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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE STRENGTH AND ENDURANCE OF PLASTIC-IMPREGNATED FIBERGLASS COMPRESSOR BLADES

By Donald F. Johnson and André J. Meyer, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF THE STRENGTH AND ENDURANCE OF PLASTIC-IMPREGNATED FIBERGLASS COMPRESSOR BLADES

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SUMMARY

Compressor blades made of fiberglass impregnated with phenolic resins were subjected to several strength tests including tensile, cantilever bending, cantilever torsion, fatigue, and damping tests.

The modulus of elasticity was calculated using the standard formula for bending deflection of a cantilever beam and utilizing tensile-test data. The result of the formula method was $E = 4.37\times10^6$ psi, and of the data method, $E = 3.03\times10^6$ psi. The dynamic modulus of elasticity was calculated to be 3.63×10^6 psi.

The modulus of rigidity was 0.92×10^6 psi. The ultimate tensile strength was 17,000 psi, the ultimate bending strength was 43,000 psi, and the fatigue endurance limit at zero mean stress was 15,000 psi.

The third-stage rotor of a jet engine equipped with a full set of fiberglass blades was run for 105 hours, 28 of which were at rated speed. After 105 hours running time, no damage to the blades was apparent.

INTRODUCTION

The present trend in axial-flow compressor design is toward higher aerodynamic blade loading and longer blades of higher aspect ratios, both of which greatly increase the blade vibration problem. Compressor diameters are also being increased so that the compressor can handle more air; as a result, it becomes heavier and requires larger quantities of critical materials. New materials are being sought to alleviate these pending problems as well as the existing vibration problem. One of the new materials, laminated fiberglass bonded with plastics, is particularly promising. It is lightweight (one-fourth the weight of steel), has very high internal damping to reduce vibrations, and is noncritical, easily formed, and readily available. The laminated material has been

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suggested for the rotor and for the compressor casing, but this report is concerned only with its use for rotor blading.

According to the available literature, laminated fiberglass blades have not yet been run successfully in an engine. The object of this investigation was to endurance-test in a J47 compressor a full third-stage rotor of laminated blades impregnated with a phenolic resin. In addition, physical properties of the new material were established by bending, twisting, rupturing, and fatiguing individual blades identical to the blades used in the engine. 3306

SYMBOLS

The following symbols are used in this report:

A	amplitude of vibration
a_n	mode constant
d	deflection
E	modulus of elasticity
G	modulus of rigidity
$f(I)$	function of distribution of moment of inertia
$\varphi(I)$	function of distribution of moment of inertia
$F(K)$	polar moment of inertia function
l	length
n	number of cycles
P	load
T	torque
δ	logarithmic decrement
θ	angular displacement
μ	mass per unit length
ω	fundamental bending frequency

Subscripts:

n number of cycles

p plastic blade

s steel blade

0 start of decay curve

APPARATUS AND PROCEDURE

Fabrication of Fiberglass Blades

The compressor blades with which this investigation is concerned were made of approximately 56 laminations each of fiberglass cloth 181-114 impregnated with CTL 91LD phenolic resin. The impregnated cloth was supplied by Cincinnati Testing and Research Laboratories to Thompson Products, Inc., who fabricated the blades according to specification TAP-MS-210. The blade airfoil was built up of usually 20 laminations each about 0.008 inch thick with laminations on the outside surface equal in width to the chord of the blade and decreasing in width toward the center. The base of the blade flared out to a bulb shape, necessitating about 36 additional laminations. The whole was covered with a sheet of phenolic-impregnated 120-114 glass cloth designated TAP-MS-211. The blade was then cured in a die at approximately 300 psi at 320° to 330° F for 5 minutes. The die-cast aluminum roots were cemented in place on the blades with an epoxy adhesive. The assembly is shown in figure 1, and a comparison of the cross-sectional properties of steel and fiberglass blades is shown in figure 2. The bakelite-impregnated blades mentioned later in the report differed in that the laminations were widest at the center and became narrower toward the surface.

Determination of Physical Properties

Because physical properties of plastic-impregnated fiberglass depend on the shape of the test specimen, tests were performed on actual blades rather than on test panels.

Bending test. - Weights were attached to the end of a blade using a clamp made of a low-melting-point alloy. This clamp fit the airfoil profile perfectly from leading edge to trailing edge and spanwise 1/2 inch from the tip. Figure 1 shows a fiberglass blade and the clamp.

Weights from 1 to 8 pounds in 1-pound increments were suspended from the tip clamp in a direction which imposed compression on the concave side of the blade, and the deflection for each weight was measured with a dial gage at the tip. This procedure was repeated with each of five fiberglass blades and four standard 403 martensitic stainless-steel blades. The last fiberglass blade was loaded in 1-pound increments until failure, and the tip deflection was measured as before with a dial gage. In addition, the stress at the point of maximum thickness on the convex side at the base of the blade was measured up to failure with a bakelite, wire-resistance strain gage.

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The formula for the deflection at the tip of a cantilever blade of arbitrary distribution of moment of inertia along the span and with a concentrated load at the tip is

$$d = \frac{Pl^3}{3E} f(I)$$

where $f(I)$ is a function depending on the distribution of moment of inertia along the span. Comparing the deflections obtained from the steel blades with those from the fiberglass blades and assuming the lengths and the moment of inertia distributions to be the same gave an expression for the bending modulus of elasticity of the fiberglass blade in terms of the known modulus of elasticity of steel.

$$E_p = \frac{d_s}{d_p} E_s$$

The value used for the modulus of elasticity of 403 stainless steel was 28×10^6 psi.

Torsion test. - The end of the blade tip clamp was supported by a ball bearing at the approximate center of torsion so that there could be no bending of the blade. A torsional lever arm and a pointer were attached to the clamp. Several torques ranging from 0 to 120 inch-pounds were applied by hanging weights on the lever arm. Angular deflections were obtained using the pointer and a fixed scale.

The formula for the angle of twist of a cantilever blade due to a moment at the tip is

$$\theta = \frac{Tl}{G} F(K)$$

where $F(K)$ is a function of the polar moment of inertia. Comparing the angular deflections obtained from the steel blades with those from the fiberglass blades and assuming the lengths and the torsional spring constant functions to be the same yielded an expression for the modulus of rigidity of the fiberglass blade in terms of the known modulus of rigidity of steel.

$$G_p = G_s \frac{\theta_s}{\theta_p}$$

The value used for the modulus of rigidity of the steel blade was $G = 10 \times 10^6$ psi.

Tension test. - Approximately 2 inches of the end of a blade was immersed in a low-melting-point alloy. In this way a contour-fitting form similar to the tip clamp in figure 1, only longer, was obtained. This form was in two halves which were cemented with bakelite to the blade. This clamp along with the metal blade root at the other end supplied the necessary gripping surface for the grips of a conventional tensile machine. The blade was pulled in tension to failure, the strain being measured by a bakelite wire-resistance strain gage mounted at the base of the blade.

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Damping test. - It was desired to obtain blade damping values at high base bending stresses. Because of the low modulus of elasticity of plastic, the strain is much larger in plastic for a given stress than in steel, and it was found that strain gages would not stand up in the desired stress range. Since the stress and hence the strain decreases spanwise toward the tip, two strain gages were mounted on a blade, one at the base and one about halfway between the base and the tip. The blade was deflected by a triggering mechanism and rapidly released, and the decay curve was recorded on film. Data were taken at progressively larger deflections of the tip of the blade using both strain gages until the gage at the base failed, and then from the gage at midspan only. Thus, the stress at the location of the outer gage was calibrated against the stress at the base. This calibration was used to compute the stress at the base for large deflections.

The damping was calculated by measuring the amplitude of the decay curve at the start and n cycles from the start and applying the formula

$$\delta = \frac{1}{n} \ln \frac{A_0}{A_n}$$

This procedure was followed for a new blade impregnated with a phenolic resin made by the Bakelite Corporation and for a blade impregnated with the CTL resin and which had vibrated for 1.75×10^7 cycles at a stress of ±15,000 psi. The fundamental bending frequency was determined from the damping curve to be 185 cps.

Fatigue test. - A small air exciter was used to excite blades to vibration (fig. 3). Fatigue tests were run by exciting a blade at its natural frequency at a given tip amplitude until failure.

The formula for the frequency of the fundamental bending mode of a cantilever blade is

$$\omega = a_n\sqrt{\frac{E}{\mu l^4}\,\varphi(I)}$$

Comparing the frequencies obtained for a steel blade with that for a fiberglass blade and considering that l, $\varphi(I)$, and a_n are the same for both blades gave an expression for the dynamic modulus of elasticity 3306
of the plastic blade in terms of the known dynamic modulus of elasticity of the steel blade.

$$E_p = \frac{\mu_p}{\mu_s}\left(\frac{\omega_p}{\omega_s}\right)^2 E_s$$

The values used for the density and dynamic modulus of the steel blade were 0.277 pound per cubic inch and 32×10^6 psi, respectively, and the density of the plastic-impregnated fiberglass blade was experimentally determined to be 0.067 pound per cubic inch.

Engine test. - The third-stage rotor of a J47 was completely outfitted with CTL 91LD impregnated fiberglass blades. The engine was run under static, sea-level conditions as shown in figure 4. The first $28\frac{1}{2}$ hours were at rated speed (7950 rpm); then the speed was reduced to 7800 rpm to decrease the number of breakdowns of engine components other than the compressor. This resulted in a decrease in centrifugal stress of only 4 percent. The engine was run for two 8-hour shifts a day, being shut down, or throttled down to idle, at various times as shown in figure 4 to add oil, change oil filters, and make repairs.

After a total running time of about 105 hours, the compressor was disassembled and the fiberglass blades were examined for damage. As a detector of any internal separation of laminations, two weights were hung on each blade and the deflections were measured using a dial indicator.

RESULTS AND DISCUSSION

The flexural strength of a fiberglass blade in bending is compared with the flexural strength of a steel blade in figure 5(a). The bending modulus of elasticity of the fiberglass blades was calculated on the basis of these data to be 4.37×10^6 psi, and the ultimate bending strength was 43,000 psi. Only the data for blade 5 are plotted, as the fiberglass blades were sufficiently uniform that the data for all blades fell on the straight line shown. Figure 5(b) shows that the tip deflection at failure for the fiberglass blade was 0.899 inch. The load at this point was 31.56 pounds.

The dynamic modulus of elasticity calculated by comparing the natural frequencies of a fiberglass and a steel blade was $E = 3.63\times10^6$ psi.

The torsional stiffness of fiberglass blades is compared with that
3306 of steel blades in figure 6, and the modulus of rigidity was calculated on the basis of this comparison to be $G = 0.92\times10^6$ psi or approximately $\frac{1}{10}$ the value for steel.

The results of the tensile test of a fiberglass blade are shown in figure 7. There possibly was some eccentricity of loading, but the ratio of ultimate tensile strength to ultimate bending strength agrees favorably with ratios reported for plastic specimens. The straight-line variation of stress with strain to failure is to be expected for a rather brittle material. The tensile modulus of elasticity was calculated to be $E = 3.03\times10^6$ psi, and the ultimate tensile strength was 17,000 at a load of 2100 pounds.

A rough S-N diagram (stress against fatigue cycles) showing the fatigue strength of fiberglass blades is given in figure 8. Many more blades would have to be tested in fatigue in order to establish accurately the shape of the curve. However, it can be seen that at a stress above $\pm15,000$ psi, the life of a plastic-impregnated fiberglass blade is limited to 10×10^6 cycles or less. In all cases after 1 or 2×10^6 cycles, an outside lamination at the base appeared to separate from the blade. This separation did not progress any farther at a given stress. Results from the fatigue tests of two fiberglass blades impregnated with phenolic resin supplied by the Bakelite Corporation are also plotted on figure 8. They apparently have about the same fatigue strength as those impregnated with CTL 91LD phenolic resin.

A comparison of the flexural strength in bending of 50 blades after the engine endurance run of 105 hours is shown in figure 9. The uniformity of the blade deflections indicates that no apparent internal damage was sustained by any of the blades. Figure 10 shows damping curves obtained for fiberglass blades impregnated with CTL 91LD and Bakelite resins as compared with those for 403 stainless-steel blades. The damping of a plastic-impregnated fiberglass blade is about 12 percent, with little change due to stress. In comparison, stainless steel has about 3 percent damping.

SUMMARY OF RESULTS

An investigation was made of third-stage J47 compressor blades made of fiberglass impregnated with CTL 91LD phenolic resin and similar blades impregnated with Bakelite resin. The following results were obtained:

Bending modulus of elasticity, psi	4.37×10^{6}
Dynamic modulus of elasticity, psi	3.63×10^{6}
Tensile modulus of elasticity, psi	3.03×10^{6}
Modulus of rigidity, psi	0.92×10^{6} 3306
Maximum tip load for failure (bending), lb	31.56
Tip deflection at failure (bending), in.	0.899
Ultimate bending strength, psi	43,000
Maximum tensile load, lb	2100
Ultimate tensile strength, psi	17,000
Damping, logarithmic decrement	0.12

The J47 jet engine with its third-stage rotor completely equipped with fiberglass blades ran 105 hours, 28 of which were at rated speed, with no apparent damage to the blades.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 1, 1954

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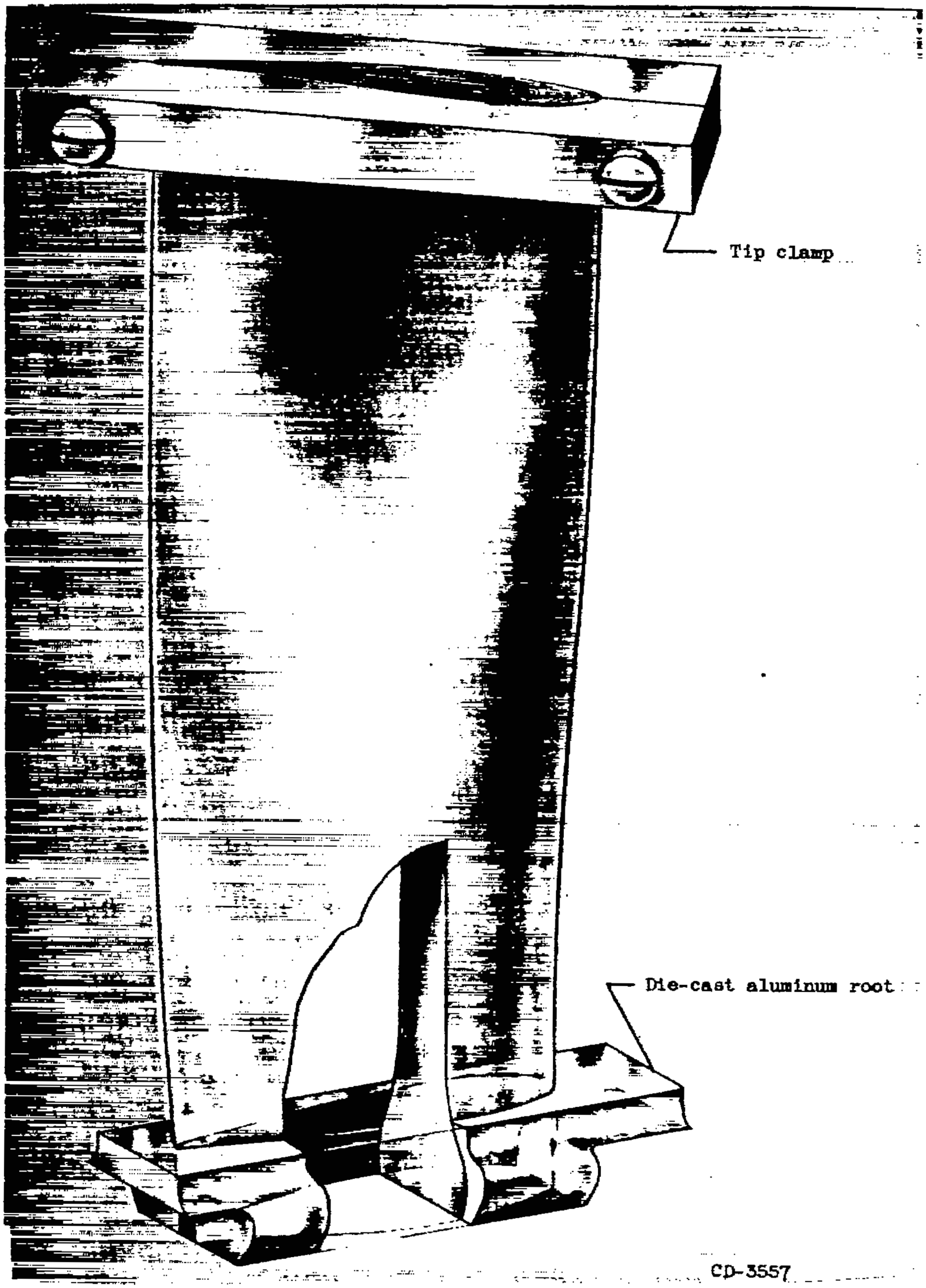

Figure 1. - Fiberglass blade showing tip clamp and die-cast root insertion.

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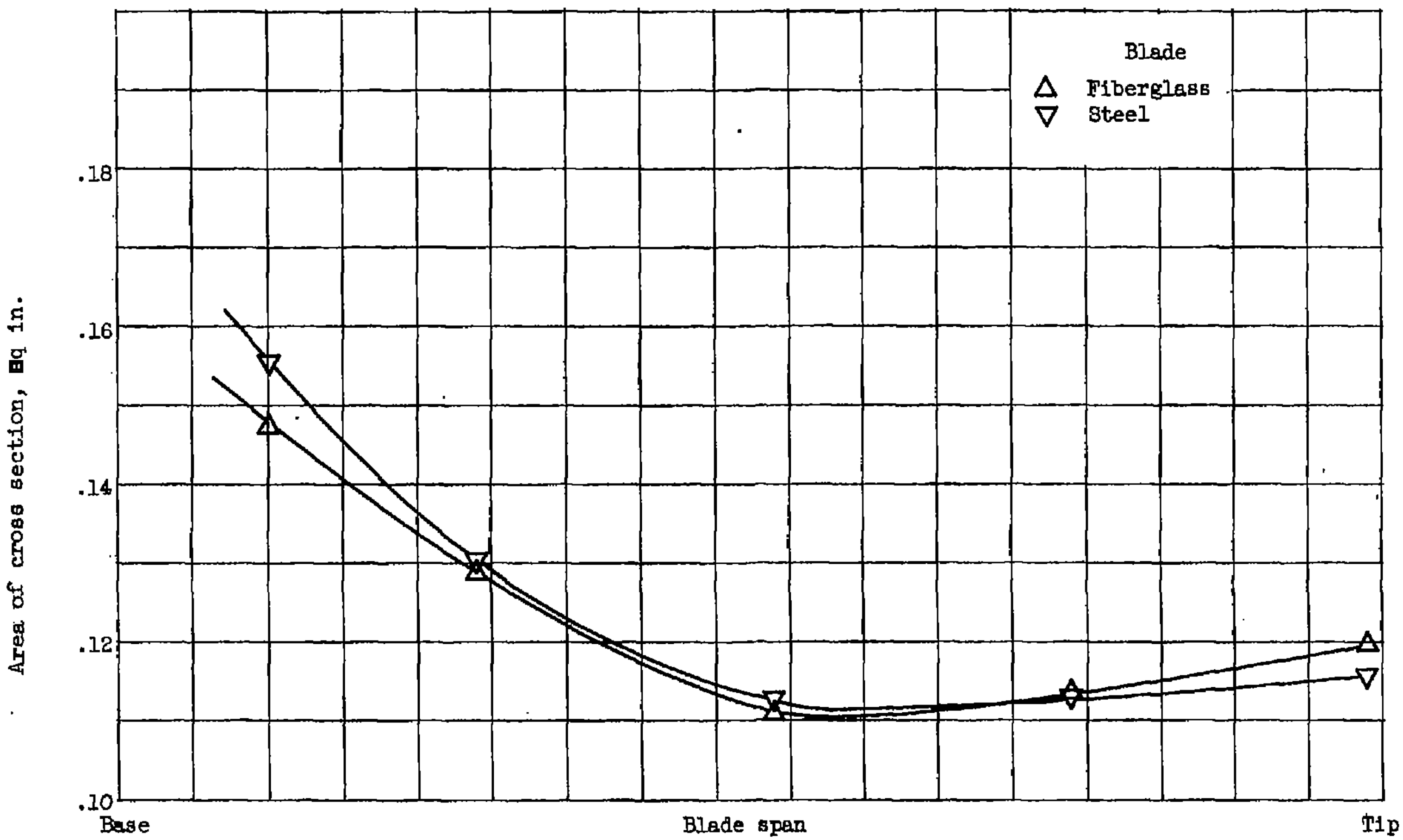
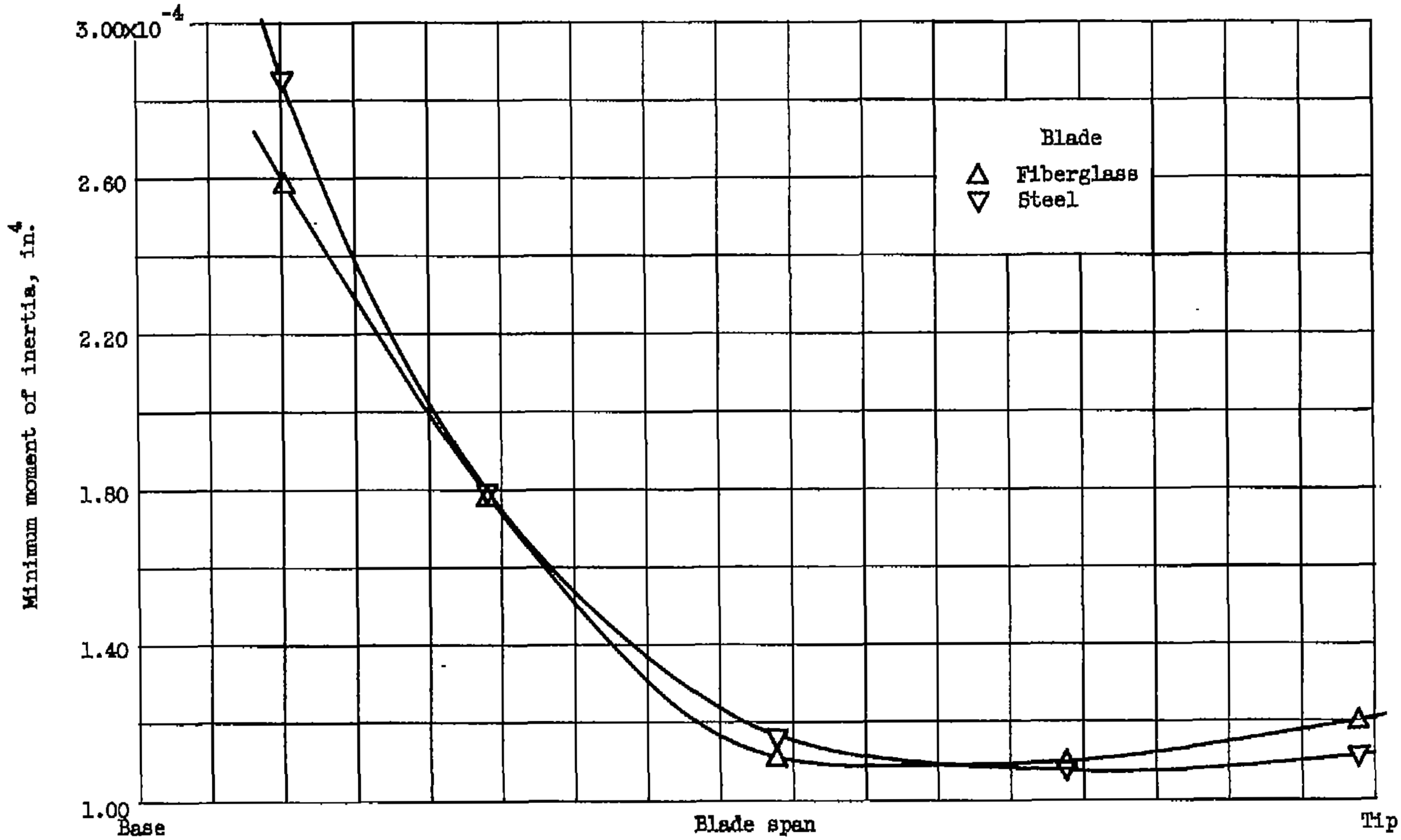


(a) Area.

Figure 2. - Variation of blade cross-sectional properties with span.



(b) Moment of inertia.

Figure 2. - Continued. Variation of cross-sectional properties with span.

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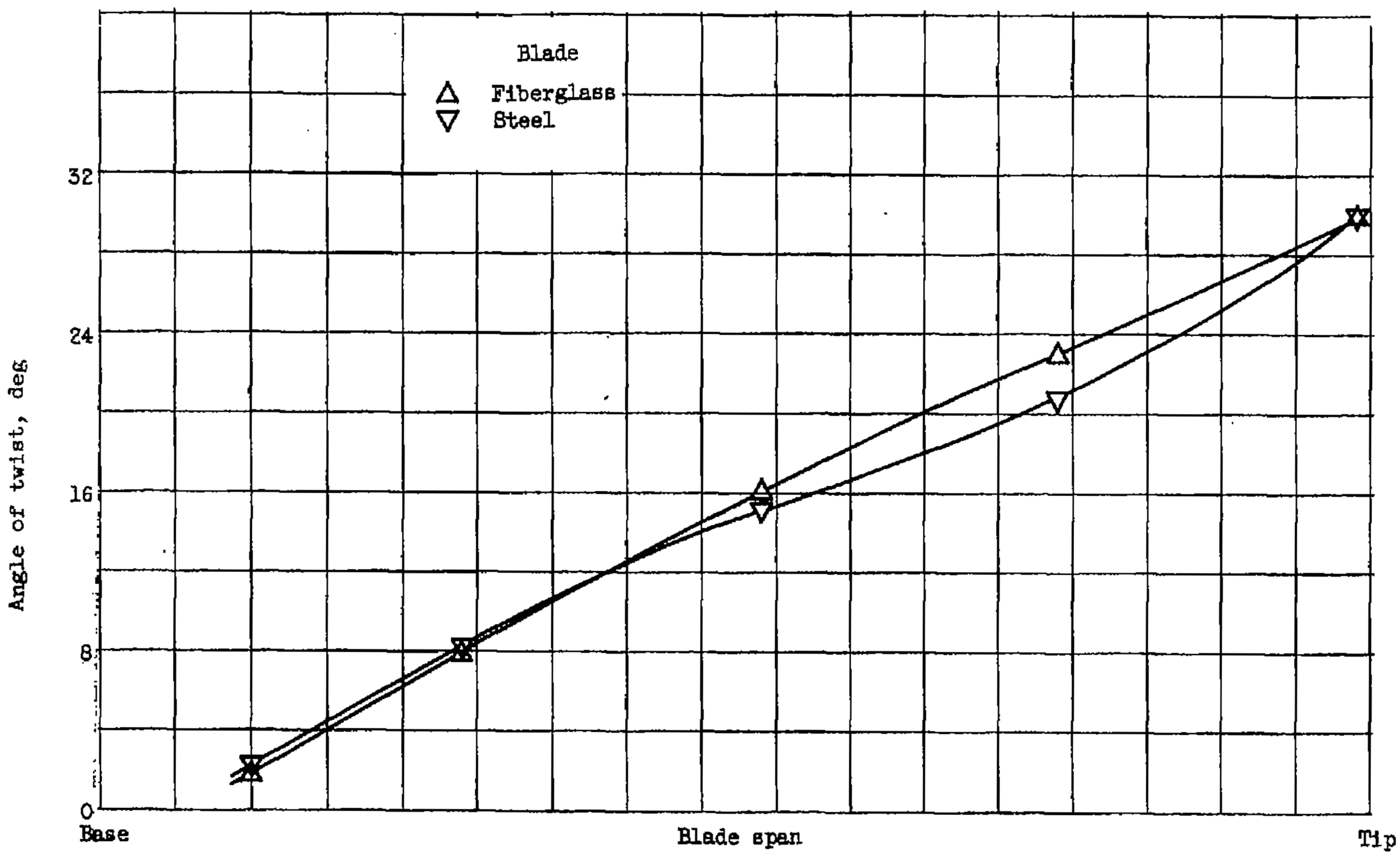

(c) Angle of twist.

Figure 2. - Concluded. Variation of cross-sectional properties with span.

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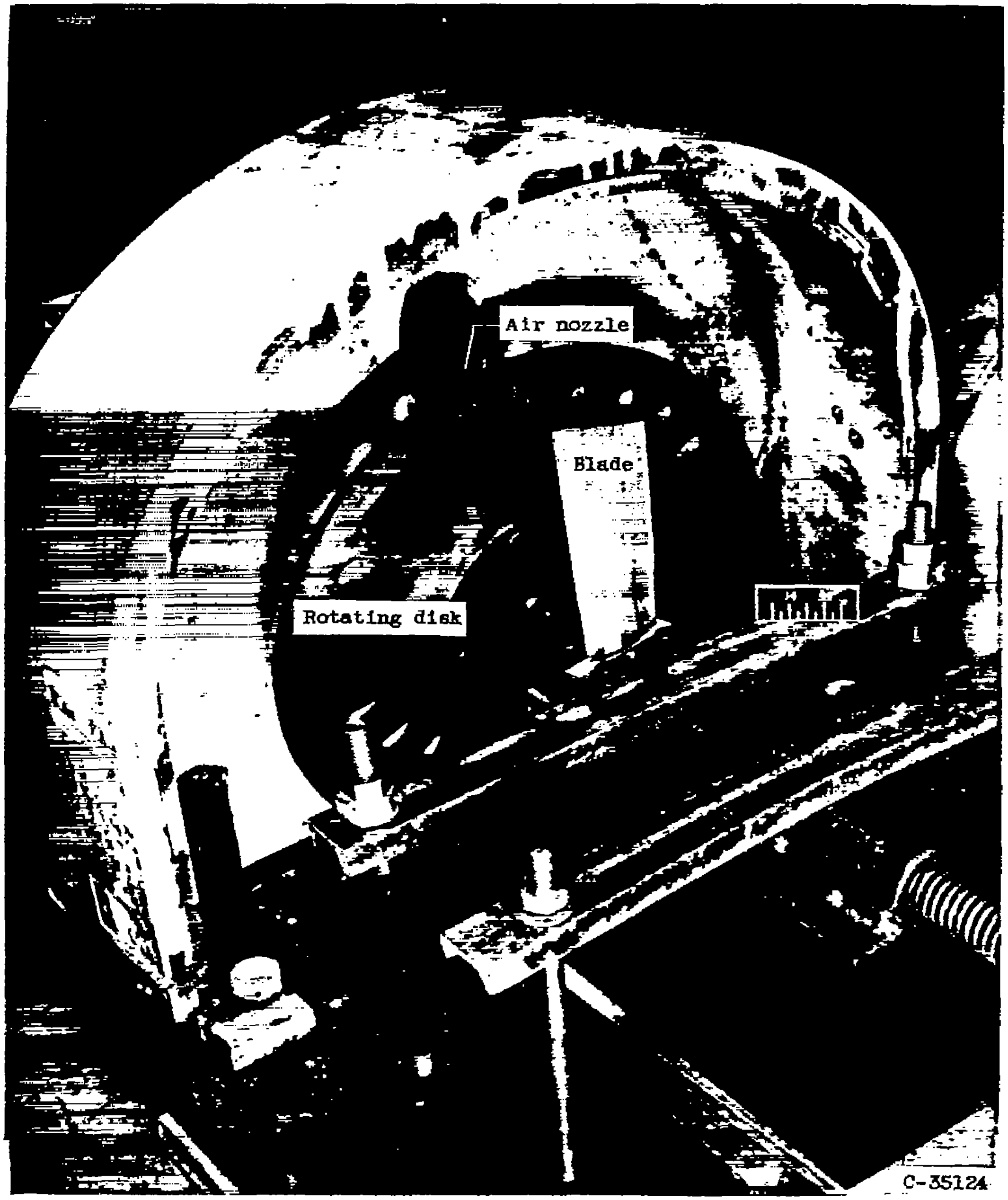


Figure 3. - Air exciter.

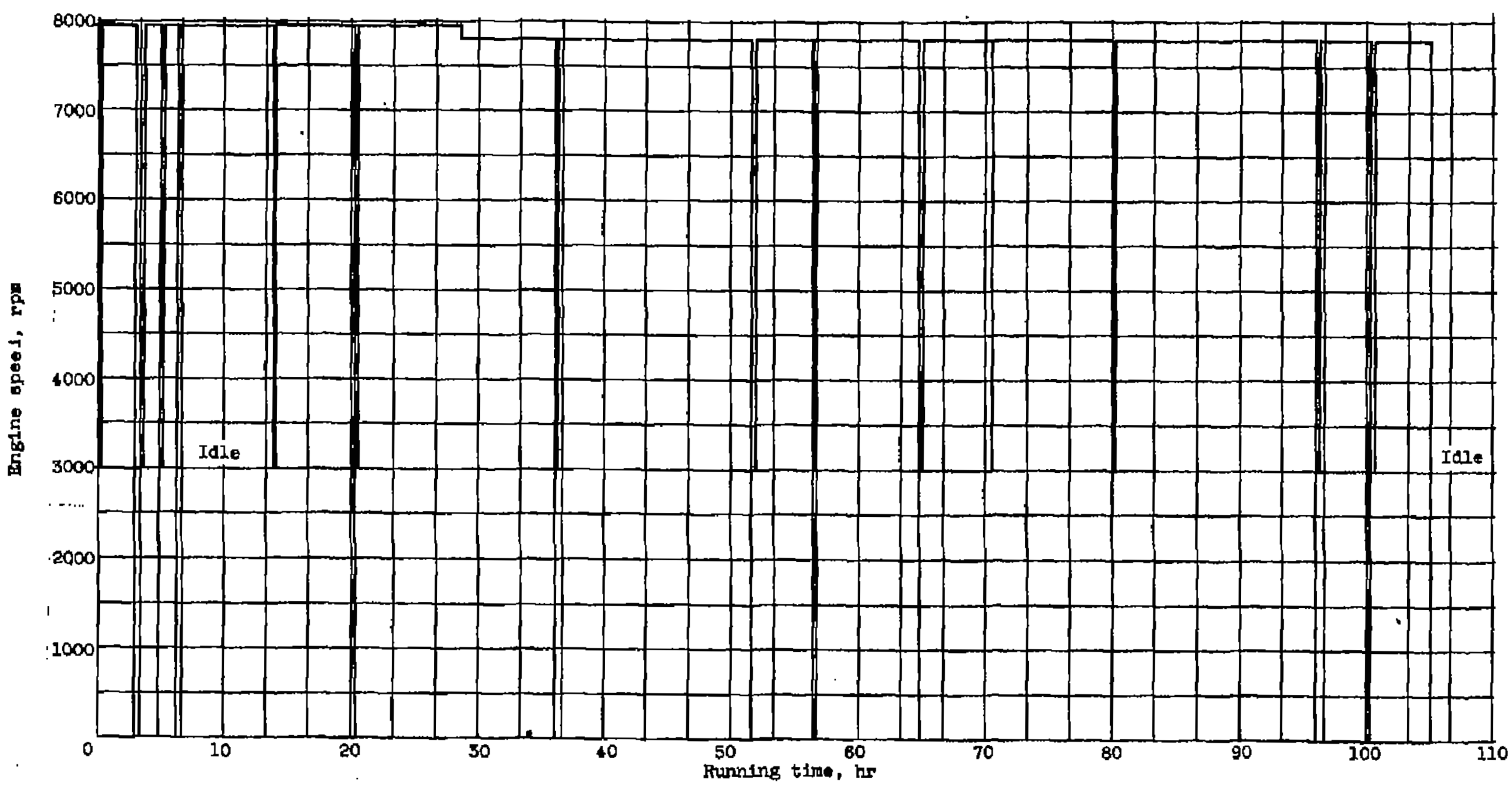
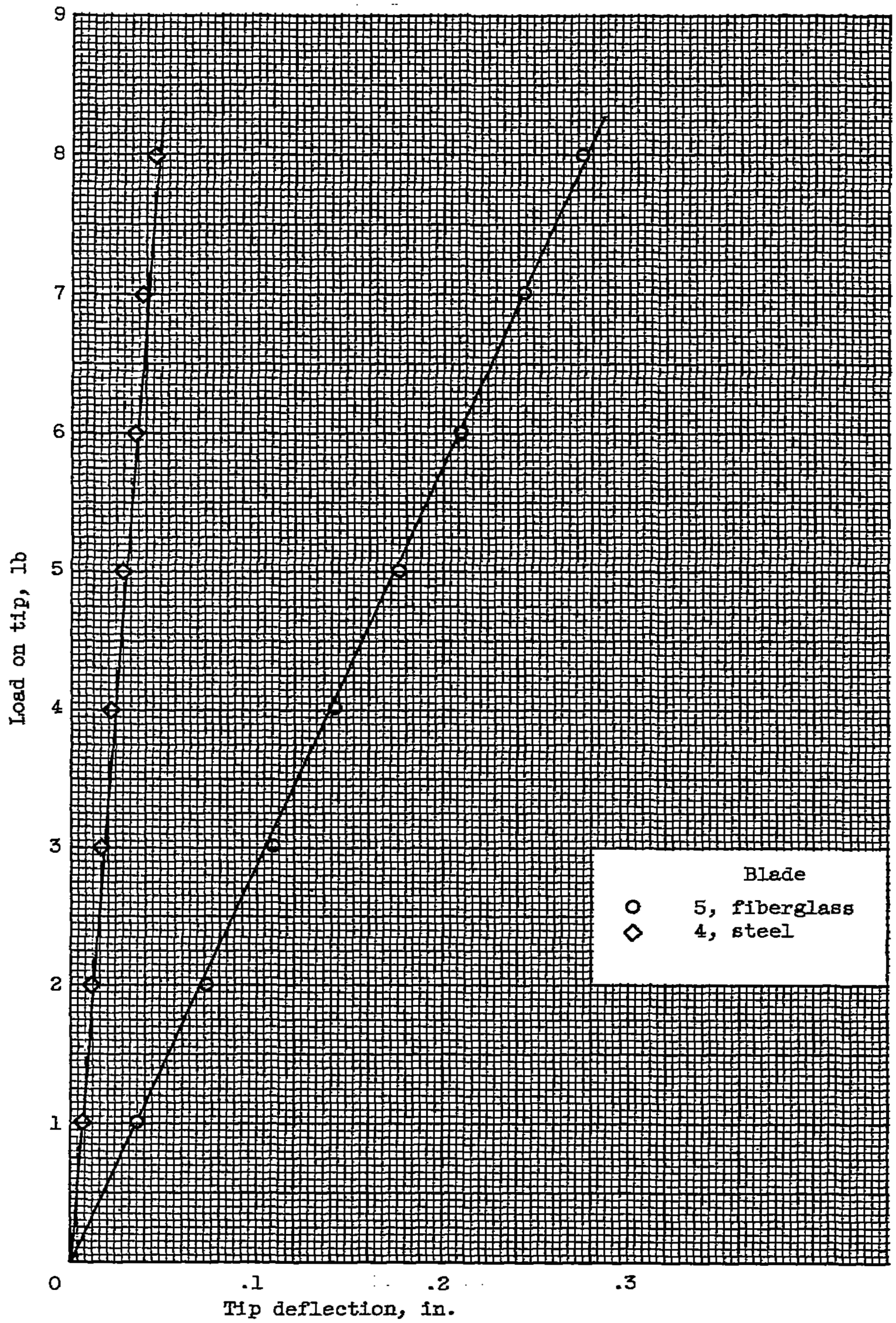


Figure 4. - Engine operation chart.



(a) Comparison of tip deflection of steel and fiberglass blades.

Figure 5. - Results of bending tests.

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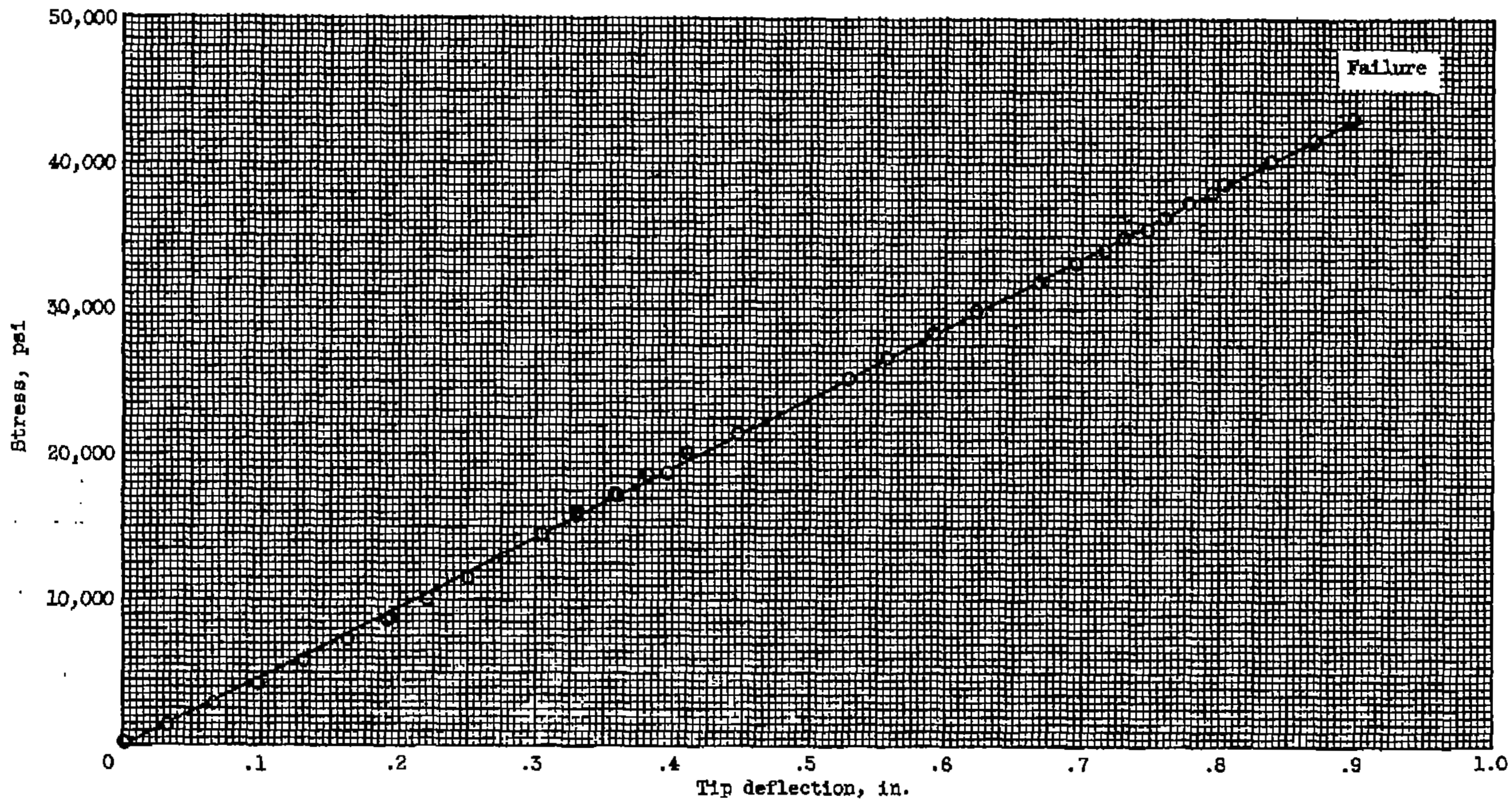

(b) Bending of fiberglass blade to failure.

Figure 5. - Concluded. Results of bending tests.

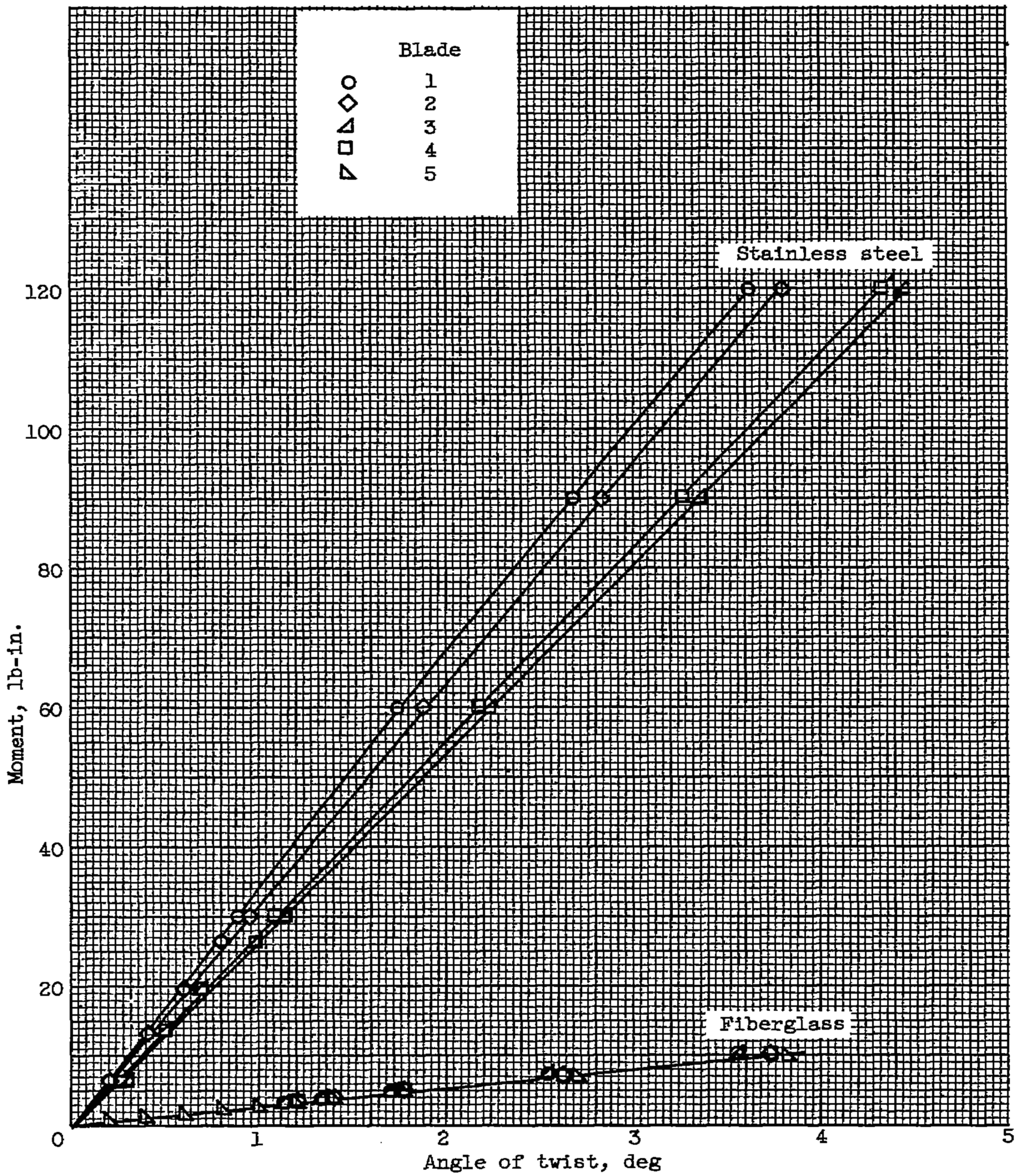

Figure 6. - Variation of angle of twist with moment.

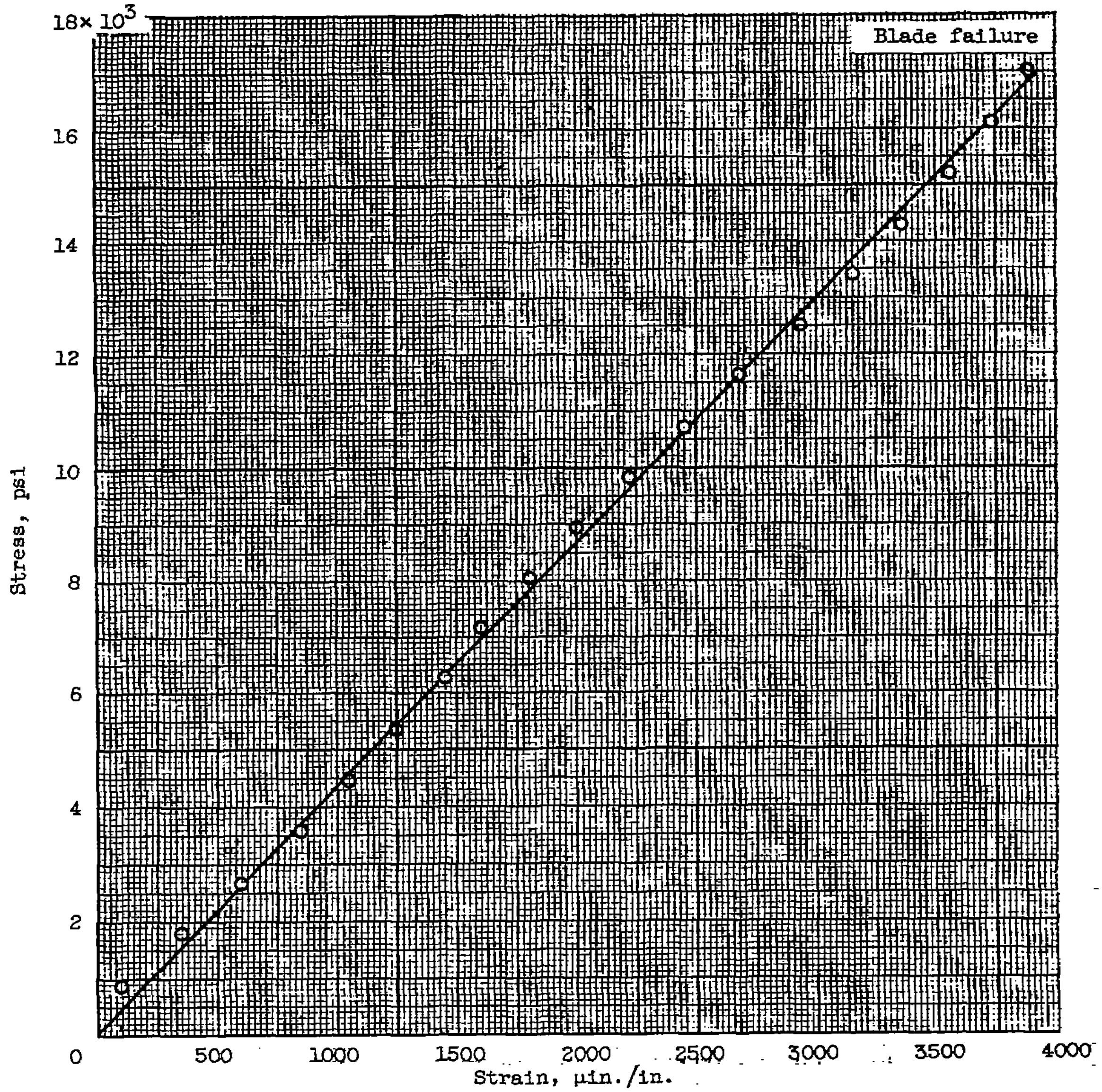

Figure 7. - Stress-strain curve of fiberglass blade.

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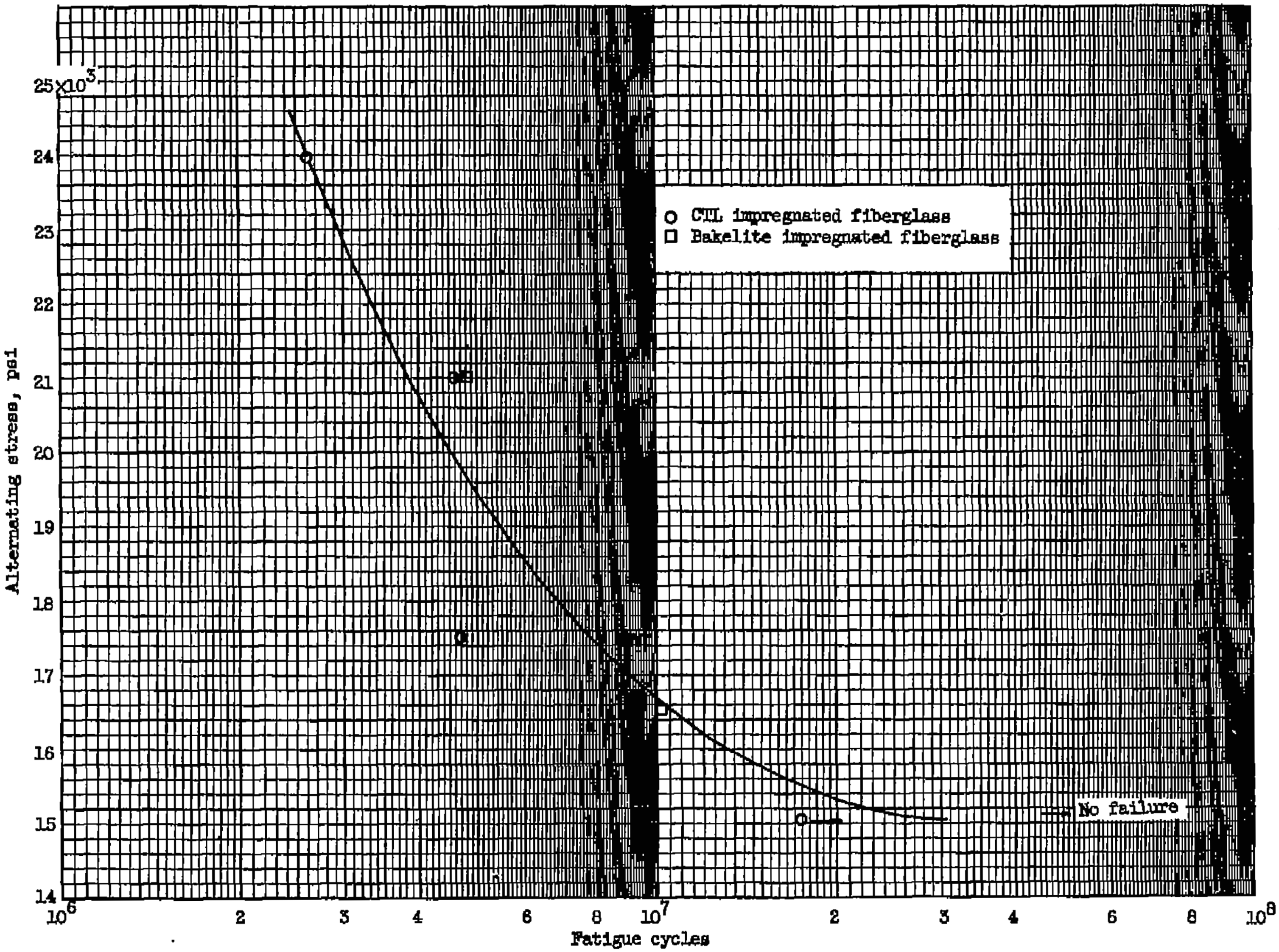

Figure 8. - Fatigue limit diagram.

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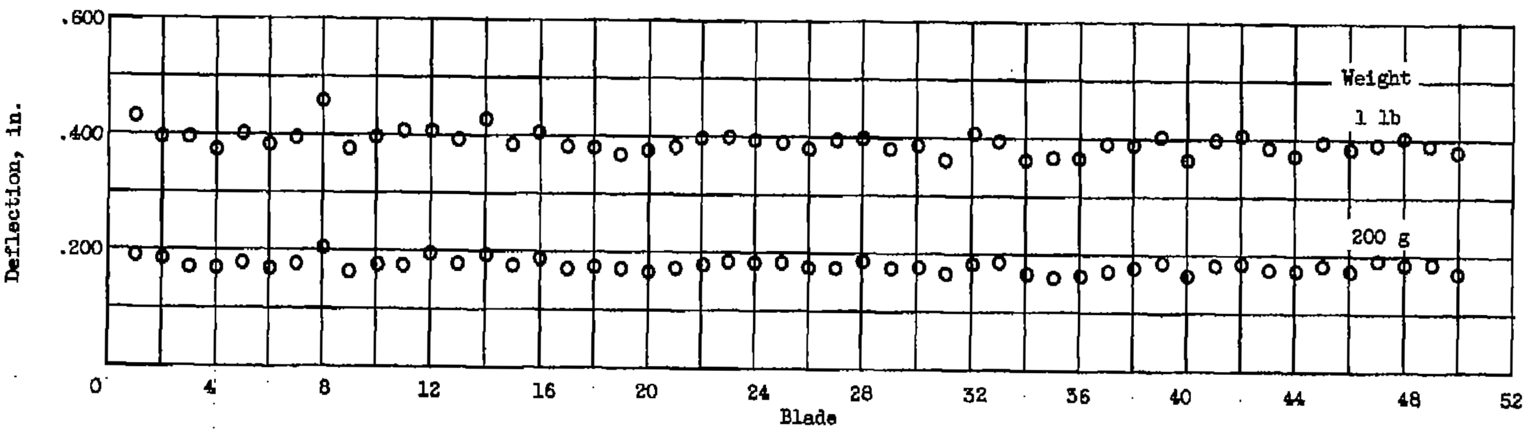

Figure 9. - Flexural strength of fiberglass blades after 105 hours running time in engine.

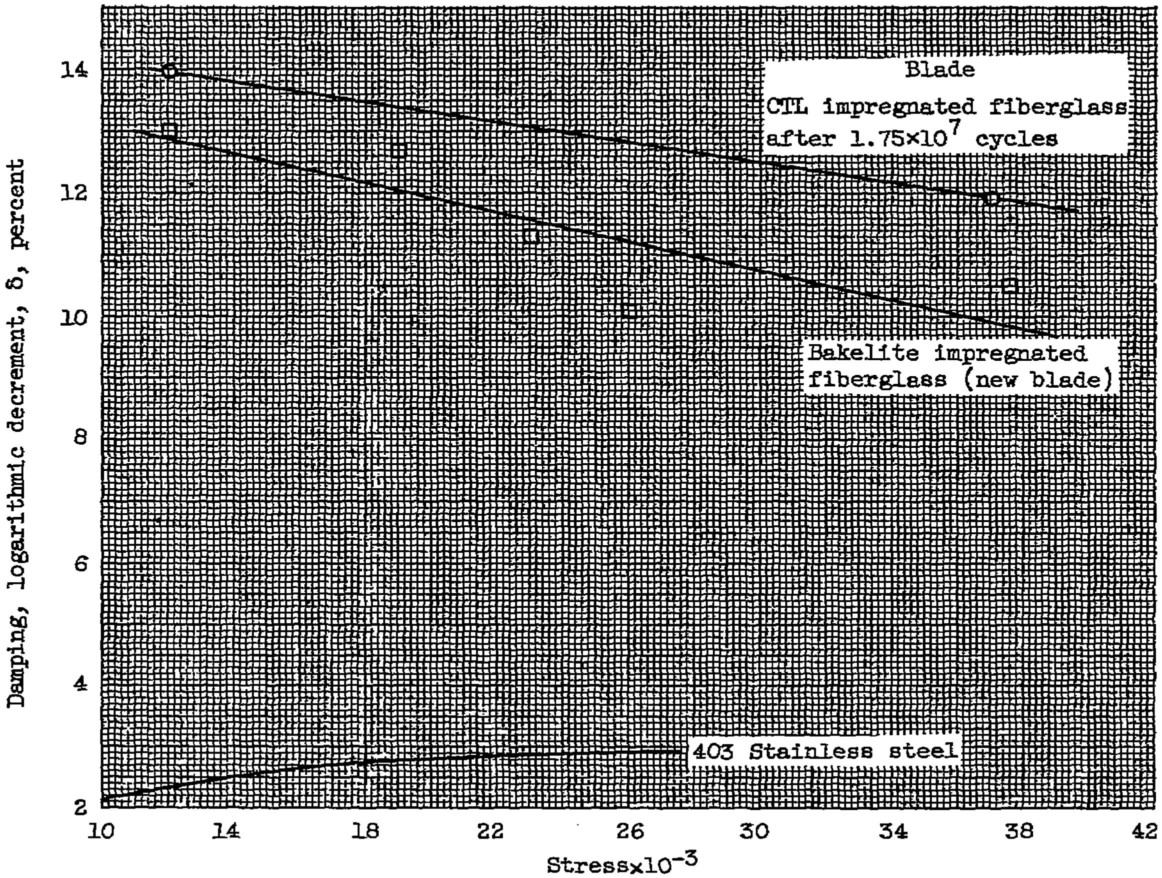

Figure 10. - Variation of logarithmic decrement with stress.

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