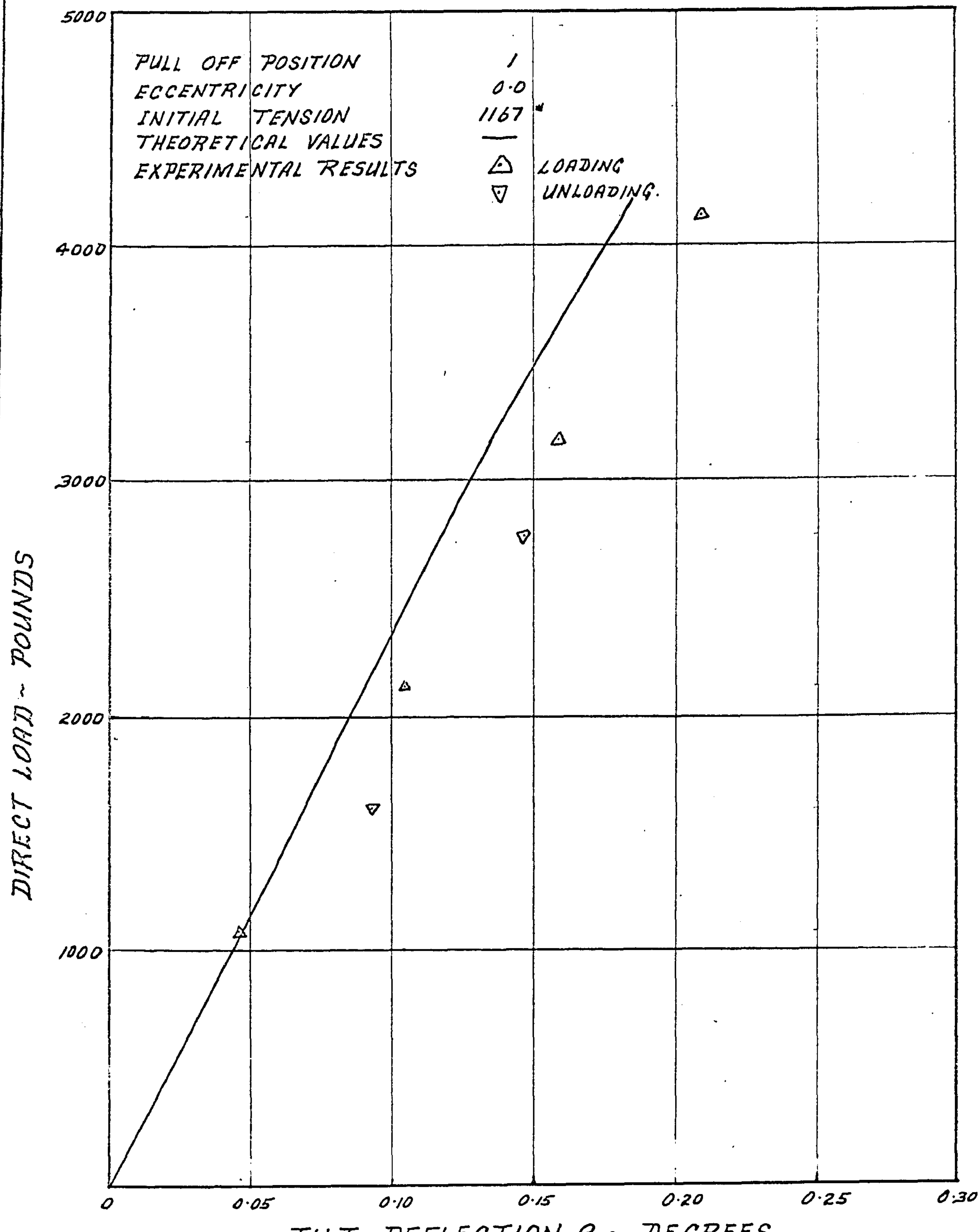
Upon examining the above figures, it can be readily deduced that the initial tension influences the relation between the tilt deflection and the applied direct load in a non-linear form as noted before. This non-linear behaviour is further illustrated in Chapter 6. Moreover, it



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 1

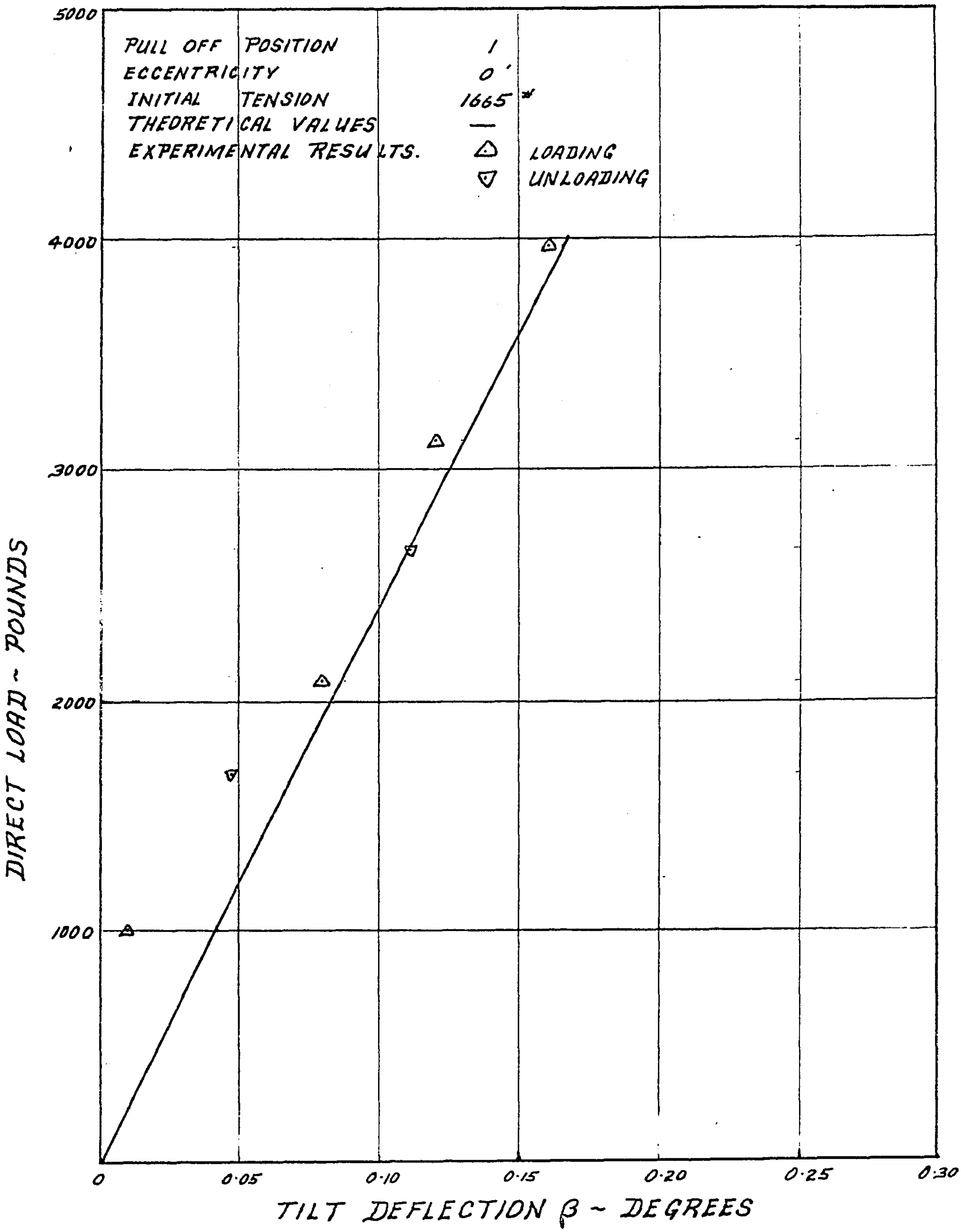
FIGURE 5-22



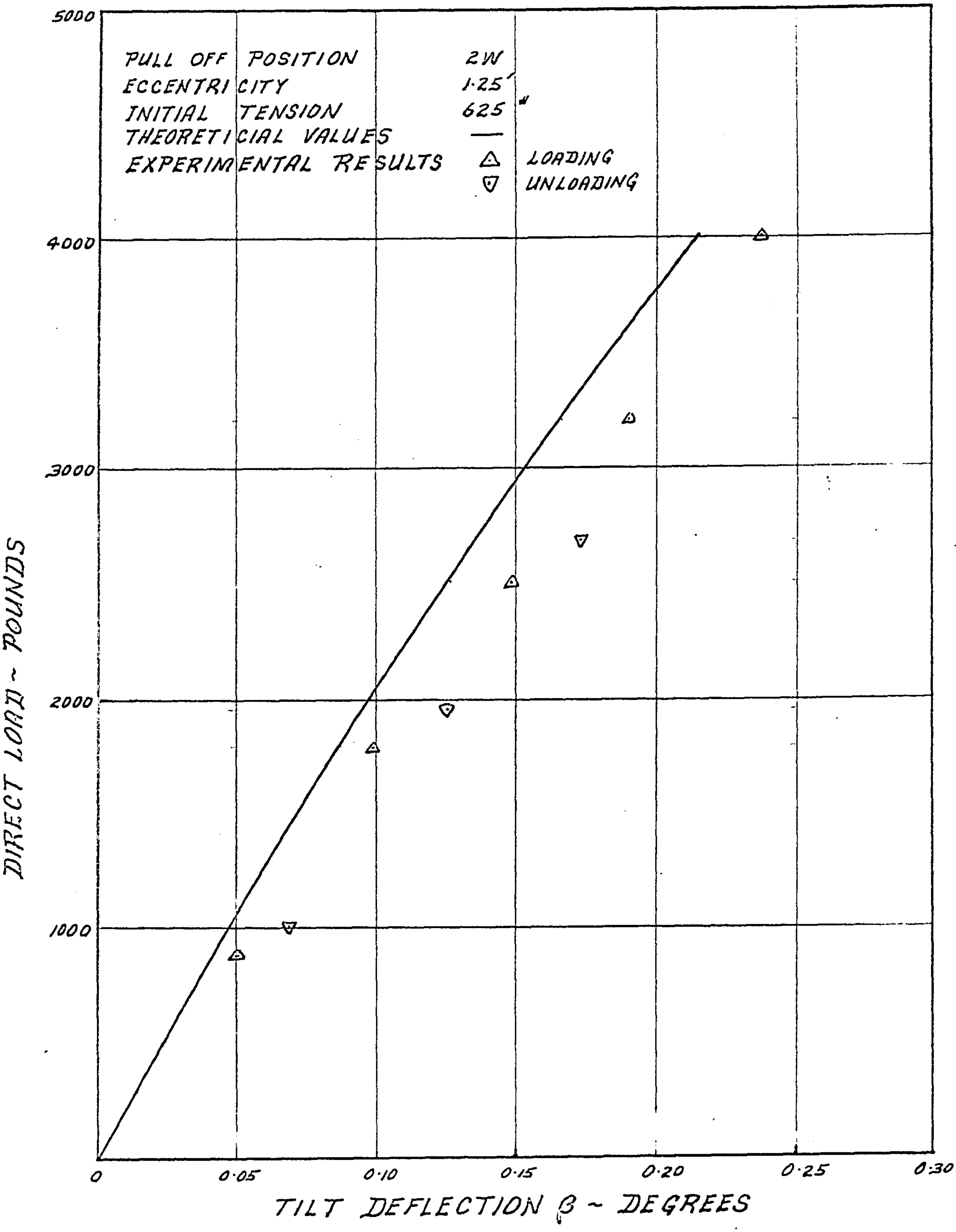
VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 2

FIGURE 5-23



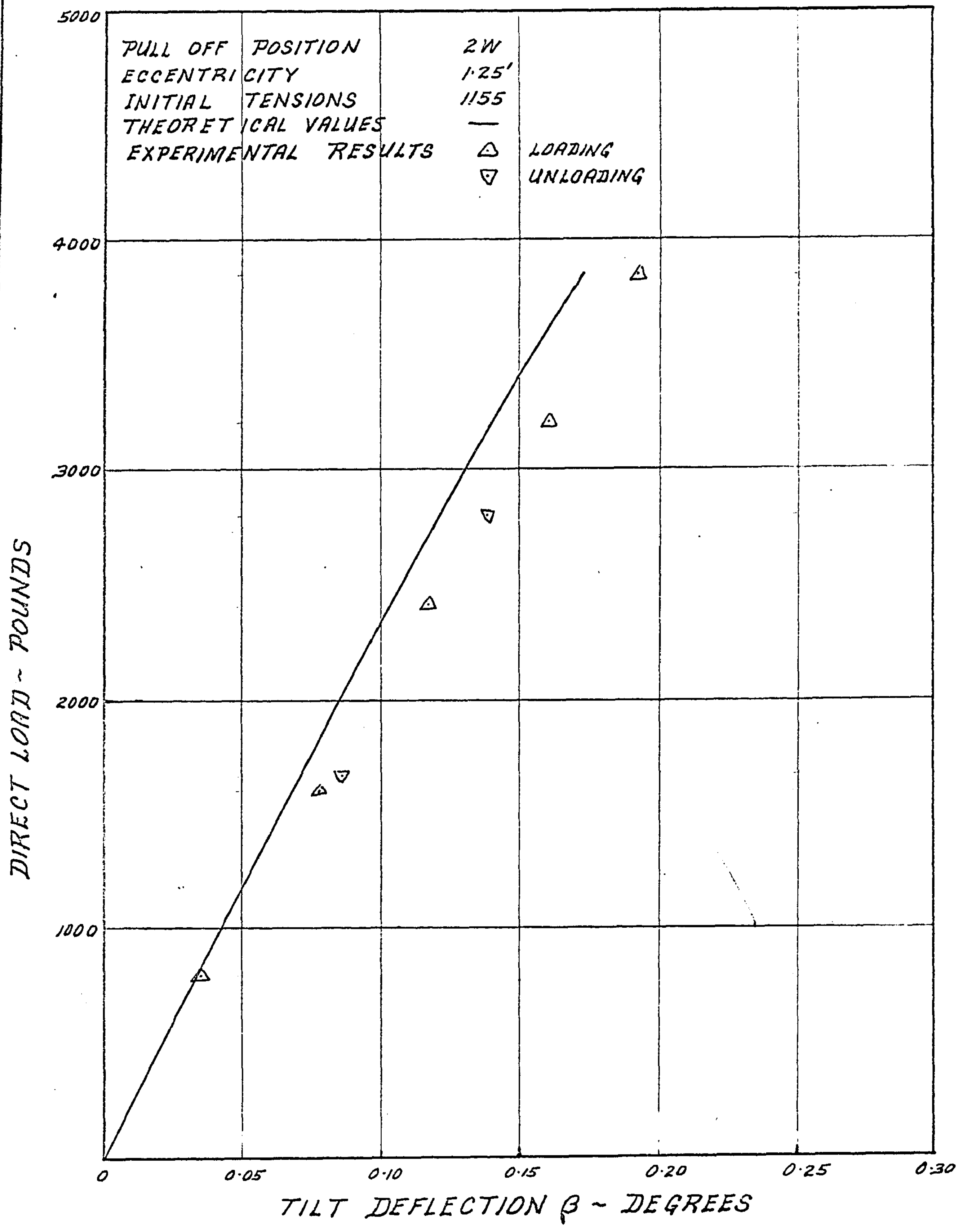
VARIATION OF TILT DEFLECTION WITH DIRECT LOAD
TEST 3
FIGURE 5-24



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 4

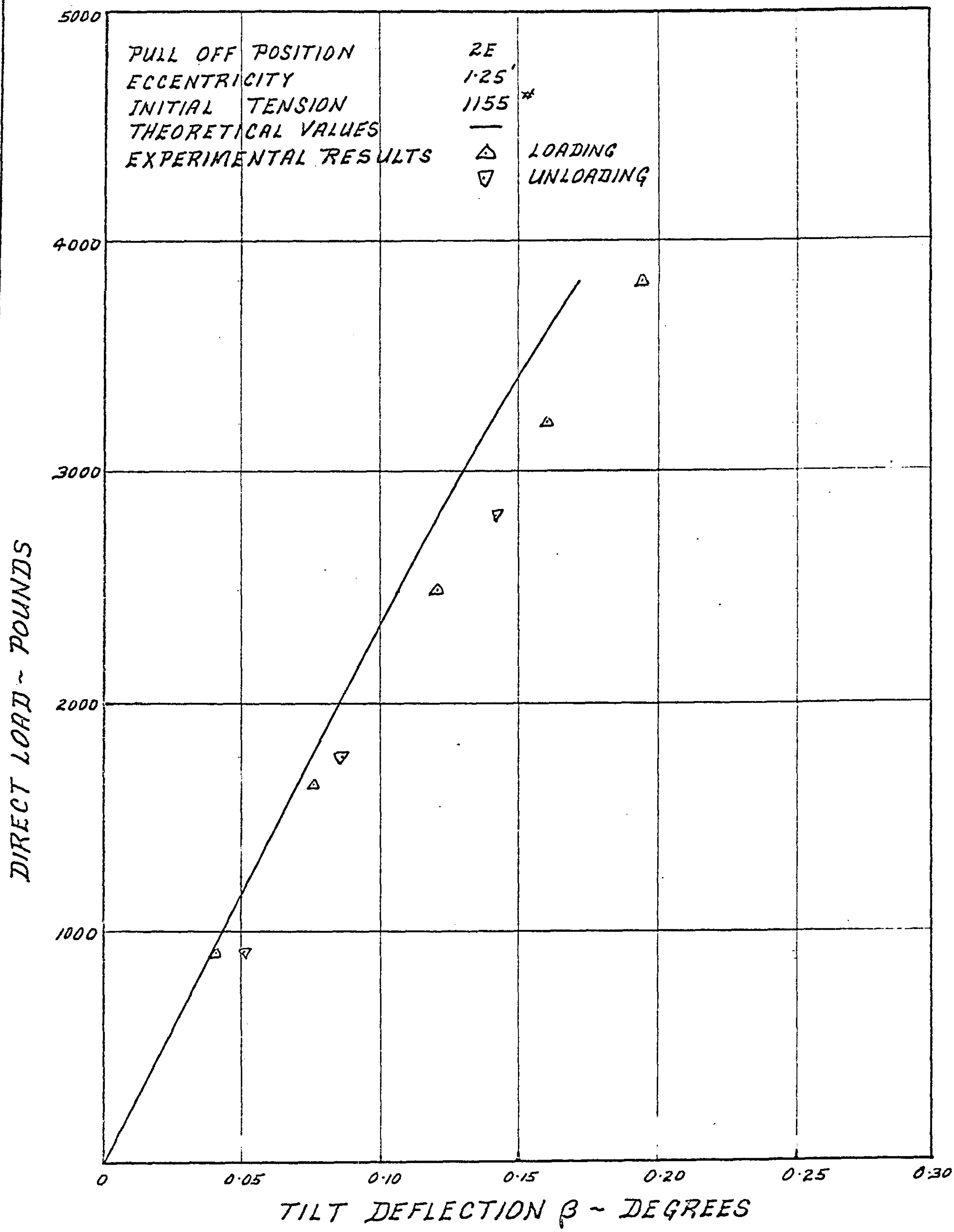
FIGURE 5-25



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 5

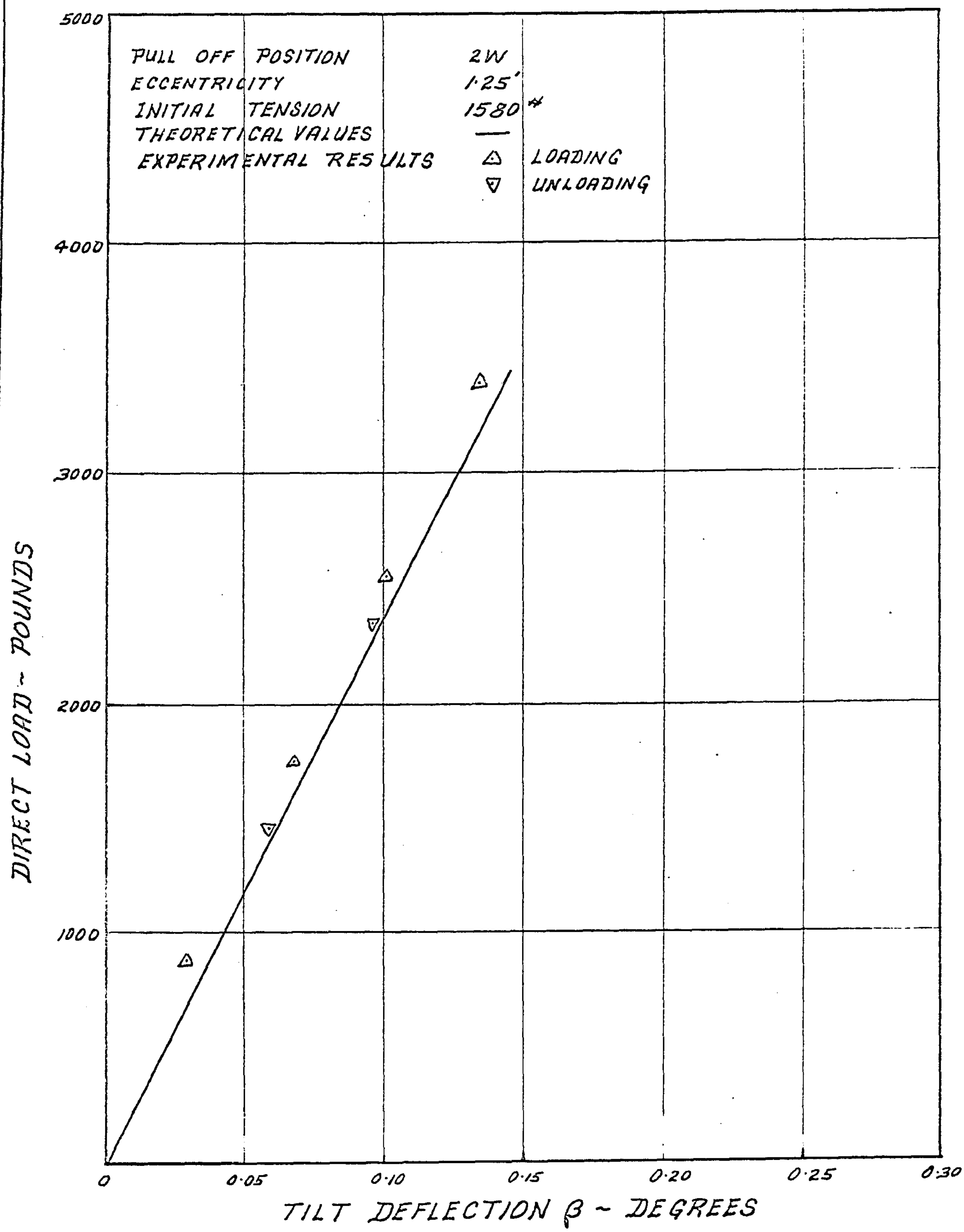
FIGURE 5-26



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 6

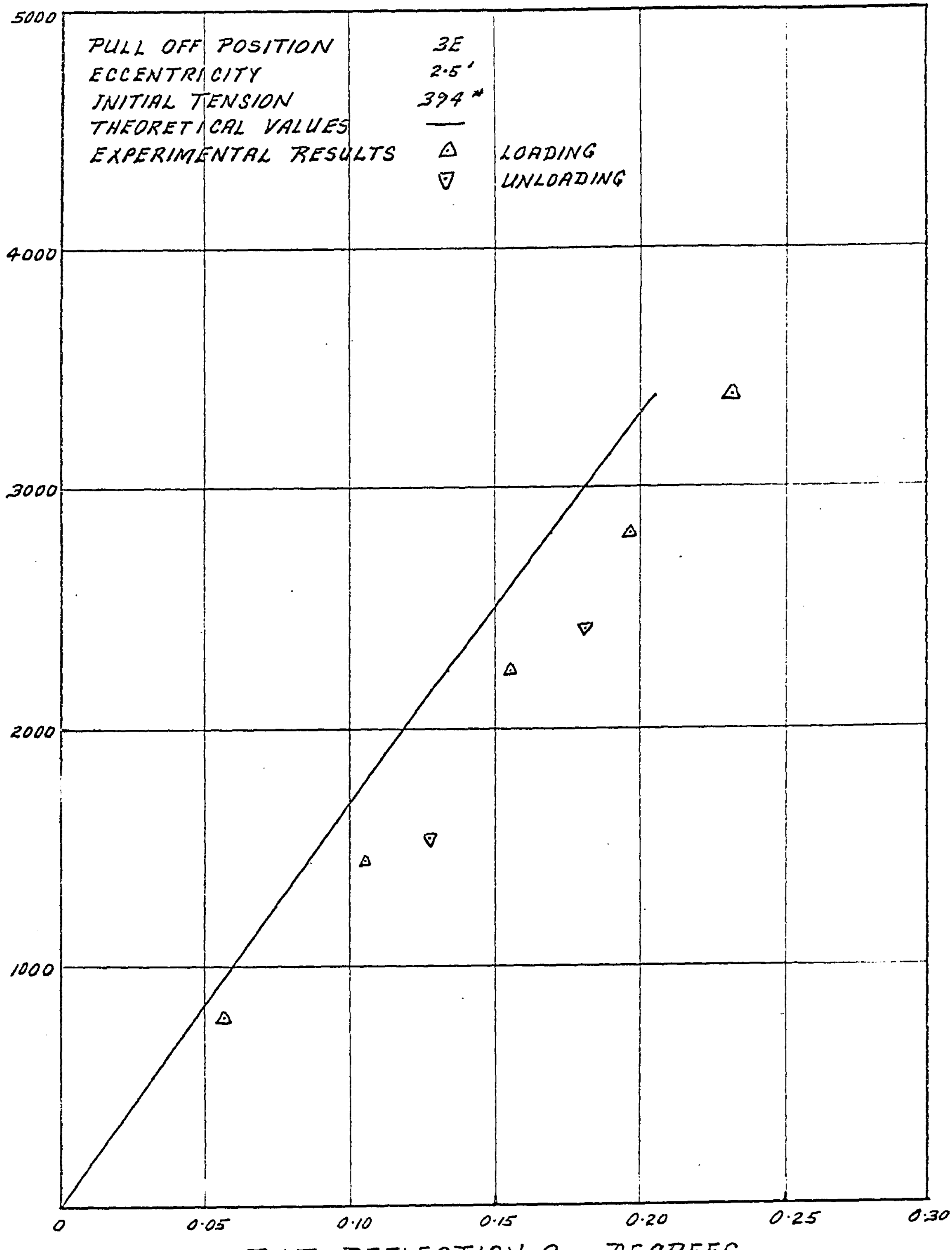
FIGURE 5-27



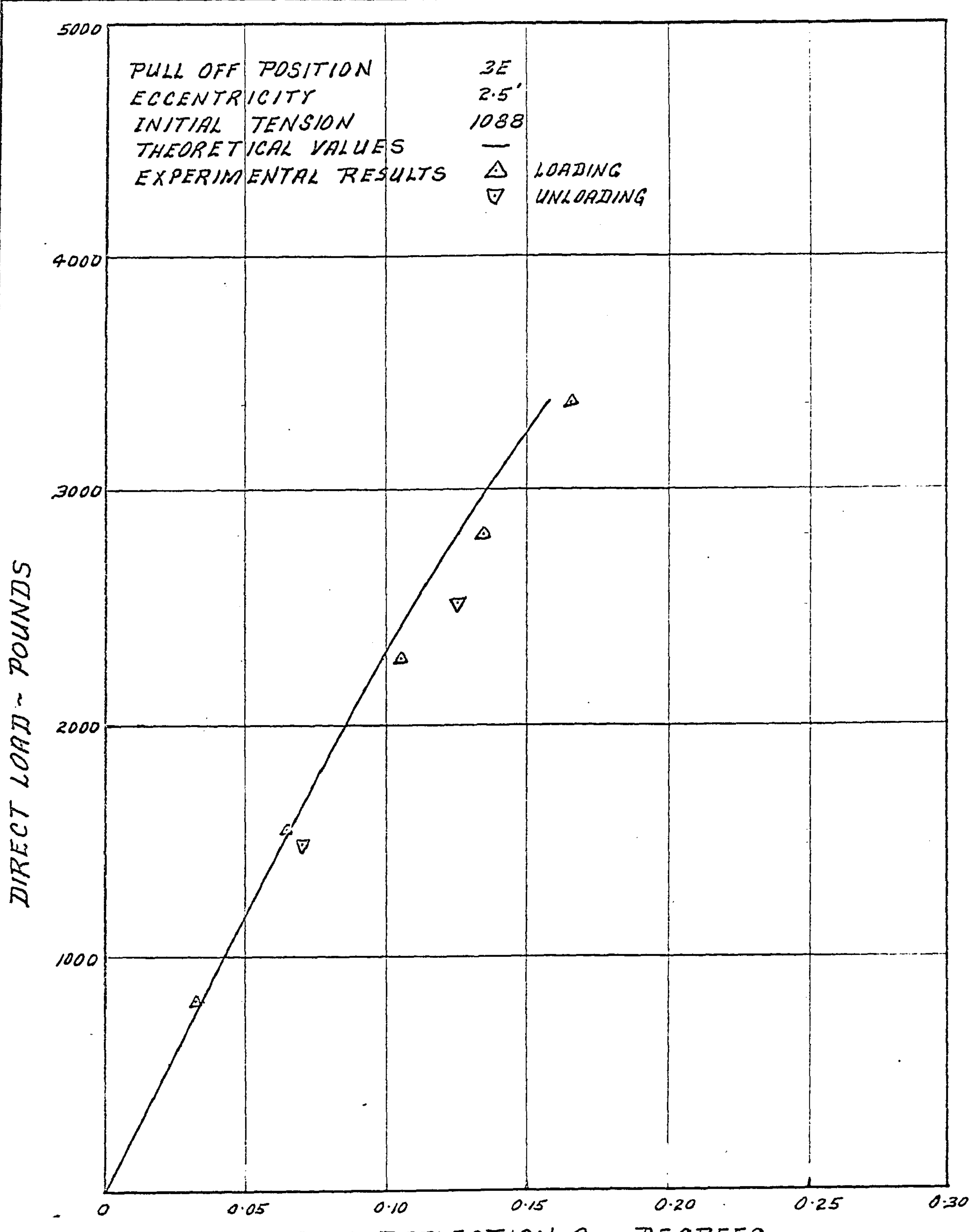
VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST 7

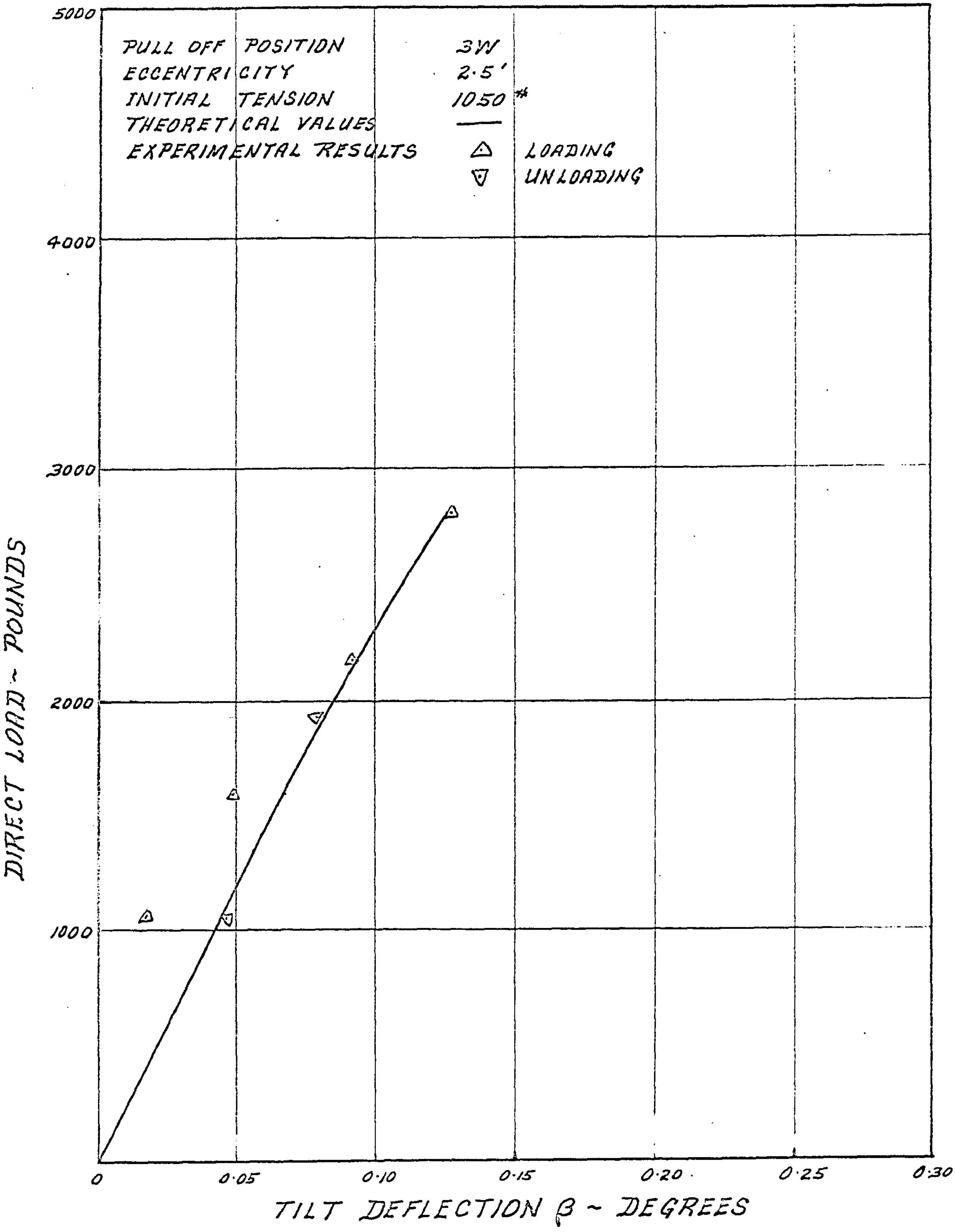
FIGURE 5-28



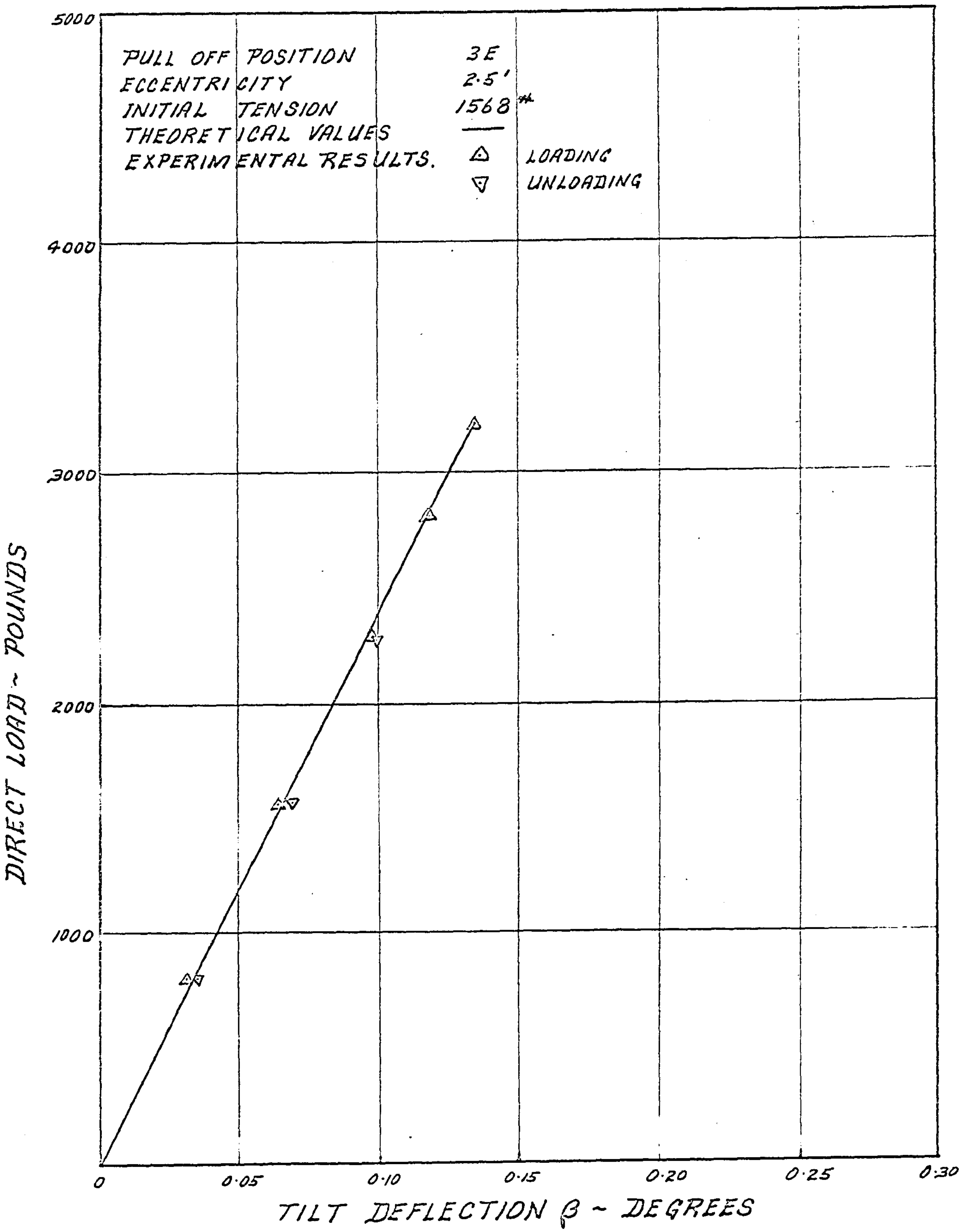
VARIATION OF TILT DEFLECTION WITH DIRECT LOAD
TEST 8
FIGURE 5-29



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD
TEST 9
FIGURE 5-30



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD
TEST 10
FIGURE 5-31



VARIATION OF TILT DEFLECTION WITH DIRECT LOAD

TEST II

FIGURE 5-32

seems that the relationship between tilt deflection and applied direct load is more linear than between twist deflection and applied torque; this is quite evident for the low initial tension conditions.

When the experimental values of the tilt deflections for tests 5 and 6 (Figures 5-26 and 5-27) and for tests 9 and 10 (Figures 5-30 and 5-31) are compared, they are found to be sensibly the same. Thus neither the raised east anchorage, nor the direction of the applied moment seem to have an effect on the tilt deflections.

5.5 Distribution of Resisting Torque

Figures 5-33 and 5-34 show the fractional distribution of the resisting torque among the three pairs of guys for tests 4 to 11. Only the experimental values for G1-G2 are shown plotted, since the results for the other two pairs of guys were erratic. It may be recalled that the final tensions in these guys were below the 10% level of the load-cells and hence the erratic behaviour of the results. See Section 5.2.

The experimental values for the final tensions in guys G1 and G2 substantiate the theoretical values quite well at the higher applied twisting moments. Greater deviations between the experimental and theoretical results occur at the lower values of the twisting moment. This may be due in part to twisting moments being induced in the system during the initial tensioning stage, which, of course, are not taken into

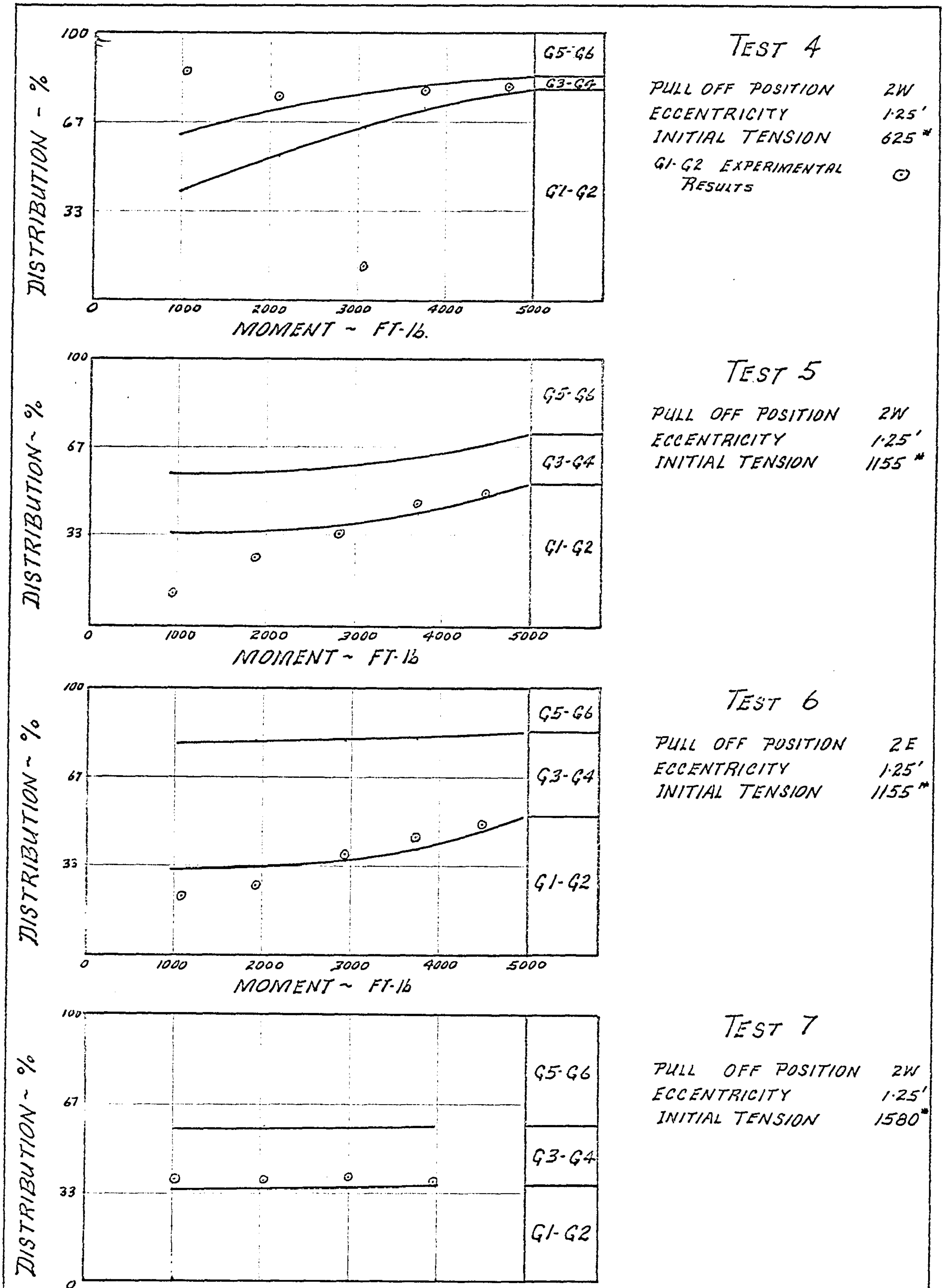

TEST 4
PULL OFF POSITION 2W
ECCENTRICITY 1.25'
INITIAL TENSION 625 #
G1-G2 EXPERIMENTAL RESULTS
DISTRIBUTION - %
MOMENT ~ FT-lb.
G5-G6
G3-G4
G1-G2
100
67
33
0
1000
2000
3000
4000
5000
TEST 5
PULL OFF POSITION 2W
ECCENTRICITY 1.25'
INITIAL TENSION 1155 #
TEST 6
PULL OFF POSITION 2E
ECCENTRICITY 1.25'
INITIAL TENSION 1155 #
TEST 7
PULL OFF POSITION 2W
ECCENTRICITY 1.25'
INITIAL TENSION 1580 #

FIGURE 5-33

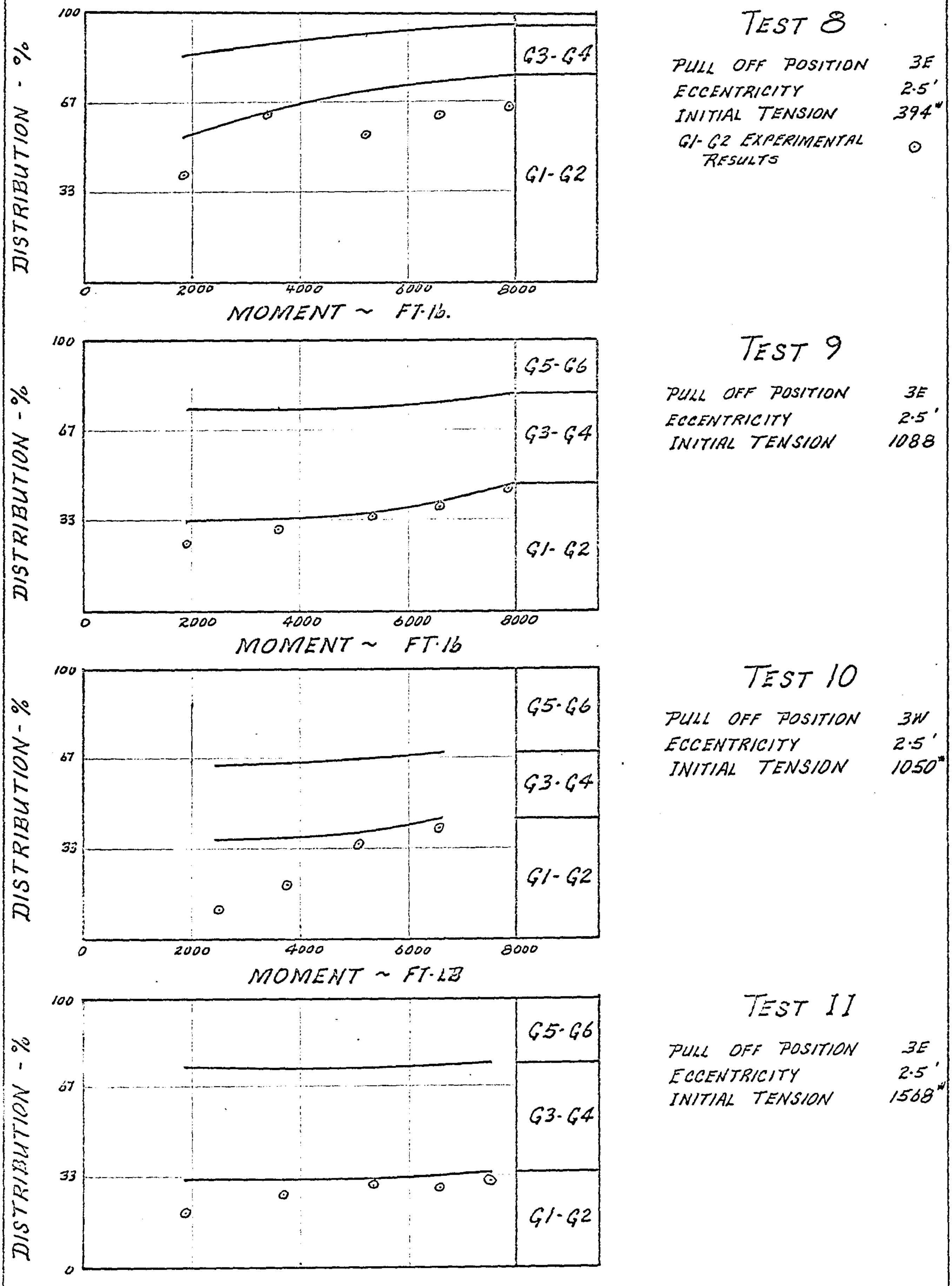

TEST 8
PULL OFF POSITION 3E
ECCENTRICITY 2.5'
INITIAL TENSION 394#
G1-G2 EXPERIMENTAL RESULTS ⊙
G3-G4
G1-G2
DISTRIBUTION - %
MOMENT ~ FT-lb.
TEST 9
PULL OFF POSITION 3E
ECCENTRICITY 2.5'
INITIAL TENSION 1088
G5-G6
G3-G4
G1-G2
DISTRIBUTION - %
MOMENT ~ FT-lb
TEST 10
PULL OFF POSITION 3W
ECCENTRICITY 2.5'
INITIAL TENSION 1050#
G5-G6
G3-G4
G1-G2
DISTRIBUTION - %
MOMENT ~ FT-LB
TEST 11
PULL OFF POSITION 3E
ECCENTRICITY 2.5'
INITIAL TENSION 1568#
G5-G6
G3-G4
G1-G2
DISTRIBUTION - %

FIGURE 5-34

account in analyzing the mathematical model. The effect of such twisting moments on the resisting guy system will be substantial when the system is acted upon by a relatively small applied twisting moment.

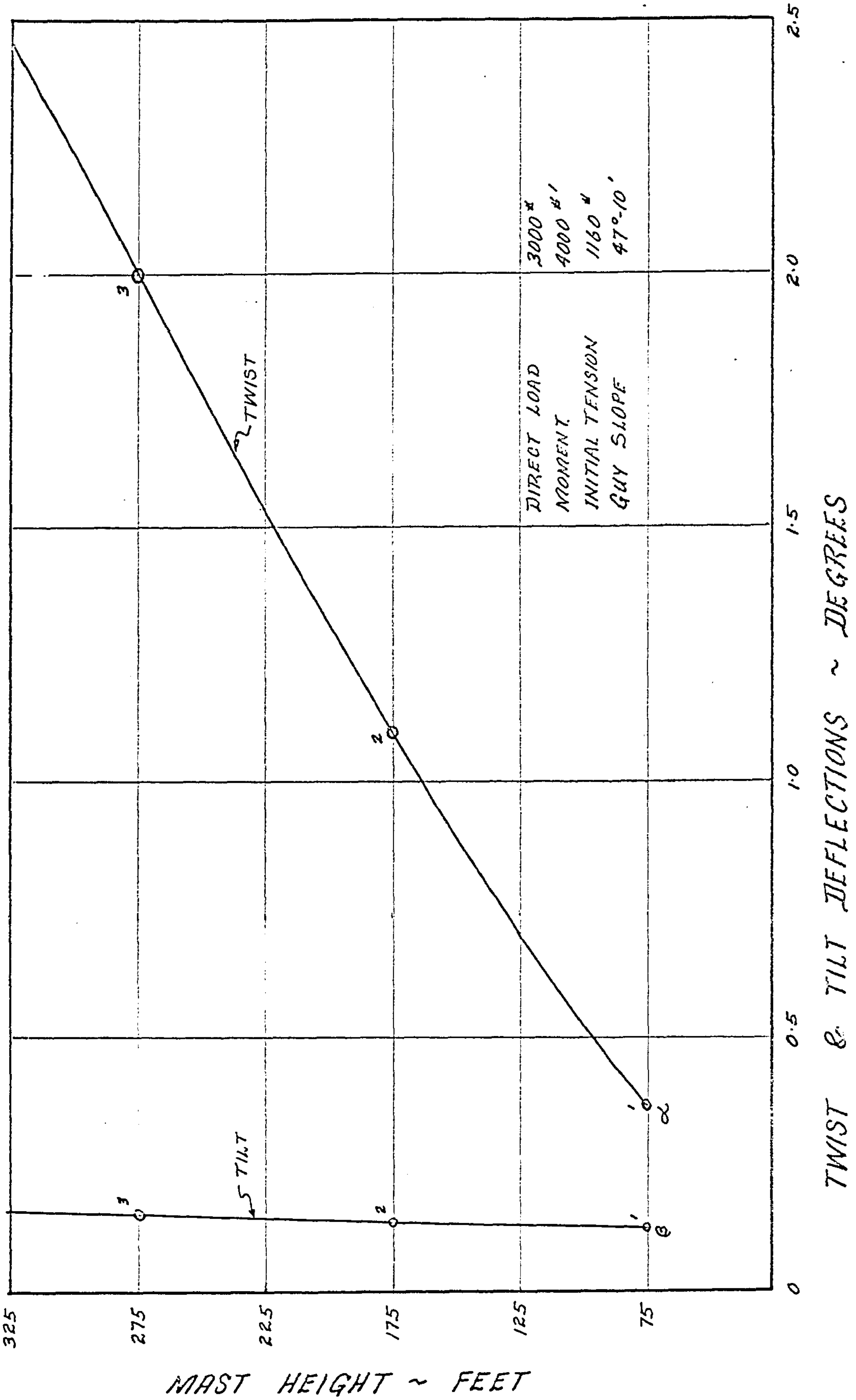
It can be noted that the higher the initial tensions, the more evenly the resisting torque becomes distributed among the three pairs of guys. The side on which the pull-off position was located determined which pair of slack guys provided the greater resistance. Since the pull-off position was located off centre it had a component in the Y direction which resulted in higher tensions in one pair of slack guys than the other pair. The side with the higher tensions offered the greater resistance.

6.0 THE EFFECT OF CHANGES IN THE INDEPENDENT VARIABLES

The experimental and theoretical results of Chapter five were for a mast of specific height, specific guy slope, specified direction of applied load, and three initial guy tension conditions. To evaluate the effect a change in any one of these variables might have on the guy tensions and mast deflections,a series of theoretical studies were run on the computer. The condition common to all of these studies, is one similar to the test mast with the medium initial tension, i.e. 1160 lb. The direct load is taken as 3000 lb. and the applied torque 4000 ft-lb. unless otherwise noted. The results of these studies are shown in Figures 6-1 to 6-5 and Tables 6-1 and 6-2.

6.1 Variation in the Height of the Mast

Figure 6-1 shows the variation in twist and tilt deflections, in degrees, with height of mast. It can be observed that the tilt deflection is negligibly affected by changes in the mast height; whereas the twist deflections are very much influenced by the mast height. Such observations can be explained in the following manner: as the mast height is increased the length of the guys also increases, with a corresponding increase in the elastic stretch of the guys; also the actual deflection of the mast increases as the height



VARIATION OF DEFLECTIONS WITH HEIGHT OF MAST

FIGURE 6-1

MAST HEIGHT	INITIAL TENSION	FINAL GUY TENSION G1	G2	G3	G4	G5	G6	DISTRIBUTION OF RESISTING TORQUE G1-G2	G3-G4	G5-G6
75'	580	1828	2728	133	334	147	275	·732	·163	·104
	870	2064	2731	182	513	221	451	·543	·269	·188
	1160	2335	2829	302	759	338	665	·402	·372	·226
	1450	2618	3052	526	1041	642	922	·353	·419	·228
	1740	2905	3324	798	1328	922	1203	·341	·431	·228
	2030	3194	3608	1082	1617	1209	1490	·337	·435	·229
	2320	3484	3895	1370	1906	1497	1778	·335	·436	·228
175'	580	1881	2852	258	407	262	382	·783	·120	·096
	870	2106	2887	336	586	349	558	·630	·201	·169
	1160	2356	2968	454	797	479	763	·494	·277	·229
	1450	2625	3130	636	1043	674	1002	·407	·328	·264
	1740	2904	3360	874	1313	920	1265	·367	·354	·278
	2030	3189	3623	1141	1594	1191	1544	·350	·365	·284
	2320	3476	3901	1421	1880	1472	1828	·343	·370	·287
275'	580	1901	2936	331	443	332	427	·833	·090	·077
	870	2137	2997	433	637	440	619	·691	·164	·145
	1160	2383	3082	555	843	568	824	·562	·232	·206
	1450	2643	3219	720	1075	739	1051	·464	·285	·251
	1740	2915	3416	933	1330	958	1302	·403	·319	·277
	2030	3194	3656	1181	1601	1210	1571	·372	·338	·290
	2320	3479	3920	1449	1881	1480	1849	·356	·347	·297

VARIATION OF GUY TENSIONS WITH INITIAL TENSIONS & HEIGHTS

TABLE 6-1

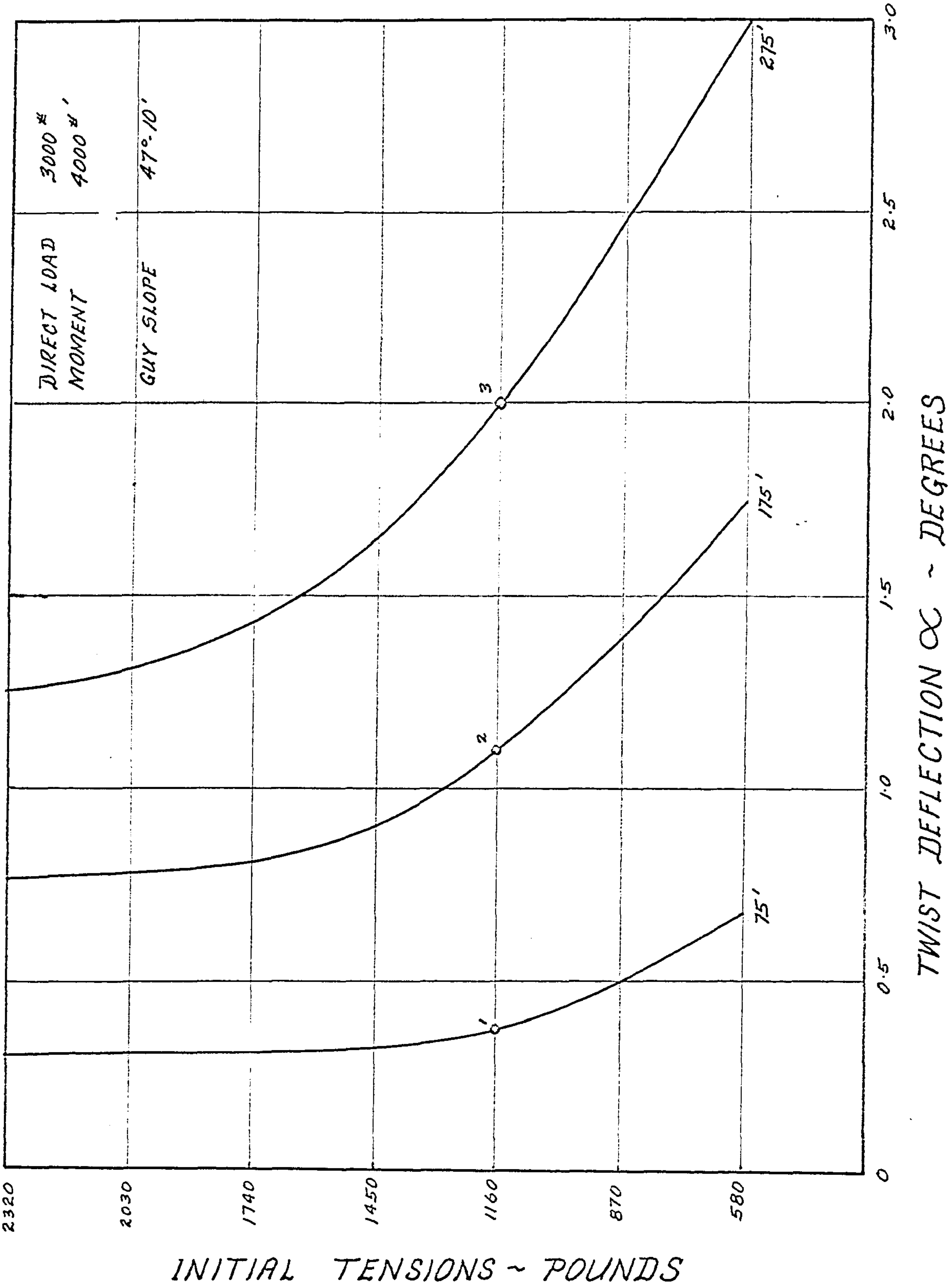
increases. However, when the angle of tilt is calculated the increased mast height offsets the increased deflection and a nearly constant value results. Regarding the twist deflections, the length of the outrigger arms remains constant throughout so that the increased length of guy, and hence deflection, results in an increased angle of rotation.

Table 6-1 gives the values of the guy tensions for three of the heights investigated. For a given initial tension, the guys with the largest tensions, exhibit less than 10% increase in tension as the height is increased; while the slack guys exhibit a greater increase, the magnitude depending on the value of the initial tension. These investigations are run to correspond to the investigations of the test tower, hence the effect of wind on the guys for the final condition has been neglected. If such an effect was included, as required in an actual design, a greater variation in the magnitude of the tensions would probably result.

6.2 Variation in the Initial Tensions

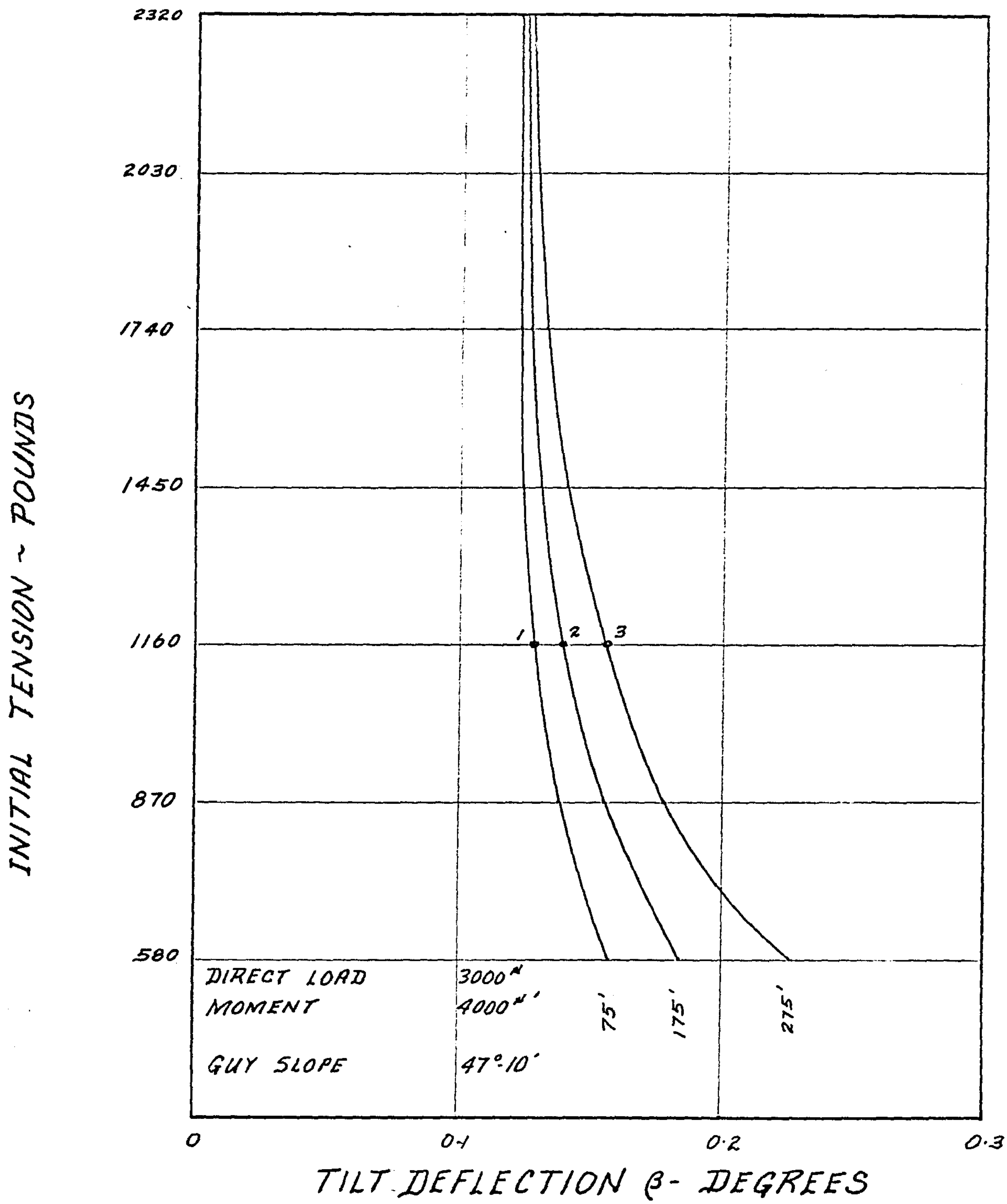
Figure 6-2 shows the variation in the twist deflections, (in degrees) with initial tension, for three different heights of mast. Points 1, 2 and 3, correspond to similar conditions shown in Figures 6-1 to 6-4.

Depending on the height of the mast, there is a point beyond which increasing the initial tension has no significant effect in reducing the twist deflection. However at the lower



VARIATION OF TWIST DEFLECTIONS WITH INITIAL TENSION

FIGURE 6-2



VARIATION OF TILT DEFLECTION WITH INITIAL TENSION

FIGURE 6-3

initial guy tensions, the twist deflections change rapidly, and more so with an increase in mast height.

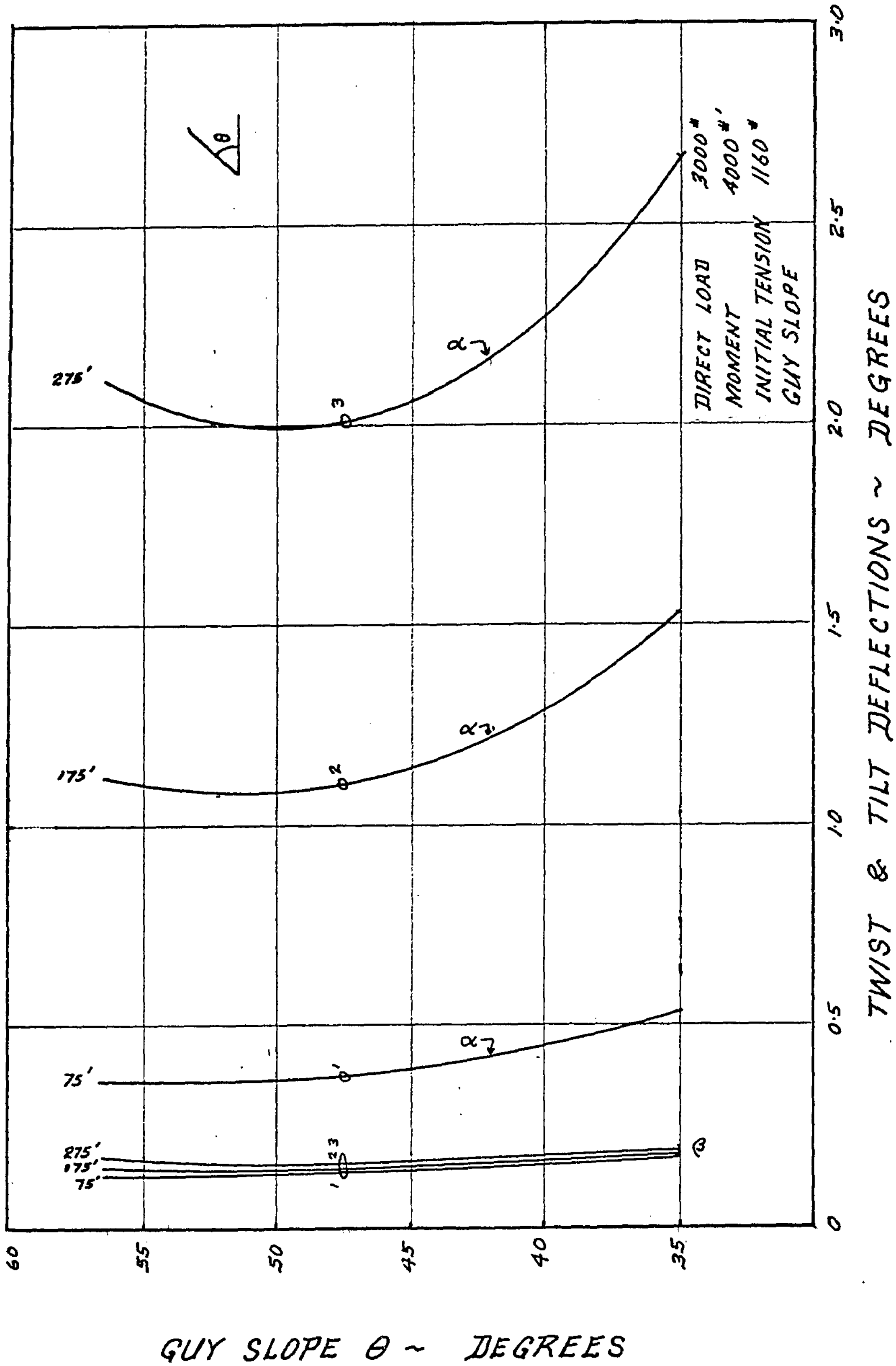
Table 6-1 shows the variation of the final guy tensions with the initial guy tension for three mast heights. Also shown are the fractional distribution of the resisting torque with respect to the initial tensions. It can be noted that the initial tension influences the distribution of the resisting torque. With an increase in mast height and initial tension the fractional distribution of resisting torque among the three pair of guys tend to become nearly the same.

Figure 6-3 shows the variation of the tilt deflection in degrees with the initial tension. These curves follow a pattern of variation similar to that of the twist deflections shown in Figure 6-2.

6.3 Variation in the Guy Slope

Figure 6-4 shows the variations in the twist and tilt deflections for different guy slopes for three mast heights.

The tilt deflections do not exhibit very much variation over the range of guy slopes usually found on guyed masts. However the twist deflections do show a considerable variation with the slope of the guy, particularly as the mast height increases. It appears that the optimum guy slope for minimum tilt and twist deflections, is when the chord of the guys makes an angle (θ) with the horizontal of 50°.



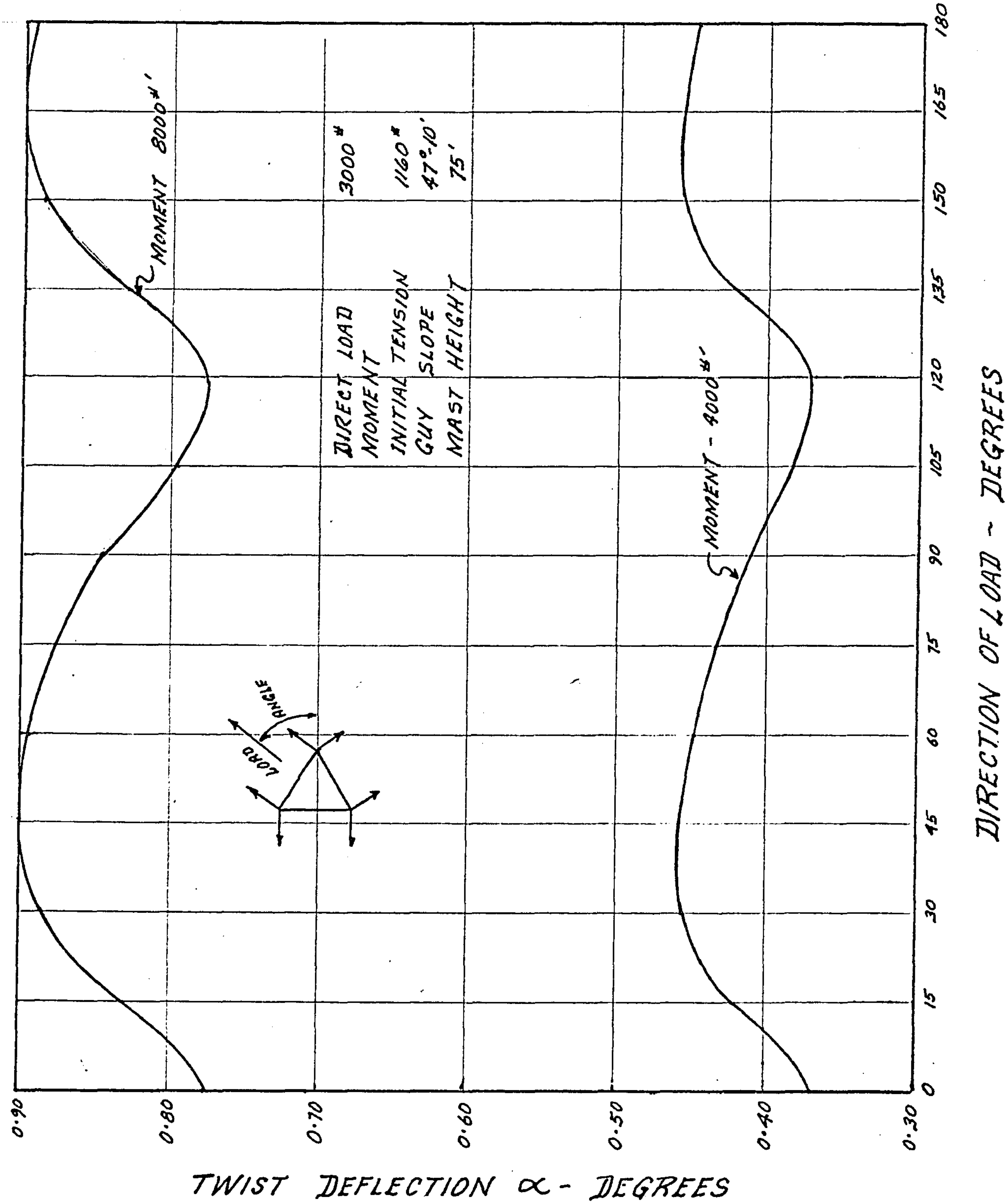
VARIATION OF DEFLECTIONS WITH SLOPE OF THE GUY

FIGURE 6-4

6.4 Variation in the Direction of the Load

Figure 6-5 shows the variation in the twist deflections (degrees) as the direction of the applied load is changed from 0^o to 180^o, for two different values of applied moment, which remains constant as the direct load is rotated.

It is seen that the deflection curves for the two moments are similar in shape, the larger moment curve having a larger amplitude. The curves repeat themselves every 120^0 which is the angle between the normals to the faces of the triangulated mast. However the curve is not symmeterical about the 60^o direction or its multiples. This can be explained as follows: since each pair of guys meet at a common anchorage point, these guys, as noted before, make a small angle γ with the normal to the mast. Therefore one of the guys of the pair will carry a greater tension from the direct load than the other one except when the external load is applied directly in line with the normal to one of the faces of the mast. The effect of the applied torque is to increase the tension in one guy and reduce the tension in the other guy of the pair. When the applied torque in conjunction with the direct load, is in a direction such that the larger tension from the direct load is augmented by the increased tension from the torque, the deflection will be greater than when the direction of the moment is in the opposite direction causing a decrease in the larger tension, and a reduced deflection. Thus the shape of the twist deflection curve is



VARIATION OF TWIST DEFLECTION WITH DIRECTION OF LOAD

FIGURE 6-5

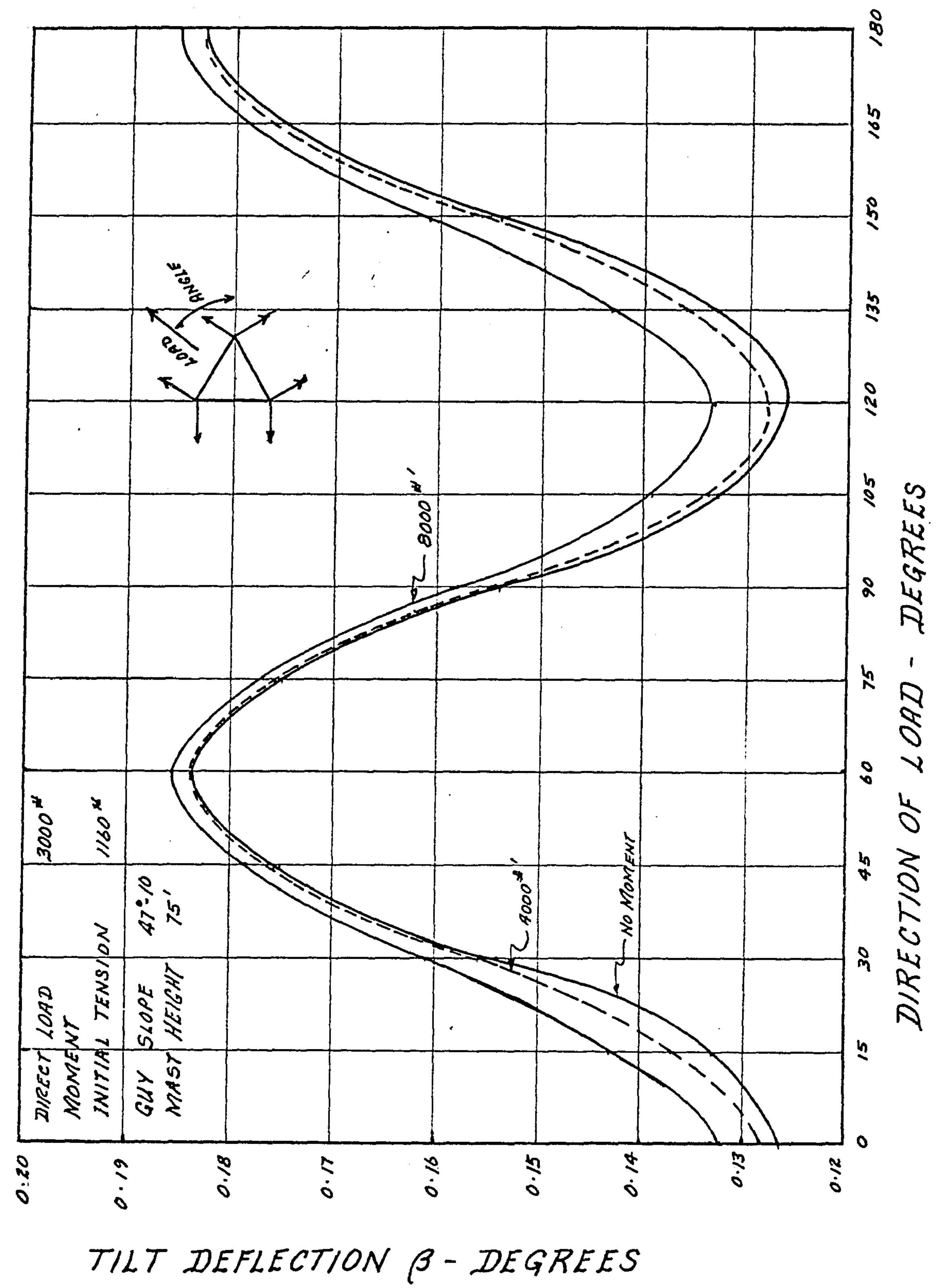
dependant on the direction of the applied torque.

Figure 6-6 shows the variation of the tilt deflections in degrees as the direction of the applied load is changed from 0^{o} to 180^{o}, for three different twisting moment conditions. The curves again repeat every 120^{o}. The curve for the no twisting moment condition is seen to be symmetrical about the 60^{o} direction and its multiples. The curves for the other two twisting moment conditions are asymmetrical which is caused by the direction of the applied torque as explained in the last paragraph for the twist deflections.

It can be noted from Figure 6-6 that the increase in the tilt deflection with the direction of the load can be as much as 45%, which is very significant.

Table 6-2 gives the guy tensions and the fractional distribution of resisting torque for various directions of the applied direct load for three different values of applied twisting moment.

The maximum guy tension occurs when the direct load makes an angle of 30^{o} with the normal to the face of the mast, e.g. final tensions for G2 and G6 at load angles of 30^{o} and 150^{o} respectively. The maximum resistance to the applied twisting moment, contributed by one pair of guys occurs when the direct load is parallel to the normal to the face of the mast and in a direction such that two pairs of guys are resisting this direct load. Also it can be noted that this maximum resistance to the applied twisting moment



VARIATION OF TILT DEFLECTION WITH DIRECTION OF LOAD

FIGURE 6-6

APPLIED TORQUE	ANGLE OF LOAD	FINAL GUY TENSIONS						DISTRIBUTION OF RESISTING TORQUE		
		G1	G2	G3	G4	G5	G6	G1-G2	G3-G4	G5-G6
ZERO	0	2564	2564	459	563	563	459	–	–	–
	15	2523	2602	248	295	946	820	–	–	–
	30	2472	2613	166	179	1432	1280	–	–	–
	45	2336	2515	138	142	1904	1721	–	–	–
	60	2085	2278	132	132	2278	2085	–	–	–
	75	1721	1904	142	138	2517	2338	–	–	–
	90	1277	1431	179	166	2612	2471	–	–	–
	105	821	946	295	248	2602	2523	–	–	–
	120	459	563	562	459	2564	2564	–	–	–
	135	249	296	946	820	2521	2600	–	–	–
	150	166	179	1432	1278	2472	2613	–	–	–
	165	138	142	1904	1721	2336	2518	–	–	–
	180	132	132	2277	2084	2084	2277	–	–	–
4000#'	0	2335	2828	302	759	388	665	.401	.372	.225
	15	2283	2903	182	413	713	1093	.504	.187	.309
	30	2200	2923	139	228	1149	1565	.588	.073	.339
	45	2052	2825	121	169	1603	2011	.629	.039	.332
	60	1798	2587	117	154	1975	2378	.642	.030	.328
	75	1437	2212	124	163	2215	2630	.631	.032	.337
	90	1003	1731	147	208	2319	2759	.593	.050	.357
	105	585	1215	211	354	2341	2797	.512	.116	.371
	120	302	759	389	665	2336	2829	.372	.225	.402
	135	183	414	714	1093	2282	2900	.188	.308	.503
	150	138	228	1150	1566	2199	2923	.073	.339	.588
	165	121	168	1605	2013	2054	2828	.038	.332	.630
	180	117	153	1974	2377	1798	2587	.030	.328	.642
8000#'	0	2120	3162	207	976	258	904	.424	.313	.263
	15	2063	3235	145	554	510	139	.477	.166	.357
	30	1950	3247	120	306	892	1865	.528	.076	.396
	45	1791	3143	108	210	1317	2309	.555	.042	.403
	60	1520	2904	105	186	1681	2675	.563	.033	.404
	75	1163	2527	110	200	1925	2928	.555	.038	.408
	90	751	2045	126	276	2048	3061	.527	.061	.412
	105	392	1513	162	495	2109	3113	.456	.136	.408
	120	207	977	257	903	2121	3163	.313	.263	.424
	135	145	555	510	1387	2061	3232	.167	.357	.476
	150	120	306	894	1866	1948	3247	.076	.396	.528
	165	108	210	1319	2310	1781	3146	.041	.403	.555
	180	105	186	1680	2674	1520	2903	.033	.404	.563

VARIATION OF GUY TENSIONS WITH DIRECTION OF LOAD AND APPLIED TORQUE

TABLE 6-2

does not coincide with the condition of maximum guy tension.

It seems that as the applied twisting moment increases, the maximum fractional distribution of torque resisted by a pair of guys decreases.

7.0 CONCLUSIONS

From the work reported herein the following conclusions can be made: For taut cables, as found on guyed masts, the parabolic and catenary equations for guy cables are identical.

Using an electronic digital computer, the indeterminate non-linear condition of six guys at one level of a guyed mast resisting both direct load and an applied twisting moment can be readily solved using Newton's Method in an iterative process.

Experimental tests performed on a full scale prototype guyed mast verified the theory developed. Comparing the experimental results to the theoretical results it can be stated that:

1. Prestressing of the cables is necessary to establish a constant modulus of elasticity, and to be able to predict the deflections accurately.

2. A pair of guys of the system resist the applied twisting moment by means of an increase in tension in one of the guys with a similar decrease in tension in the other guy.

3. The theoretical results for the maximum final guy tensions are conservative when compared to the experimental values.

4. The guy system is not perfectly elastic, and some

residual deflection remains after the applied load has been removed.

5. The twist and tilt deflections decrease in a non-linear manner as the initial guy tensions are increased.

6. While the loaded guys of the system provide the greatest resistance to the applied twisting moment, the slack guys are also effective in providing resistance. The actual distribution of the resistance between the loaded and slack guys is dependent on the initial guy tensions and the direction of the applied load.

7. The condition of a guy anchorage at a slightly different elevation than the base of the mast has no significant effect on the tilt deflections and only a minor effect on the twist deflections.

From the theoretical results obtained by varying some of the independent variables, it was found that:

8. A change in mast height has only a minor effect on the tilt deflections, but a significant effect on the twist deflections.

9. For a given initial tension, a variation in mast height produces a change in the maximum final guy tensions of not more than 10%.

10. The distribution of the resisting torque among the guys is influenced by the height of the mast and the initial tensions of the guys.

11. The twist and tilt deflections exhibit a non-linear

relationship, with variations in the initial guy tensions, which increases as the mast height increases.

12. The slope of the guy does not seem to have a significant effect on the tilt deflections; however, it has a considerable influence on the twist deflections, exhibiting a non-linear relationship.

13. The optimum guy slope for minimum twist and tilt deflections is when the chord of the guy makes an angle with the horizontal of 50°.

14. The curve for the variation of twist deflections with direction of applied load is asymmetrical in shape, and is dependant on the direction of the applied twisting moment.

15. The tilt deflections can increase as much as 45% with a change in the direction of the applied load.

16. The maximum guy tensions occur when the direction of the load makes an angle of 30° with the normal to the face of the mast.

17. The maximum tilt and twist deflections do not occur simultaneously for any direction of the applied load.

18. As the applied twisting moment increases, the maximum fractional distribution of torque resisted by a pair of guys decreases.

This study should prove useful to the designer by providing a guide to the optimum arrangement of the system to resist the applied loads, and by indicating which conditions should be investigated for the maximum design values.

The general computer programme developed herein can be readily used to investigate the design of any mast with any arbitrary independant variables.

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APPENDIX A

WIND LOADS ON GUY CABLES

Wind pressure on guys have been dealt with by several investigators (4, 6, 7, 11). With the aid of such investigations, a relatively simple approach to this problem is developed below, which is suitable to the theoretical study presented herein.

The general expression relating pressure to wind velocity is

$$P = 0.00256 \ C_n R V^2 \qquad \text{A-1}$$

where P = pressure in p.s f.

C_n = a shape coefficient for pressure normal to a surface

V = wind velocity in M.P.H.

R = a factor relating the direction of the wind to the surface.

The National Building Code of Canada recommends the formula

$$P = 0.0027 \ C_n R V^2 \qquad \text{A-2}$$

to allow for the colder denser air which usually prevails in this country at maximum design conditions.

Table A-1

Values of the Pressure Coefficient C_n

N.R.C. Report Mer.-1	1.245	
Cohen and Perrin	1.25	
N.B.C. (Canada) Suppl # 3	When $(.67\ d\sqrt{q}) < 1.5$	When $(.67\ d\sqrt{q}) > 1.5$
Smooth Wires, Rods, Pipes	1.2	0.5
Moderately Smooth Wires & Rods	1.2	0.7
Fine Wire Cables	1.2	0.9
Thick Wire Cables	1.3	1.1

d = Diameter of Cable $q = 0.0027\ V^2$

Table A-1 lists a number of values, from different sources, for values of C_n. A value of 1.25 is the best average of the group for the range of guy sizes usually encountered. If the diameter of the guy or if the diameter of the guy with ice exceeds about 2½" it would appear (4) that the value of C_n could be reduced. However this reduction should be used with caution and only after careful consideration of the problem.

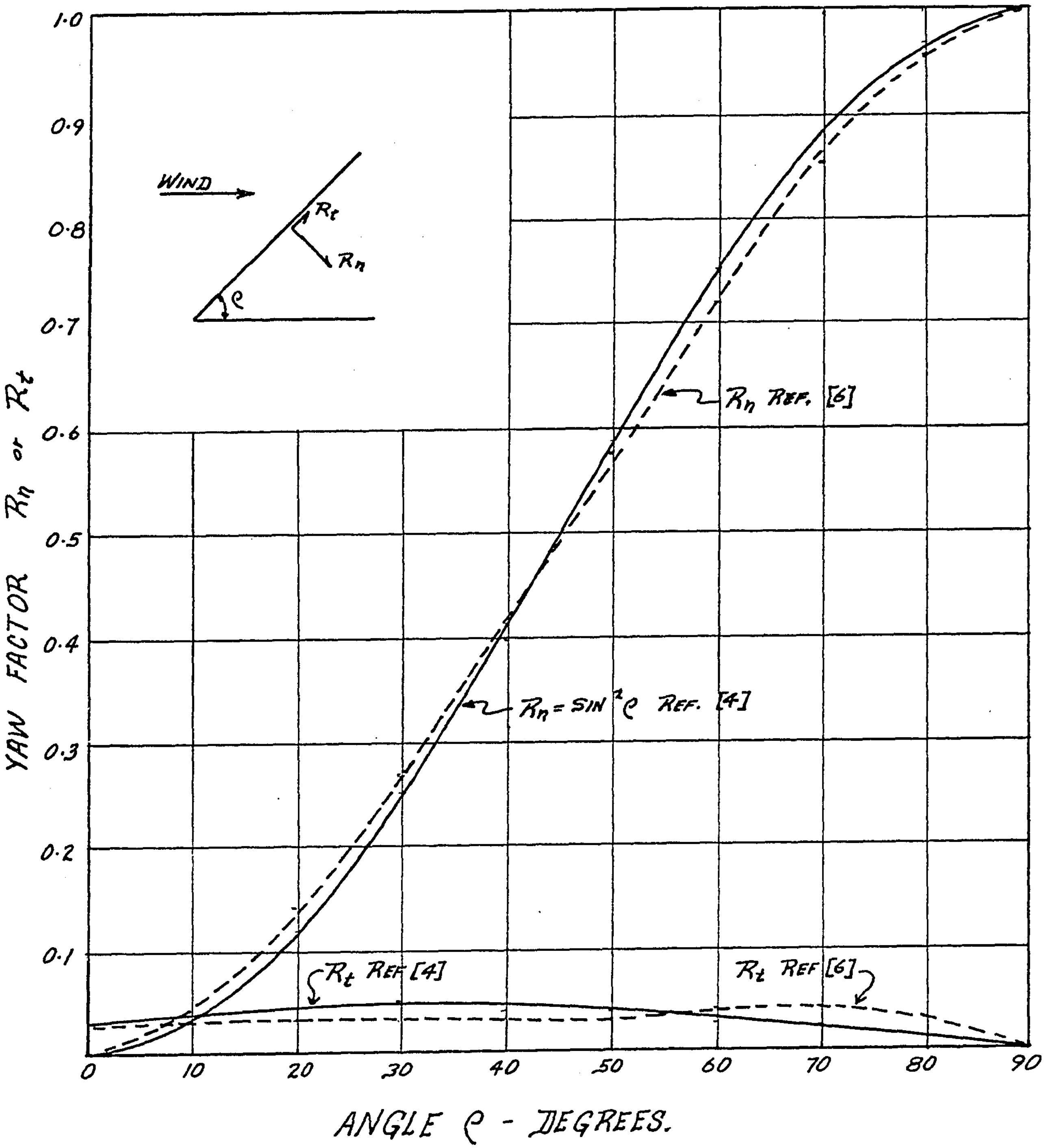
Therefore Equation A-2 can be written

$$P = 0.00338\ RV^2 \qquad \text{A-3}$$

C.S.A. specification S37-1965 gives

$$P = 0.004\ V^2 \qquad \text{A-4}$$

for the pressure-velocity relationship on flat surfaces of



VARIATION OF PRESSURE COEFFICIENT WITH GUY SLOPE

FIGURE A-1

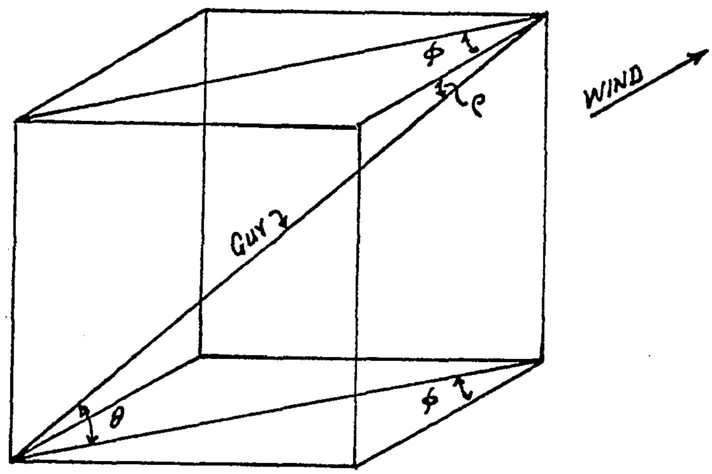
masts and towers. 67% of this value is to be used for cylindrical surfaces. Comparing equations A-3 and A-4 the ratio is 85%. Thus a higher pressure acts on the guys than on the cylindrical surfaces of members of the shaft truss. This difference should be kept in mind when calculating wind load on guys.

When the surface under consideration is inclined to the direction of the wind a reduction (Rn) in the pressure acting normal to the surface occurs. The N.R.C. Report (4) gives the relationship shown in Figure A-1. This relationship is seen to agree very closely with the values given by Cohen and Perrin (6). $R_n = \sin^2 \rho$, given by (4) is in preference to that given by (6) since ρ can be readily found from the guy geometry, and is sufficiently accurate since the average pressure is used over the entire length of the guy. The tangential (Rt) component is small and is neglected.

If the direction of the wind is in the plane of the guy then $\rho = \theta$ where θ is the angle which the guy makes with the horizontal. If the direction of the wind is not in the plane of the guy then the relationship is

$$\cos \rho = \cos \theta \cdot \cos \phi \qquad \text{A-5}$$

where ϕ is the angle between the direction of the wind and the plane of the guy. This is illustrated in Figure A-2.



$$\cos \rho = \cos \theta \cdot \cos \phi$$

Figure A-2 Relationship Between Guyslope and Wind Direction

The effect of wind on the guys must be added to the reaction from wind on the shaft in order to obtain the total reaction to be resisted by the guys. Since the wind load is normal to the chord, only the horizontal component is resisted by the guy, and the vertical component by the shaft. The horizontal component acting in the direction of the wind is $W_w \sin \rho$, and the horizontal reaction at the guy attachment point is

$$H_w = W_w \cdot \sin \rho \cdot \frac{C}{2} \cdot N \qquad \text{A-6}$$

where

W_w = the wind load acting normal to the guy in pounds per foot

C = the chord length of the guy.

N = the number of guys being acted upon.

The load resulting from the wind pressure must be combined with the component of the guy weight acting normal to the chord. If the direction of the wind is in the plane of the guy, then for a windward guy the wind load (W_w) is added directly to the gravity load (W_g), and for a leeward guy the wind load is subtracted from the gravity load. This is illustrated in Figure A-3.

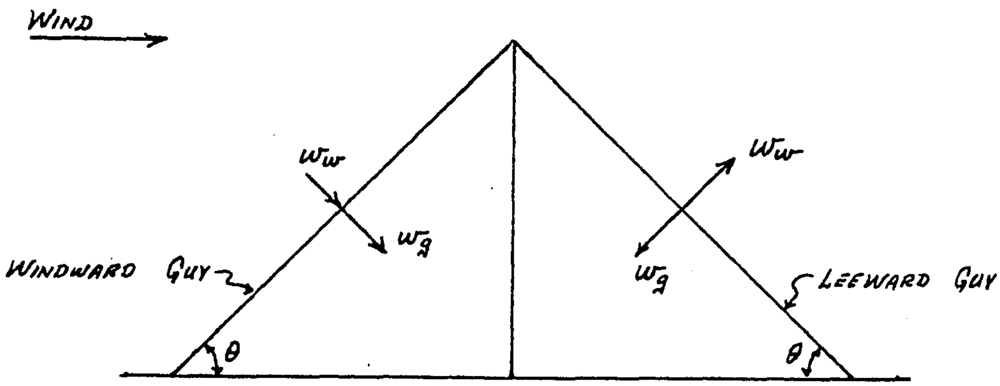


Figure A-3 Wind Load - Weight Load Relationship

When the direction of the wind is not in the plane of the guy the resultant of the two loads must be found. If σ is the angle between the gravity load and the wind load then

$$W_R = \sqrt{(w_g \pm w_w \cos\sigma)^2 + (W_w \cdot \sin\sigma)^2} \qquad \text{A-7}$$

where $(w_g + w_w \cos\sigma)^2$ is applicable to windward guys and $(w_g - w_w \cos\sigma)^2$ is applicable to leeward guys

Angle σ can be found from the relationship

$$\cos\sigma = \frac{\cos^2\phi\,(1+\sin^2\theta) - \cos^2\rho}{2\cdot\cos\rho\cdot\sin\rho} \qquad \text{A-8}$$

It is this final resultant load W_R acting normal to the chord of the guy which is used for values of w_{n2}, in the equations of Chapter Three.

APPENDIX B

NEWTON'S METHOD FOR THE SOLUTION OF EQUATIONS

For simplicity three equations will be used. Let

$$F(x, y, z) = 0$$
$$G(x, y, z) = 0$$
$$H(x, y, z) = 0$$

Let x = a, y = b and z = c be approximations to the root and (a + f, b + g, c + h) be the real roots then by Taylor's series:

$$F(a+f, b+g, c+h) = F(a,b,c) + \left(\frac{\partial F}{\partial x}\right)_{abc} f + \left(\frac{\partial F}{\partial y}\right)_{abc} g + \left(\frac{\partial F}{\partial z}\right)_{abc} h + O(f^2, g^2, h^2) = 0$$

$$G(a+f, b+g, c+h) = G(a,b,c) + \left(\frac{\partial G}{\partial x}\right)_{abc} f + \left(\frac{\partial G}{\partial y}\right)_{abc} g + \left(\frac{\partial G}{\partial z}\right)_{abc} h + O(f^2, g^2, h^2) = 0$$

$$H(a+f, b+g, c+h) = H(a,b,c) + \left(\frac{\partial H}{\partial x}\right)_{abc} f + \left(\frac{\partial H}{\partial y}\right)_{abc} g + \left(\frac{\partial H}{\partial z}\right)_{abc} h + O(f^2, g^2, h^2) = 0$$

Thus

$$\left(\frac{\partial F}{\partial x}\right)_{abc} f + \left(\frac{\partial F}{\partial y}\right)_{abc} g + \left(\frac{\partial F}{\partial z}\right)_{abc} h = -F(a,b,c)$$
$$\left(\frac{\partial G}{\partial x}\right)_{abc} f + \left(\frac{\partial G}{\partial y}\right)_{abc} g + \left(\frac{\partial G}{\partial z}\right)_{abc} h = -G(a,b,c)$$
$$\left(\frac{\partial H}{\partial x}\right)_{abc} f + \left(\frac{\partial H}{\partial y}\right)_{abc} g + \left(\frac{\partial H}{\partial z}\right)_{abc} h = -H(a,b,c)$$

The solution of the above set of linear simultaneous equations will yield f, g and h. Hence the new approximations to the real roots become $a_1 = a + f$, $b_1 = b + g$ and $c_1 = c + h$.

This iterative process is repeated until the desired accuracy for the roots is achieved.

APPENDIX C

LISTING OF COMPUTER PROGRAMME

GUY TENSIONS AND DEFLECTIONS
OF
GUYED MICROWAVE MASTS UNDER TORSIONAL LOADING

```
      DIMENSION A(12,12),Z(12,12),W(12),BIGM(9,9),ANS(9),VR(9),V(9)
     1,ANS1(9)
      COMMON A,MA,NA,Z,MB,NB,W
  373 READ 99,H1,H2,H3,H4,H5,H6,V1,V2,V3,V4,V5,V6,VM,T11,T21,T31,
     1 T41,T51,T61,AR,E,WT,B,PX,PY,TM,WIND1,WIND2,WIND3,
     2 WIND4,WIND5,WIND6
   99 FORMAT(8F10.5)
      PUNCH 98,H1,V1,T11,AR,PX,PY,TM,E
   98 FORMAT (4H H1=E16.8,4H V1=E16.8,5H T11=E16.8,3HAR=E16.8/
     14H PX=E16.8,4H PY=E16.8,4H TM=E16.8,3H E=E16.8)
      MA = 9
      NA = 9
      C=0.8660254
      CB=C*B
      CB2=CB*CB
      BH=B/2.0
      H11=SQRTF((H1- BH)*(H1-BH)+CB2)
      H21=SQRTF((H2-BH)*(H2-BH)+CB2)
      H31=SQRTF((H3-BH)*(H3-BH)+CB2)
      H41=SQRTF((H4-BH)*(H4-BH)+CB2)
      H51=SQRTF((H5-BH)*(H5-BH)+CB2)
      H61=SQRTF((H6-BH)*(H6-BH)+CB2)
      C1=SQRTF(H11*H11+V1*V1)
      C2=SQRTF(H21*H21+V2*V2)
      C3=SQRTF(H31*H31+V3*V3)
      C4=SQRTF(H41*H41+V4*V4)
      C5=SQRTF(H51*H51+V5*V5)
      C6=SQRTF(H61*H61+V6*V6)
      G1=ATANF(CB/(H1-BH))
      G2=ATANF(CB/(H2-BH))
      G3=ATANF(CB/(H3-BH))
      G4=ATANF(CB/(H4-BH))
      G5=ATANF(CB/(H5-BH))
      G6=ATANF(CB/(H6-BH))
      W11=WT*H11/C1
      W21=WT*H21/C2
      W31=WT*H31/C3
      W41=WT*H41/C4
      W51=WT*H51/C5
      W61=WT*H61/C6
      W12=W11+WIND1
      W22=W21+WIND2
      W32=W31+WIND3
      W42=W41+WIND4
      W52=W51+WIND5
      W62=W61+WIND6
      R12=-W12*W12*(C1**4)/(24.*H11)
      R22=-W22*W22*(C2**4)/(24.* H21)
      R32=-W32*W32*(C3**4)/(24.*H31)
      R42=-W42*W42*(C4**4)/( 24.*H41)
      R52=-W52*W52*(C5**4)/(24.*H51)
      R62=-W62*W62*(C6**4)/(24.*H61)
      DO 11 M=1,9
      DO 11 N=1,9
   11 A(M,N)=0.0
      TH1=0.52359878
      A(1,1)=C1*C1/(AR*E*H11)
      A( 1,7)=-COSF(G1)
      A(1,8)=SINF(G1)
      A(1,9)=COSF(TH1-G1)
```

```
      A(2,2)=C2*C2/(AR*E*H21)
      A(2,7)=-COSF(G2)
      A(2,8)=-SINF(G2)
      A(2,9)=-COSF(TH1-G2)
      A(3,3)=C3*C3/(AR*E*H31)
      A(3,7)=SINF(TH1+G3)
      A(3,8)=COSF(TH1+G3)
      A(3,9)=COSF(TH1-G3)
      A(4,4)=C4*C4/(AR*E*H41)
      A(4,7)=SINF(TH1-G4)
      A(4,8)=COSF(TH1-G4)
      A(4,9)=-COSF(TH1-G4)
      A(5,5)=C5*C5/(AR*E*H51)
      A(5,7)=SINF(TH1-G5)
      A(5,8)=-COSF(TH1-G5)
      A(5,9)=COSF(TH1-G5)
      A(6,6)=C6*C6/(AR*E*H61)
      A(6,7)=SINF(TH1+G6)
      A(6,8)=-COSF(TH1+G6)
      A(6,9)=-COSF(TH1-G6)
      A(7,1)=-COSF(G1)*H11/C1
      A(7,2)=-COSF(G2)*H21/C2
      A(7,3)=SINF(TH1+G3)*H31/C3
      A(7,4)=SINF(TH1-G4)*H41/C4
      A(7,5)=SINF(TH1-G5)*H51/C5
      A(7,6)=SINF(TH1+G6)*H61/C6
      A(8,1)=SINF(G1)*H11/C1
      A(8,2)=-SINF(G2)*H21/C2
      A(8,3)=COSF(TH1+G3)*H31/C3
      A(8,4)=COSF(TH1-G4)*H41/C4
      A(8,5)=-COSF(TH1-G5)*H51/C5
      A(8,6)=-COSF(TH1+G6)*H61/C6
      A(9,1)=COSF(TH1-G1)*B*H11/C1
      A(9,2)=-COSF(TH1-G2)*B*H21/C2
      A(9,3)=COSF(TH1-G3)*B*H31/C3
      A(9,4)=-COSF(TH1-G4)*B*H41/C4
      A(9,5)=COSF(TH1-G5)*B*H51/C5
      A(9,6)=-COSF(TH1-G6)*B*H61/C6
      V(1)=-(W11*W11*C1*C1/(24.*T11*T11)-T11/(AR*E))*C1*C1/H11
      V(2)=-(W21*W21*C2*C2/(24.*T21*T21)-T21/(AR*E))*C2*C2/H21
      V(3)=-(W31*W31*C3*C3/(24.*T31*T31)-T31/(AR*E))*C3*C3/H31
      V(4)=-(W41*W41*C4*C4/(24.*T41*T41)-T41/(AR*E))*C4*C4/H41
      V(5)=-(W51*W51*C5*C5/(24.*T51*T51)-T51/(AR*E))*C5*C5/H51
      V(6)=-(W61*W61*C6*C6/(24.*T61*T61)-T61/(AR*E))*C6*C6/H61
      V(7)=-PX
      V(8)=-PY
      V(9)=-TM
      PUNCH 6,H11,C1,G1,W11,W12,R12
    6 FORMAT((4E16.8))
      DO 15 M=1,9
      DO 15 N=1,9
   15 BIGM(M,N)=A(M,N)
      CALL KJINV(DETRM)
      DO 13 I=1,9
      ANS(I)=0.0
      DO 13 J=1,9
   :3 ANS(I)=ANS(I)+A(I,J)*V(J)
      DO 14 I=1,9
      V(I)=0.
      DO 14 J=1,9
    4 V(I)=V(I)+BIGM(I,J)*ANS(J)
    6 DO 18 I=1,6
      IF(ANS(I))17,18,18
```

```
 17  ANS(I)=T11*0.75
 18  CONTINUE
 50 VR(1)=-(-V(1)+R12/(ANS(1)*ANS(1))+BIGM(1,1)*ANS(1)+
   1 BIGM(1,7)*ANS(7)+BIGM(1,8)*ANS(8)+BIGM(1,9)*ANS(9))
    VR(2)=-(-V(2)+R22/(ANS(2)*ANS(2))+BIGM(2,2)*ANS(2)+
   1 BIGM(2,7)*ANS(7)+BIGM(2,8)*ANS(8)+BIGM(2,9)*ANS(9))
    VR(3)=-(-V(3)+R32/(ANS(3)*ANS(3))+BIGM(3,3)*ANS(3)+
   1 BIGM(3,7)*ANS(7)+BIGM(3,8)*ANS(8)+BIGM(3,9)*ANS(9))
    VR(4)=-(-V(4)+R42/(ANS(4)*ANS(4))+BIGM(4,4)*ANS(4)+
   1 BIGM(4,7)*ANS(7)+BIGM(4,8)*ANS(8)+BIGM(4,9)*ANS(9))
    VR(5)=-(-V(5)+R52/(ANS(5)*ANS(5))+BIGM(5,5)*ANS(5)+
   1 BIGM(5,7)*ANS(7)+BIGM(5,8)*ANS(8)+BIGM(5,9)*ANS(9))
    VR(6)=-(-V(6)+R62/(ANS(6)*ANS(6))+BIGM(6,6)*ANS(6)+
   1 BIGM(6,7)*ANS(7)+BIGM(6,8)*ANS(8)+BIGM(6,9)*ANS(9))
    VR(7)=-(BIGM(7,1)*ANS(1)+BIGM(7,2)*ANS(2)+BIGM(7,3)*ANS(3)+
   1 BIGM(7,4)*ANS(4)+BIGM(7,5)*ANS(5)+BIGM(7,6)*ANS(6)+PX)
    VR(8)=-(BIGM(8,1)*ANS(1)+BIGM(8,2)*ANS(2)+BIGM(8,3)*ANS(3)+
   1 BIGM(8,4)*ANS(4)+BIGM(8,5)*ANS(5)+BIGM(8,6)*ANS(6)+PY)
    VR(9)=-(BIGM(9,1)*ANS(1)+BIGM(9,2)*ANS(2)+BIGM(9,3)*ANS(3)+
   1 BIGM(9,4)*ANS(4)+BIGM(9,5)*ANS(5)+BIGM(9,6)*ANS(6)+TM)
    DO 20 M=1,9
    DO 20 N=1,9
 20 A(M,N)=BIGM(M,N)
    A(1,1)=BIGM(1,1)-2.*R12/(ANS(1)**3)
    A(2,2)=BIGM(2,2)-2.*R22/(ANS(2)**3)
    A(3,3)=BIGM(3,3)-2.*R32/(ANS(3)**3)
    A(4,4)=BIGM(4,4)-2.*R42/(ANS(4)**3)
    A(5,5)=BIGM(5,5)-2.*R52/(ANS(5)**3)
    A(6,6)=BIGM(6,6)-2.*R62/(ANS(6)**3)
    CALL KJINV(DETRM)
    DO 21 I=1,9
    ANS1(I)=0.0
    DO 21 J=1,9
 21 ANS1(I)=ANS1(I)+A(I,J)*VR(J)
    DO 24 M=1,9
 24 ANS(M)=ANS(M)+ANS1(M)
 37 DO 39 M=1,6
    IF(ANS(M))38,39,39
 38  ANS(M)=T11*0.10
 39  CONTINUE
 25 IF(ANS1(1)-ANS(1)/200.) 26,26,50
 26 IF(ANS1(2)-ANS(2)/200.) 27,27,50
 27 IF(ANS1(3)-ANS(3)/200.) 28,28,50
 28 IF(ANS1(4)-ANS(4)/200.) 29,29,50
 29 IF(ANS1(5)-ANS(5)/200.) 30,30,50
 30 IF(ANS1(6)-ANS(6)/200.) 36,36,50
 36 ALPHA=ATANF(ANS(9)/B)*57.295779
    BETAX=ATANF(ANS(7)/VM)*57.295779
    BETAY=ATANF(ANS(8)/VM)*57.295779
    DELT=SQRTF( ANS(7)*ANS(7)+ANS(8)*ANS(8))
    BETAT=ATANF(DELT/VM)*57.295779
    TOR1=(COSF(TH1-G2)*B*H21*ANS(2)/C2)-(COSF(TH1-G1)*B*H11*ANS(1)/C1)
    TOR2=(COSF(TH1-G4)*B*H41*ANS(4)/C4)-(COSF(TH1-G3)*B*H31*ANS(3)/C3)
    TOR3=(COSF(TH1-G6)*B*H61*ANS(6)/C6)-(COSF(TH1-G5)*B*H51*ANS(5)/C5)
    TORT=TOR1+TOR2+TOR3
    PCM1=TOR1/TORT
    PCM2=TOR2/TORT
    PCM3=TOR3/TORT
    PCMT=TORT/TM
    PUNCH 48,ANS(1),ANS(2),ANS(3),ANS(4),ANS(5),ANS(6),ANS( 7),
  1 ANS(8),ANS(9),ALPHA,BETAX,BETAY,BETAT,TOR1,TOR2,TOR3,TORT,
  2  PCM1,PCM2,PCM3,PCMT
 48 FORMAT(//(6X,4E16.8))
```

```
VERT1=ANS(1)*V1/C1
HOR1=ANS(1)*H11/C1
G1X=COSF(TH1-G1)*HOR1
G1Y=SINF(TH1-G1)*HOR1
VERT2=ANS(2)*V2/C2
HOR2=ANS(2)*H21/C2
G2X=COSF(TH1-G2)*HOR2
G2Y=SINF(TH1-G2)*HOR2
VERT3=ANS(3)*V3/C3
HOR3=ANS(3)*H31/C3
G3X=COSF(TH1-G3)*HOR3
G3Y=SINF(TH1-G3)*HOR3
VERT6=ANS(6)*V6/C6
HOR6=ANS(6)*H61/C6
G6X=COSF(TH1-G6)*HOR6
G6Y=SINF(TH1-G6)*HOR6
S1=(4.20/4.88)*0.5*(VERT1+VERT6)
S2=(4.20/4.04)*0.5*(G1Y+G6Y)
S3=(4.20/1.14)*0.5*(G1X-G6X)
ARM1=S1+S2+S3
ARM2=S1+S2-S3
S4=(4.20/4.88)*0.5*(VERT2+VERT3)
S5=(4.20/4.04)*0.5*(G2Y+G3Y)
S6=(4.20/1.14)*0.5*(G2X-G3X)
ARM3=S4+S5-S6
ARM4=S4+S5+S6
D1=ARM1*1.86*4.20/(0.90*29000000.)
D2=ARM2*(-1.34)*4.20/(0.90*29000000.)
D3=ARM3*(-1.34)*4.20/(0.90*29000000.)
D4=ARM4*1.86*4.20/(0.90*29000000.)
D10=D1+D2
D11=D3+D4
D12=D11-D10
TALPHA=ATANF(D12/(2.0*CB))*57.295779
TBETA=ATANF(((D10+D11)*0.5)/VM)*57.295779
TOTAL=TALPHA+ALPHA
TOTBE=TBETA+BETAX
PUNCH 48,TALPHA,TBETA,TOTAL,TOTBE
GO TO 373
END
```

```
> 5
R 5
SKKJINV
  SUBROUTINE KJINV(DETA)
  DIMENSION A(12,12),Z(12,12),W(12)
  DIMENSION IR(12),IC(12)
  COMMON A,MA,NA,Z,MB,NB,W
  DO 1  I=1,MA
  IR(I)=0
  IC(I)=0
  DETA=1.0
  S=0.0
  R=MA
  CALL KJSUB(IR,IC,I,J)
  PIV=A(I,J)
  DETA=PIV*DETA
  IF (PIV) 3,17,3
  IR(I)=J
  IC(J)=I
  PIV=1.0/PIV
  A(I,J)=1.0
  DO 5 K=1,MA
  A(I,K)=A(I,K)*PIV
  DO 9 K=1,MA
  IF (K-I) 6,9,6
  PIV1=A(K,J)
  DO 8 L=1,MA
  IF (L-J) 7,8,7
  A(K,L)=A(K,L)-A(I,L)*PIV1
  CONTINUE


  CONTINUE
  DO 11 K=1,MA
  IF (K-I) 10,11,10
  A(K,J)=-PIV*A(K,J)
  CONTINUE
  S=S+1.0
  IF (S-R) 2,12,12
  DO 16 I=1,MA
  K=IC(I)
  M=IR(I)
  IF (K-I) 13,16,13
  DETA=-DETA
  DO 14 L=1,MA
  TEMP=A(K,L)
  A(K,L)=A(I,L)
  A(I,L)=TEMP
  DO 15 L=1,MA
  TEMP=A(L,M)
  A(L,M)=A(L,I)
  A(L,I)=TEMP
  IC(M)=K
  IR(K)=M
  CONTINUE
  RETURN
  PRINT 18
  FORMAT(23H KJINV, SINGULAR MATRIX)
  RETURN
  END
```

```
OB 5
OR 5
ISKKJSUB
      SUBROUTINE KJSUB(IR,IC,I,J)
      DIMENSION A(12,12),Z(12,12),W(12)
      DIMENSION IR(12),IC(12)
      COMMON A,MA,NA,Z,MB,NB,W
      I=0
      J=0
      TEST=0.0
      DO 5 K=1,MA
      IF (IR(K)) 5,1,5
    1 DO 4 L=1,NA
      IF (IC(L)) 4,2,4
    2 X=ABSF(A(K,L))
      IF (X-TEST) 4,3,3
    3 I=K
      J=L
      TEST=X
    4 CONTINUE
    5 CONTINUE
      RETURN
      END
```

VITA AUCTORIS

1931	Born January 5, Windsor, Ontario, Canada.
1946	Graduated from King George Public School, Windsor, Ontario, Canada.
1951	Graduated from Walkerville Collegiate Institute, Windsor, Ontario, Canada.
1955	Granted Bachelor of Science Degree in Civil Engineering by Queen's University, Kingston, Ontario, Canada.
1955	Employed as Design Engineer by DOSCO Industries Ltd., Canadian Bridge Division, Walkerville, Ontario, Canada.

Technical Societies

Member of The Association of Professional Engineers of Ontario

Member of The Engineering Institute of Canada.