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STATIC TORSION TEST OF A CENTRIFUGALLY CAST STEEL SHAFT

by

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PERSONNEL

The test was conducted by personnel of the Charleston Navy Yard. The strain measurements were taken by E.E. Johnson and C.A. Wagley of the David W. Taylor Model Basin staff. This report is the work of E.E. Johnson.

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ABSTRACT

An experimental hollow steel shaft with flanged ends, fabricated by welding together two centrifugally cast steel shaft sections, was tested under static torsional loading to determine the strength of the weld, the flange fillets, and the main shaft section. The measurements showed that plastic deformation occurred over the whole length of the main shaft section whereas at the weld and flange fillet zones the results were less conclusive; here they indicated that only incipient yielding occurred. The limitations of the test setup did not permit twisting the shaft to failure for determination of the ultimate strength.

INTRODUCTION

The Bureau of Ships has undertaken a development program to make available hollow steel propeller shafts for naval vessels, which can be manufactured simply, inexpensively and expeditiously by the centrifugal casting method, which has been in use for many years for the manufacture of cast-iron water pipe.

A few experimental cast-steel hollow shafts were manufactured by the American Cast Iron Pipe Company of Birmingham, Alabama. To facilitate withdrawal of the casting from the mold after casting, and to allow for shrinkage, they could be formed with a flange on only one end. A short length of shaft was cast with the second flange and the two parts were then welded together, as shown in Figure 1, to form a shaft section with flanged ends. The characteristics and history of the shaft, as assembled and annealed by the Charleston Navy Yard, are given in Appendix 1. The welding, the subsequent annealing, and the torsion test following, were conducted by the Charleston Navy Yard. The David W. Taylor Model Basin was requested by the Bureau of Ships to assist in the test. The immediate object of the test was to determine the loads at which yielding occurred in the weld, in the flange fillets, and in the shaft proper.

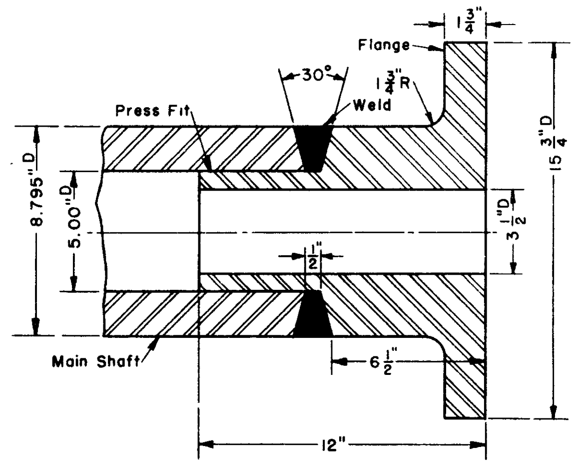


Figure 1 - Section through the Shaft Weld

The shaft was machined all over on the outside. The whole shaft section between the flanges, including the weld, was turned down to a diameter of 8.795 inches. The inside of the shaft was not machined.

TEST PROCEDURE AND APPARATUS

The shaft was mounted in a horizontal position as shown in Figure 2, and torsion tests were conducted on 16 and 17 September 1942.

Upon the application of torque by placing weights in the loading tray, the jack under the other end of the loading arm was manipulated to exert an upward force equal to the weights on the tray. Thus pure torsion load increments were applied to the shaft. Readings were taken for increments of 2100 foot-pounds torque.

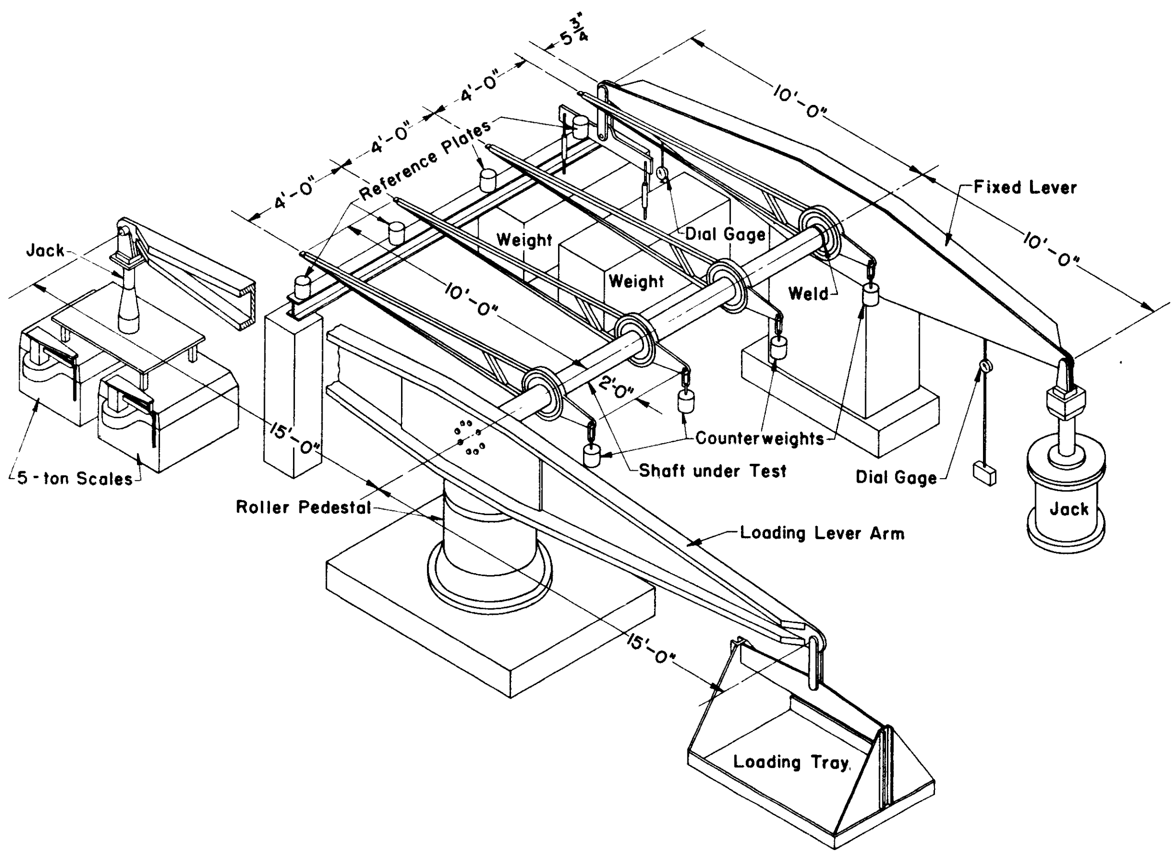


Figure 2 - Arrangement of Test Apparatus

The flange nearest the weld, in the upper right hand portion of the diagram, was bolted to a fixed lever-arm and support. At the opposite or near end in the diagram, the shaft rested on rollers, and a loading lever arm extending 15 feet on either side of the shaft was bolted to the flange. From one end of the loading lever arm a tray was suspended, upon which lead weights were placed to give load increments. A jack supported on scales pushed upward on the other end of the loading lever arm.

Rotation of the fixed lever arm due to deformation of the fixed support was indicated by dial gages mounted between the floor and the lever on each side of the shaft. For each set of readings the fixed arm was rotated back to its original position by adjustment of the weights hanging on one end of the arm and a jack under the other end, so that the original position of the arm was maintained.

Angular deflection or twist in the shaft was measured for three 4-foot sections along its length and for one short section near the welded flange. Four 10-foot steel arms were rigidly attached normal to the shaft as shown in Figure 2. The arms were attached to the shaft by clamping rings built into the arms. The arms extended over a steel reference plate supported from the floor. As torque was applied the varying distances between the datum plate and the ends of the arms were measured with inside micrometers.

Eight Huggenberger strain gages were mounted at the welded end of the shaft, in the locations shown in Figure 4. They were placed at 45 degrees to the longitudinal axis of the shaft and thus measured the principal tensile and compressive strains, from which the shearing stresses could be computed.

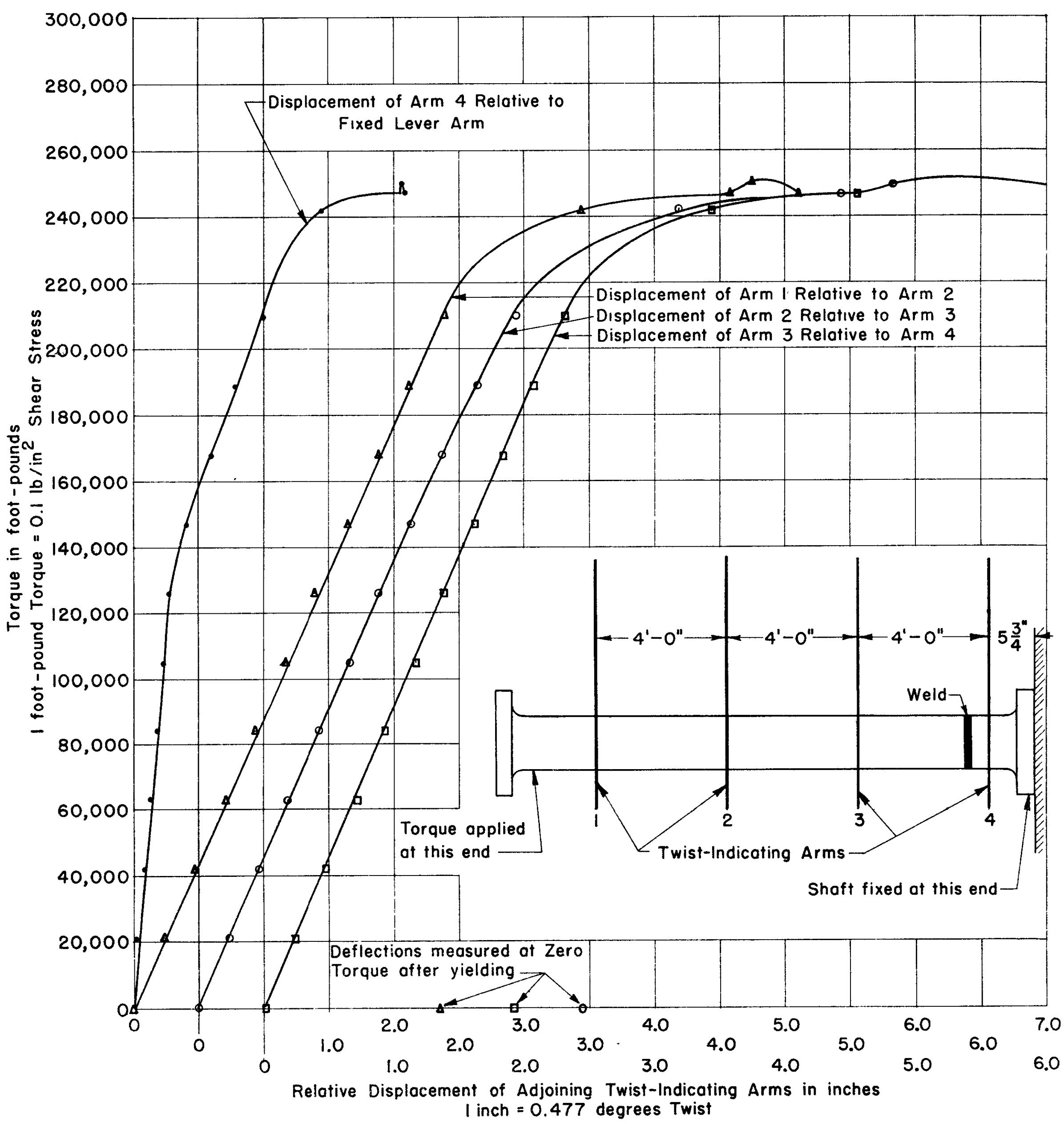


Figure 3 - Torque-Twist Curves

TEST RESULTS AND DISCUSSION

Stresscoat, a strain-indicating lacquer, was applied over the entire length of the shaft and in the fillet zone. This was done to determine the yield point in the fillets where no other means of instrumentation were available, and to locate any localized yielding in the shaft.

Torque-twist curves are given in Figure 3. The curves of twist in the three 4-foot sections show that the proportional limit was reached first in the center section at a torque corresponding to a shearing stress of about 18,000 pounds per square inch. General yielding throughout the shaft occurred at a shearing stress of about 21,000 pounds per square inch, at which point the test was stopped.

The curve of torsional deflection for the arm nearest the fixed end shows a definite change of slope for torques greater than that corresponding to a shearing stress in the shaft of 12,500 pounds per square inch. This arm measured the twist in the short section of the shaft and in the flange fillets, but in addition the readings included twist resulting from distortion in the connection between the shaft flange and the fixed-end support. Upon disassembly of the apparatus appreciable yielding in the connecting bolts was in evidence. While this does not completely exclude the

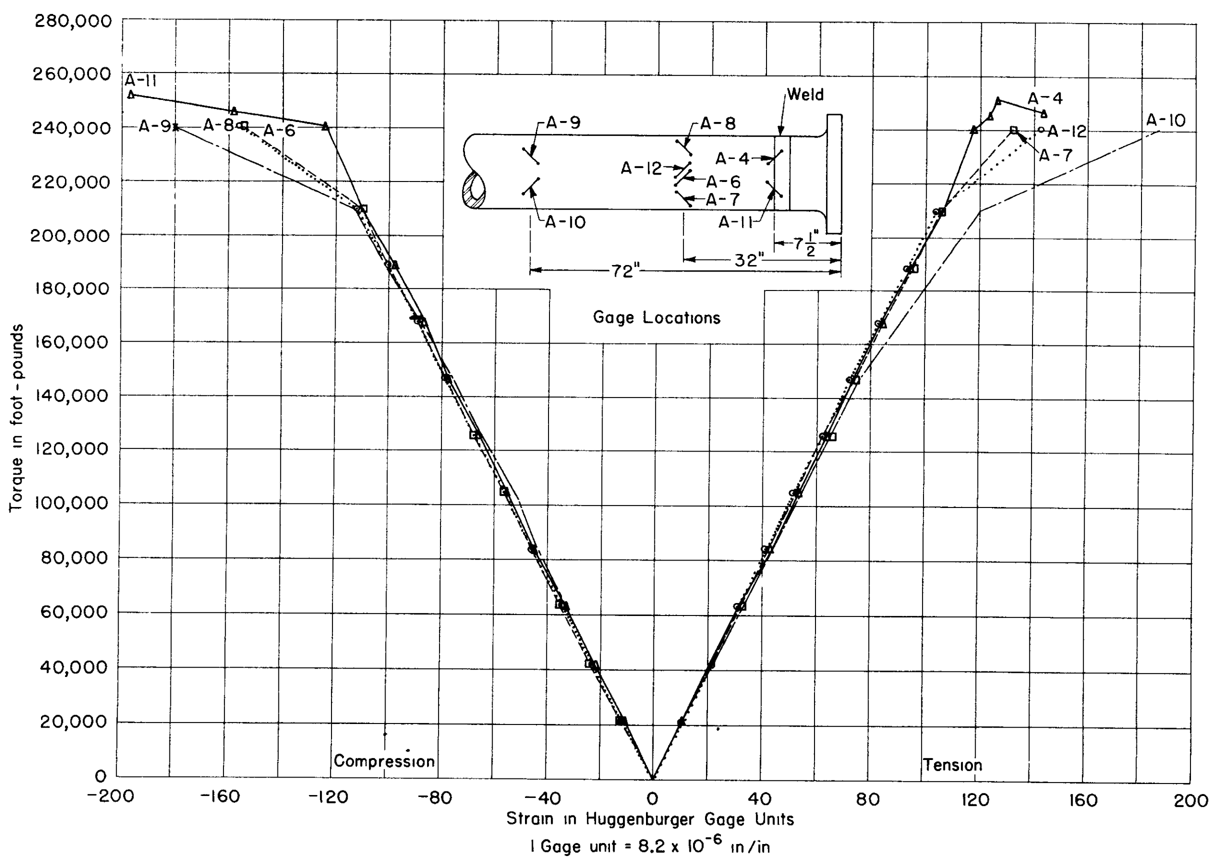


Figure 4 - Torque-Strain Curves

The strains occurred at 45 degrees to the axis of the shaft.

TABLE 1

Comparison of Shearing Stress by Strain Gage with
Theoretical Shearing Stress for 100 foot-kips Torque

Gage Station	Strain Measured at 45 degrees to Shaft Axis, inches per inch x 10^{-4}	Stress σ* at 45 degrees to Shaft Axis, pounds per square inch	Section	Average Stress σ at Section, pounds per square inch	Deduced** Shear Stress τ_d at Section, pounds per square inch	Theoretical† Shear Stress τ_t at Section, pounds per square inch
A- 9	-4.26	- 9 800	A	- 9 800		
A-10	+4.26	+ 9 800		+ 9 800	9800	10 400
A- 8	-4.43	-10 600				
A-12	+4.02	+ 8 900		+ 9 000	9800	10 400
A- 6	-4.43	-10 600	B	-10 600		
A- 7	+4.10	+ 9 100				
A- 4	+4.18	+ 9 600		+ 9 600	9800	10 400
A-11	-4.26	- 9 900	C	- 9 900		

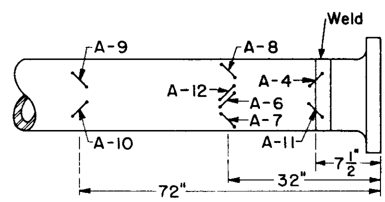
* $\sigma = \frac{E}{1-u^2}\left(\epsilon_x + u\epsilon_y\right)$

where E is the modulus of elasticity, assumed as 3×10^7 pounds per square inch

ϵ_x is the strain measured in the direction of stress

ϵ_y is the strain measured normal to direction of stress

u is Poisson's ratio, assumed as 0.3



Gage Locations

** Deduced Shear Stress = $\frac{\text{Tensile Stress minus Compressive Stress}}{2}$

† Theoretical Stress = $\frac{Td_1}{2I_p}$ where T is the torque in inch-pounds

d_1 is the outside diameter of shaft = 8.8 inches

I_p is the polar moment of inertia of shaft = $\frac{\pi}{32}\left[(8.8)^4 - (5.0)^4\right]$

possibility of premature plastic yielding in the fillets it suggests that the change in slope at the relatively low load resulted from yielding in the bolts.

Torque-strain curves are given in Figure 4. These data are in agreement with the torsion data and show that the proportional limit was reached first in the center section of the shaft. They also show that the shaft yielded last in the vicinity of the weld. Figure 1 shows that the inside diameter is smaller in the flange piece than in the main shaft section. Therefore at the weld the section modulus is slightly greater than in the main shaft section and the weld would be expected to yield last if the material of both shaft and weld were homogeneous.

Shear stresses deduced from measured strains are compared in Table 1 with theoretical shear stresses based on the shaft dimensions. Stresses obtained by the two methods are in good agreement.

The testing conditions were not favorable for the use of strain-indicating lacquer and data from this source were not conclusive. Temperature and humidity variations during the preparatory period and the test greatly exceeded those permissible for satisfactory results. Furthermore, the method of loading required about six hours to reach the yield load, and this permitted plastic flow of the lacquer.

Tensile test data from specimens cut from the shaft are included in Appendix 1. They show a yield strength of 39,000 pounds per square inch. Since the yield stress in pure shear is about 0.6 times the yield stress in pure tension, the shear yield strength for this steel based on the tensile test data would be about 23,000 pounds per square inch. The test result of 21,000 pounds per square inch is in fair agreement with this figure.

CONCLUSIONS

1. The weld showed satisfactory mechanical properties in that it was stronger than the main shaft. The endurance strength of the weld was not investigated.

2. The shaft showed uniform properties and yielded throughout its length at approximately the same torsion load.

3. The yield stress was slightly lower than might have been expected on the basis of tensile tests of shaft samples.

RECOMMENDATION

Shafts manufactured in this manner should prove satisfactory, but they should be given endurance and service tests by installing them in operating vessels.

REFERENCE

Charleston Navy Yard letter report DE281-300(2)/S43/D11(N-3-34) of 21 September 1942.

APPENDIX 1

HISTORY* OF CENTRIFUGALLY CAST STEEL SHAFT SUBJECTED TO TORSION TEST

The shaft was manufactured by the American Cast Iron Pipe Company of Birmingham, Alabama. It was composed of two flanged sections, one 13 feet 9 1/2 inches long (1009A), and the other 6 1/2 inches long (1051A), welded together to form an intermediate shaft, as shown on Charleston plan DE-38-2, piece 101.

The chemical analysis of the metal is given in Table 2.

TABLE 2

	C	Mn	P	S	Si
Shaft 1009A	0.32	0.78	0.041	0.024	0.41
Flange 1051A	0.35	0.87	0.045	0.019	0.31

The fabricating operations were performed at the Charleston Yard in the order listed

1. The shaft castings were tested by the Magnaflux method and found to be satisfactory.
2. The two sections were normalized in an oil-fired, high-ceiling furnace, where they were held at 1650 degrees Fahrenheit for 4 hours. They were then withdrawn from the furnace and cooled in still air.
3. Samples were cut from the normalized shaft and drawn at 1200 degrees Fahrenheit for 3 hours. Test specimens turned from these samples gave the following results:

Diameter inch	Yield Point lb/in^2	Tensile Stress lb/in^2	Elongation per cent	Reduction of Area per cent	Hardness Rockwell B	Bend Test degrees
0.505	39 400	69 950	31.0	32.0	70-73	180
0.505	39 000	68 750	30.0	39.0	71-75.	180

* Summarized from enclosure (H) of Charleston Navy Yard Report DE281-300(2)/S43/D11(N-3-34) of 21 September 1942.

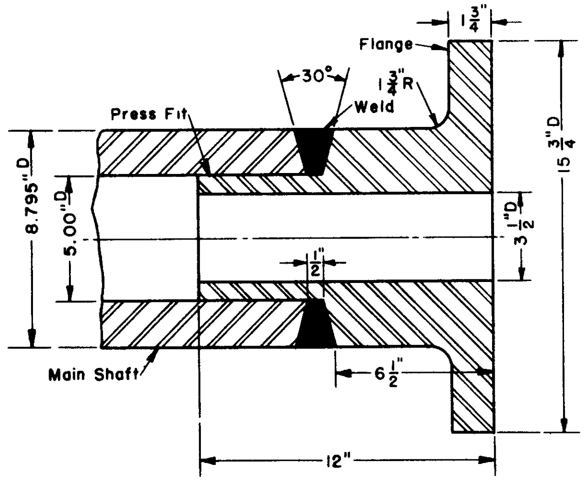


Figure 1 - Section through the Shaft Weld

4. For welding, a 30-degree included angle with a 1/2-inch root opening was used, as shown in Figure 1. The first pass was made with 3/16-inch diameter, Grade EA, Class II electrodes, using direct current with straight polarity. The first pass was magnafluxed and found to be free from cracks. The succeeding passes were made in the same way except that 7/32-inch diameter electrodes were used.
5. Radiographs of the weld showed it to be free from flaws.
6. The welded shaft was then drawn at 1200 degrees Fahrenheit for 3 hours and allowed to cool in the furnace.
7. The shaft was machined all over on the outside. The whole shaft section between the flanges, including the weld, was turned down to a diameter of 8.795 inches. The inside of the shaft was not machined.