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AN ANALYSIS OF THE DEFORMATION OF THE MOORING SPINDLE OF THE "SHENANDOAH"

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AN ANALYSIS OF THE DEFORMATION OF THE MOORING SPINDLE OF THE "SHENANDOAH"

By L. B. Tuckerman and C. S. Aitchison

ABSTRACT

This article presents the results of the examination and tests on the mooring spindle of the U. S. Navy airship *Shenandoah*, which was bent when the airship was torn loose from her mooring mast during a storm on the night of January 16, 1924. The object of the examination and tests was to determine as closely as possible the actual wind forces which acted upon the ship at the time she broke away. Although the forces which produced a permanent deformation in the structure can not, in general, be determined with accuracy, an approximate method of analysis and examination was developed applicable to any axially symmetrical deformed structure. Among the conclusions reached by this analysis are that the material evidently met specifications for yield point and also that the load producing deformation was certainly greater than 13,400 pounds and probably greater than 27,000 pounds.

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I. INTRODUCTION

The U. S. Navy airship *Shenandoah*, while under mooring trials at Lakehurst, was torn loose from her mast by a storm on the night of January 16, 1924. That the conditions were unusually severe is evidenced from the reports of the Weather Bureau, which state that the storm was one of the worst in the 52 years in which records have been kept.

Wind velocities of 50 miles per hour with gusts rising probably to 75 miles per hour and changing rapidly in direction were reported at the Lakehurst hangar at 6.30 p. m. on the above date. The ship at this time was riding easily at the mast. Shortly afterwards, however, she was struck by a series of violent wind gusts of unknown velocity which first damaged the upper vertical fin, and finally caused the ship to tear away abaft the nose cap. The mooring spindle was wrenched free from the ship and remained attached to the mast. Figure 1 is a photograph showing the damage done to the bow of the ship. This picture was taken

after the *Shenandoah* had safely ridden out the storm and was again housed at Lakehurst.

The Bureau of Aeronautics of the Navy wished to determine as closely as possible the actual wind forces to which the ship was subjected.

II. METHODS OF TESTS

There were three methods available through which the extent of the forces acting on the ship at the time she broke away could be investigated. One was by estimates of the air forces acting on the hull of the ship from the very uncertain wind velocity data. A rough estimate on this basis was made by Dr. Max Munk, of the National Advisory Committee for Aeronautics. Another was by treating the cross section of the ship at the break as that of a beam and calculating the forces it could withstand. An estimate on this basis has been made by C. P. Burgess, of the Bureau of Aeronautics, who at the time of the accident was reading the strain gauges placed on logitudinal girders above the control car. This estimate was checked for reasonableness by comparison with the strain-gauge readings.

The third was through examination and tests of the deformed mooring spindle. The Bureau of Standards was requested to undertake this part of the investigation, and after consultation with the engineers of the Bureau of Aeronautics a test program was planned.

Although the forces which produced a permanent deformation in a structure can not, in general, be determined with accuracy from an examination of the deformed structure, estimates in the case of a ductile material can be obtained by making assumptions as to the law of plastic flow above the yield point. The data needed for the estimates are the extent of the observed deformation and either the residual stresses or the forces necessary to restore the form of the structure.

The residual stresses could have been determined by the method of dissection used in determining the residual stresses due to heat treatment or cold working of materials. This method has been used in some investigations on deformed rails.

III. RESULTS AND DISCUSSION OF TESTS

The second method, being simpler and apparently capable of giving as definite results, was preferred. The spindle was mounted in a lathe (see fig. 2), and by means of micrometers (*A* and *B*, fig. 2) the maximum and minimum distances that the spindle was

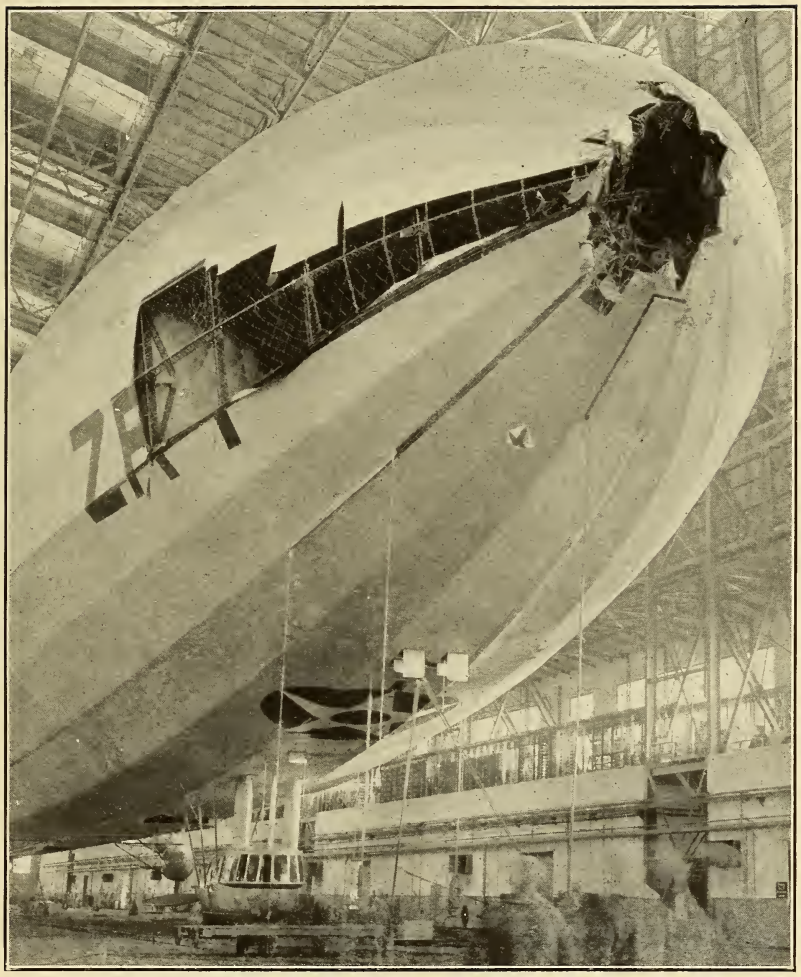

FIG. 1.—*U. S. Navy Airship Shenandoah in hangar shortly after the storm*

Shows damage at the nose of the ship

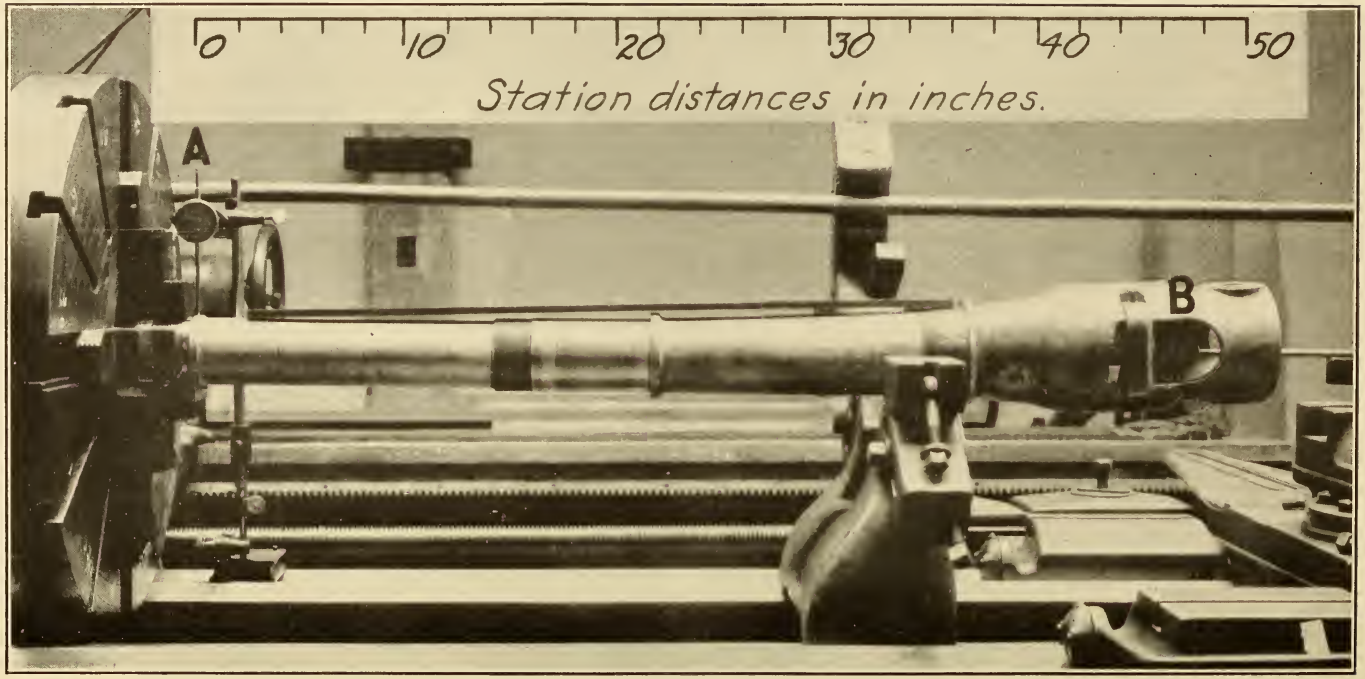

FIG. 2.—*Mooring spindle mounted in lathe for measuring off centers*

Straightedge shows bending of spindle

off center were determined for various stations along the length. At a few places micrometer readings were taken at approximately 30° intervals around the spindle. As these all plotted satisfactory sine wave curves, only maximum and minimum readings were taken at the majority of points. These readings, within experi-

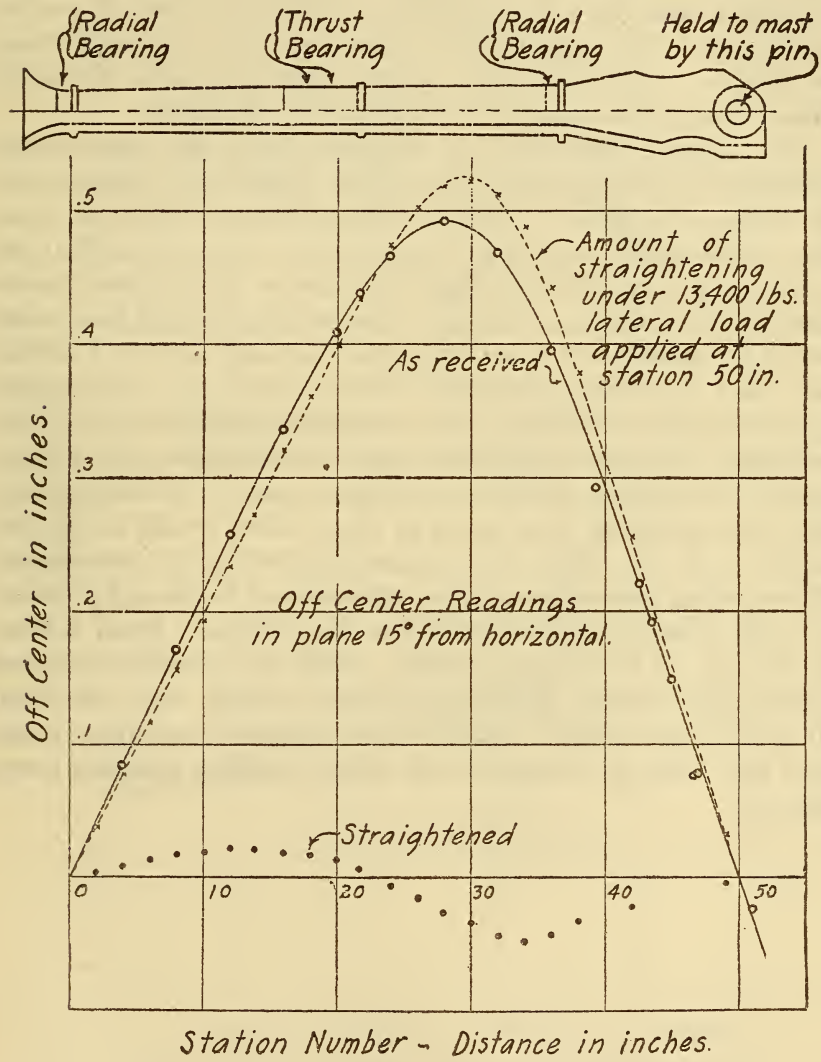

FIG. 3.—*Off-center readings in plane 15° from horizontal*

mental error, were all found to lie in the same plane. This was practically 15° from the horizontal and corresponded in direction to the break in the nose of the ship as seen in Figure 1. The results are shown by the experimental points located on or near the off-

center curve "as received" (fig. 3). The two ends were obviously straight, bending occurring only in the middle portion.

The curvature of the axis was then determined as follows: From the off-center readings first and second differences were computed. The second difference curve (Δ) (figs. 4 and 6) was smoothed, and from it smoothed first differences and off centers calculated. The computed off-center curve is shown as a full line in Figure 3. The smoothed second difference curve obviously gives a fair representation of the observed off centers.

The second differences (Δ) represent then the approximate curvature of the spindle at each station. Since they were obtained by what is, in effect, a double differentiation of observed data, they are obviously subject to large error, but it is believed that the errors do not appreciably affect the location of maximum curvature at about station 30 inches. If we assume that the load under which the spindle was bent was applied suddenly, as with a sudden jerk, and also that plastic flow will take place at a rate roughly proportional to the excess of the stress above the yield point of the material, we should expect then the total curvature at any given point to be roughly proportional to this excess. On this assumption the maximum fiber stress at any station would be proportional to $K+\Delta$, where K is some constant to be determined. The bending moments would be proportional to $(K+\Delta)\ Z$, where Z is the relative section modulus at the station. From a blueprint copy of the design drawing, which was carefully checked against the spindle, the relative section moduli were calculated at each of the stations. These were expressed in arbitrary units, and the values are shown in the relative section modulus curve (fig. 4).

Since theoretically the bending-moment curve consists of a series of straight lines from load point to load point, a maximum could only exist under a load point. K was so determined as to make $(K+\Delta)\ Z$ a maximum at station 36 inches, which is located under the forward radial bearing. Obviously, this is a very rough

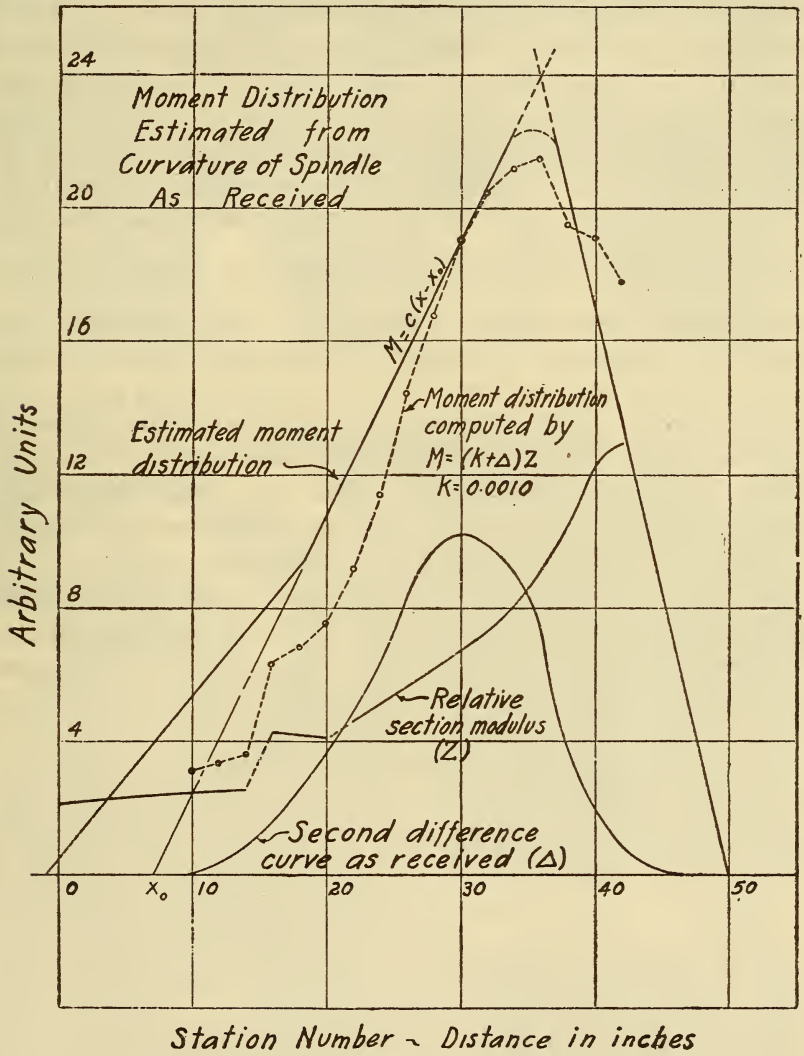

FIG. 4.—*Moment distribution estimated from curvature of spindle* As received.

determination. Values of K from 0.009 up to 0.012 corresponding to a maximum stress approximately double the yield point stress (Max. $\Delta = 0.012$) will meet this condition. For convenience 0.010 was chosen and $(0.010+\Delta)\ Z$ computed. These are plotted as

observed data on the moment distribution curve (fig. 4). It is to be noted that the value of K and, consequently, the shape of the computed moment curve is determined from the slope of the second difference curve at station 36 inches.

Reasoning backward, the moment must increase linearly from station 18 inches under the thrust bearing to station 36 inches under the forward radial bearing. It must be represented between these limits by the straight line $C\ (X-X_0)$. Here C is some constant, X represents the distance along the axis of the spindle, and X_0 the location of the point of intersection of this axis with the line of action of the resultant of the forces exerted by the thrust and rear radial bearings. Then X_0 was so determined that the stress $\frac{C\ (X-X_0)}{Z}$ should have a maximum at station 30 inches where the maximum curvature was found. The value of X_0 was found to be approximately 7 inches, so that the resultant reaction of the two rear bearings presumably passed near this point. On this assumption an estimated moment distribution was plotted on Figure 4 tangent to the previously computed curve at station 30 inches. It is to be noted that the value of X_0 and, consequently, the shape of the moment curve, is in this case determined from the location of the maximum of the second difference curve.

The agreement between the two moment curves based on these two independent assumptions was as close as could be expected from such uncertain data and rough approximations. It seemed reasonable to assume that the estimated moment curve was a fair representation of the load distribution which bent the spindle.

This calculated moment distribution was, therefore, duplicated in a testing machine (fig. 5). The spindle rested on roller bearings (R_1, R_2, and R_3) placed under the mooring-mast attachment, the thrust bearing, and rear radial bearing, and the load was applied at the forward radial bearing. To insure that the resultant force should pass through the calculated point (station 7 inches) the rollers R_2 and R_3 were mounted on an I beam, which in turn rested on the roller R_4 placed at station 7 inches. The reaction at the mooring bearing (R_1, station 50 inches) was, therefore, 29/50 of the reading of the testing machine, and the resultant reactions passed through the required points. To secure an estimate of the range of elastic deformation of the spindle as free as possible from the effects of its previous deformation, the load was first applied in the same direction as the original wind load. The spindle deflected elastically approximately at the rate of 0.14 inch

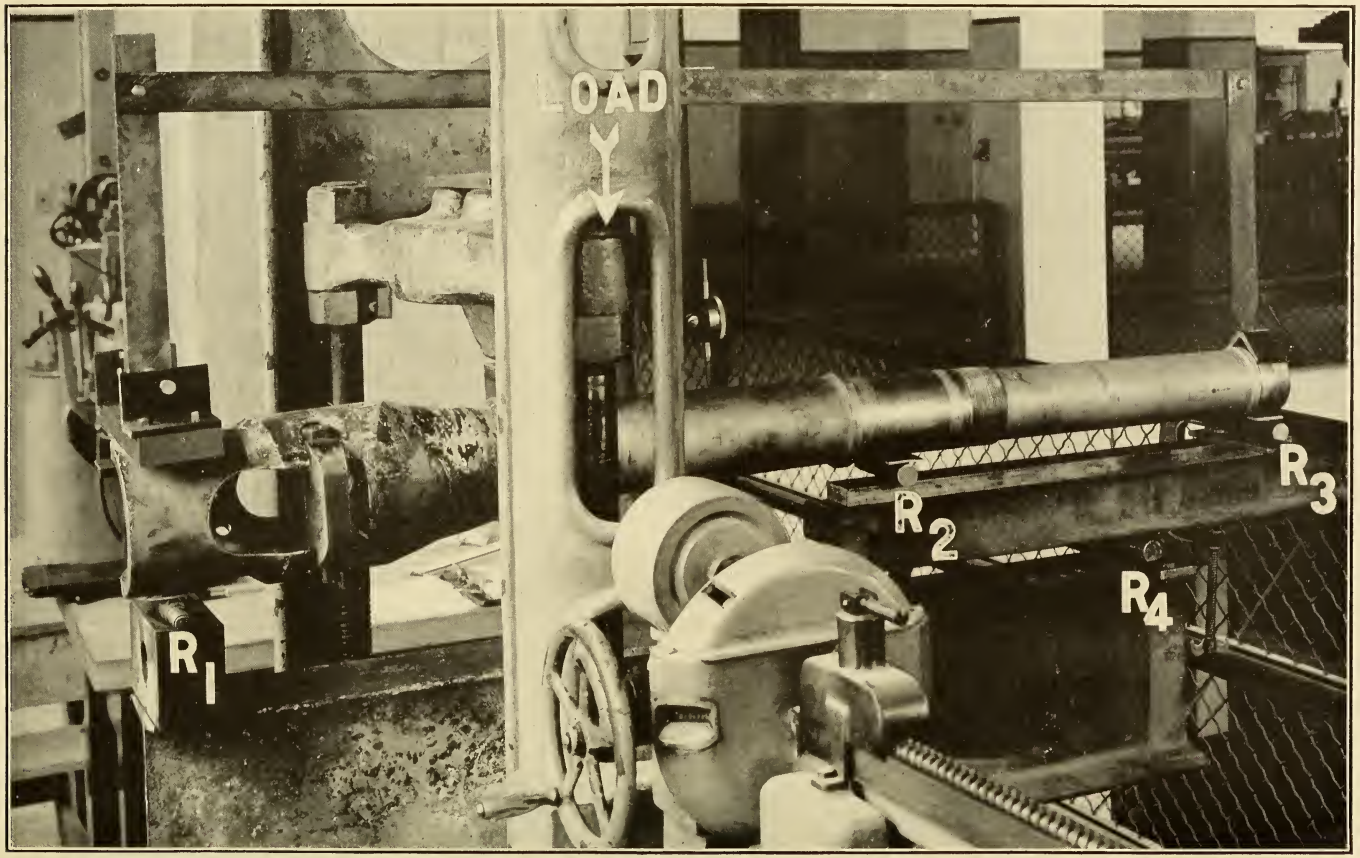

FIG. 5.—*Straightening of mooring spindle in testing machine*

per each 10,000 pounds reaction at the point of attachment of the mooring mast (R_1). At a load of 17,000 pounds, corresponding to a reaction of 9,880 pounds at R_1, a further permanent deflection of 0.003 inch was observed. A wind load of approximately 10,000 pounds would, therefore, have produced a small permanent deflection in the spindle. The corresponding extreme fiber stress is 28,300 lbs./in.^{2} The material, therefore, evidently met the specification requirements of 28,000 to 36,000 lbs./in.^{2} yield point named in specifications for 1015 steel.

The spindle was then turned over and approximately straightened under steady load. Permanent deflection became noticeable at a load of 8,000 pounds (showing the effect of the previous overstressing in the opposite direction) and increased rapidly with the load. The loading was carried to 23,100 pounds, corresponding to a reaction of 13,400 pounds at the mooring cone and an extreme fiber stress of 38,400 lbs./in.^{2}

The spindle was again mounted in the lathe and off-center distances obtained as before. These are shown as plotted points in Figure 3. The difference between the "as received" distances and the "straightened" distances represents the amount of "straightening" on the specimen.

First and second differences were computed from this "straightening." The second differences were smoothed and checked back on the original observations, as in the case of the "as received" readings. The computed curve is shown in the dotted line in Figure 3. The smoothed second differences obviously give a fair representation of the amount of "straightening." As in the case of the "as received" curve, the errors are necessarily large.

As a further comparison second differences (shown in fig. 6) were computed by the rough theory from the assumed moment distribution curve (fig. 4). The assumptions made in computing this curve are shown in Figures 7 and 8. The upward curvature of the actual curve of rate of plastic flow (fig. 7 *B*), giving relatively more flow at the higher stresses, would produce a sharper pointed second difference curve than the assumed straight line (fig. 7). The actually gradual, though rapid, rise and fall of stress (fig. 8 *B*), by approximating more closely the conditions of steady load, would also tend to produce a sharper pointed curve than the assumption of instantaneous rise and fall (fig. 8 *A*) used in the computation. Both of these probably combine to make the

observed "as received" second difference curve have a shape intermediate between the flat topped curve calculated by the rough theory and the sharp pointed curve produced by the slowly applied "straightening" load.

The assumption of Figure 8 *A* leads to an underestimate of the stress required to produce the maximum curvature observed

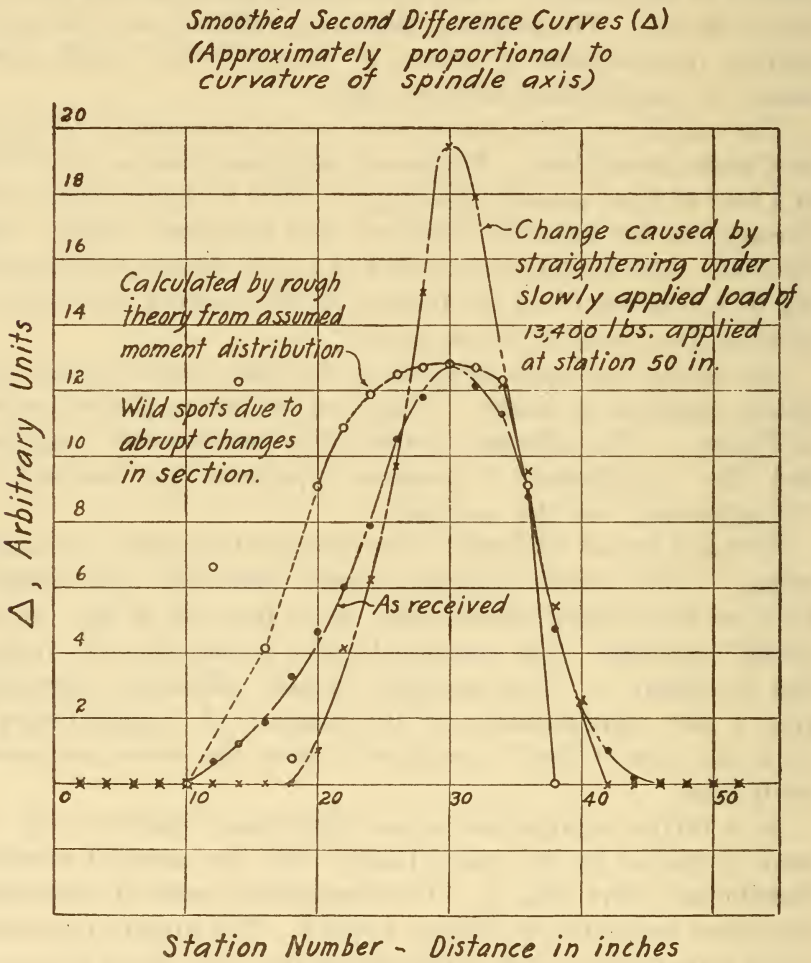

FIG. 6.—*Smoothed second difference curves* (Δ)
Approximately proportional to curvature of spindle axis

at station 30 inches, while that of Figure 7 *A*, may lead to either an under or over estimate depending upon the range of stress which actually occurred and the properties of the material. If the maximum stress corresponded to the intersection of the curves 7 *A* and 7 *B*, the rough assumption would, of course, give the same maximum curvature. It seems probable, then, that the

estimate of approximately double the yield point stress at station 30 inches is an under rather than an over estimate. One further point seems worth noting—the computed moment distribution

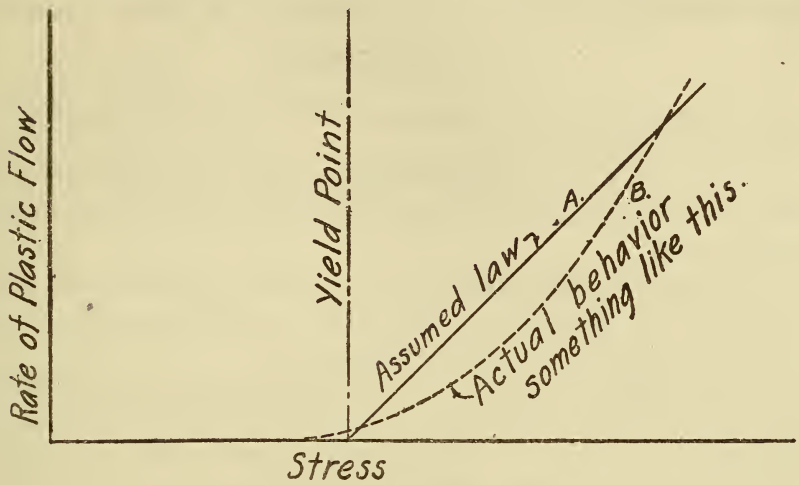

FIG. 7.—*Assumed rate of plastic flow*

curve (fig. 4) lies below the estimated curve, to the rear of station 30 inches, and extends beyond it forward of station 38 inches. Corresponding to this the second difference curve (fig. 6) shows curvatures extending forward of station 38 inches, which was the

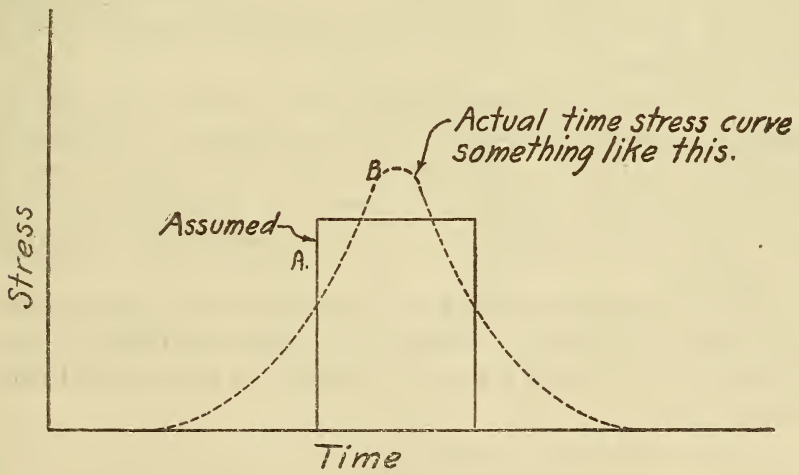

FIG. 8.—*Assumed stress time curve*

farthest point forward at which change of curvature was observed under straightening. Under an instantaneous load the inertia of the parts would produce relatively greater bending moments

forward and less aft than computed from the reactions of the bearing points alone. These apparent discrepancies are, therefore, consistent with the assumption of a suddenly applied load, to be expected under the type of load applied to the mooring spindle.

IV. CONCLUSIONS

1. The material of the spindle evidently met specification requirements for yield point.

2. The axis of the spindle bent elastically approximately 0.14 inch out of line for each 10,000 pounds of load applied at the mooring cone.

3. Permanent deformations of the mooring spindle would have commenced at transverse wind loads of approximately 10,000 pounds and increased with increasing load.

4. The measured permanent deflection of the spindle was almost wholly due to the reaction of the mooring mast to a sudden transverse wind load on the ship inclined approximately 15° to the horizontal upward and to port.

5. This load was certainly greater than 13,400 pounds, the steady load which produced the straightening in the testing machine, and probably greater than 27,000 pounds, estimated by the rough theory given. This is in as good agreement as could be expected with the estimate of Dr. Max Munk of 40,000 pounds based on aerodynamic theory from the very uncertain wind data, and of C. P. Burgess of 24,100 pounds based on the failure of the nose-cap girders.

6. Since small permanent deformations would have been produced by somewhat lower loads, it is possible some deformations had been produced in the spindle before the occurrence of the sudden load which produced the measured deformation. These may have contributed to the failure by jamming the bearings of the spindle.

7. Since the measured deformation corresponds, in general direction, with the direction in which the ship broke from the mast, it seems probable that it was due to the final gust of wind which tore it loose.

WASHINGTON, June 12, 1924.