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TECHNICAL NOTE 3275

INVESTIGATION OF THE EFFECT OF IMPACT DAMAGE ON FATIGUE STRENGTH OF JET-ENGINE COMPRESSOR ROTOR BLADES

By Albert Kaufman and André J. Meyer, Jr.

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Cleveland, Ohio

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SUMMARY

An investigation was undertaken to determine the effect of type and location of impact damage on the fatigue strength of jet-engine compressor blades. First-stage compressor rotor blades from a production engine which had suffered foreign-object damage were fatigue tested. The results showed that the most serious damage to the blades, as measured by the reduction in fatigue strength, was nicks at the leading and trailing edges in the vicinity of the maximum-vibratory-stress section of the airfoil. The farther the damage was from this section, the smaller was the decrease in blade strength. Nicks and dents on the pressure surface of the airfoil away from the leading and trailing edges did not reduce the strength. Dents were less serious than nicks, and the strength of dented blades could be restored by reworking them. The strength of seriously nicked blades could not be reliably restored by reworking.

INTRODUCTION

One of the main problems today in the maintenance of axial-flow jet engines is impact damage to compressor blades due to foreign objects. Large objects such as engine parts or tools accidentally left in the inlet ducting can cause almost instantaneous destruction of the compressor when the engine is started. Smaller objects such as pebbles and metal particles can cause damage to a blade that is only a slight nick or dent barely visible to the naked eye; yet, this damage can result in a large loss in the fatigue strength of the blade. If running is continued with a damaged blade, fatigue failure may result (because of the prevalence of repeated stresses in compressor blades) and cause a chain reaction of blade failures.

The installation of inlet screens as advocated in reference 1 would probably prevent large objects from entering the compressor, but would not solve the damage problem caused by small foreign objects. A very

fine mesh screen cannot be used, because the drag would be excessive and the air weight flow would be seriously reduced. There is, therefore, a minimum practical size of screen mesh which can be used. Many objects capable of damaging blades can pass freely through these small screen openings.

Another proposal to minimize compressor failure of this type is to inspect engines more frequently and thereby detect damaged blades before failure occurs. However, the inspectors could not reject every compressor with a minute blade defect, or the result would be the overhauling of almost all jet-engine aircraft after a few hours of flight operation. The merit of this approach, therefore, depends upon an accurate knowledge of the effect of damage of various degrees and in various locations. 3936

A third solution to the foreign-object damage problem would be to make more rugged compressor blades with greater resistance to impact damage. Here too, the merit of the approach is dependent upon the knowledge of the effect of damage, and the efficient use of materials that are more resistant to impact damage.

Both the inspector and the blade designer, therefore, require more information on the effect of foreign-object damage on blade strength. The inspector needs to know what type of damage to look for, and where to look for it, and in order to devise a more rugged blade, the designer should know where the blade is most sensitive to damage from the standpoint of loss of strength.

An investigation was undertaken to determine the effects of impact damage on the fatigue strength of compressor blades. The factors investigated were chordwise and spanwise location, depth, and type of damage, and also the effect of reworking blades with different types of damage. Fatigue strength was the criterion used to determine the extent of damage to blades, because fatigue is the principal cause of compressor failure in jet engines.

Blades that had suffered impact damage while being run in an engine were fatigue tested. From the test results it was determined what parts of the blade were sensitive to impact damage and the effects of the size and type of the damage. Some of the blades were used to see how reworking, such as filing, sanding, and straightening out the damage, affected the strength.

To evaluate the extent of damage, the number of cycles that produces failure at a constant stress level was determined. The investigation was limited by the number of damaged blades available and the range of the damage suffered. The blade damage investigated was what could normally be expected to occur in practice rather than something artificially imposed on the blade.

APPARATUS

This investigation was conducted with rotor blades from an axial-flow engine in which most of the compressor blades had suffered some impact damage.

The engine was of a type used in large quantities by the military services and was received new for use in a static test stand for research unrelated to the foreign-object damage problem. Although the engine was equipped with an inlet screen, during operation a foreign object had entered the compressor. The exact size and nature of the object were unknown, but, judged from the type of damage it caused, it was small, hard, and sharp edged.

Forty first-stage compressor blades which had been damaged to some extent were removed from the rotor and used for this investigation. One of the blades is shown in figure 1; some were more and others were less severely damaged. The damage defects were distributed over the pressure surfaces and the leading and trailing edges of the airfoils. None of the blades suffered damage on the suction surface. In this report, breaks or tears in the surface of the metal are called nicks, whereas surface deformations without breaks are termed dents (fig. 2).

The first-stage blades were fabricated from type 403 stainless steel which had been heat treated to a Rockwell B hardness of approximately 104. The airfoils of these blades were about $5\frac{1}{2}$ inches long and the base chord length was $1\frac{1}{2}$ inches.

The blades were excited in the first bending mode by an air blast from a nozzle directed at the blade tips (fig. 3). The blades were mounted in a clamp bolted to a bedplate. Bolts were tightened against the bottom of the blade root. This was done to impose, as closely as possible in the test rig, the same clamping action against the blade root that occurs during actual engine operation.

The tip deflections of the vibrating blades were measured with an optical extensometer. The natural frequency of each blade was measured with the aid of an induction pickup. The pickup, mounted on a frame, was held close to the blade tip. The signal from the pickup was fed into an oscillograph and the natural frequency was determined with an oscillator.

To record the number of cycles to failure for each blade, the induction pickup was also connected to a frequency meter and a chart recorder. When the blade began to fail, the frequency as recorded on the chart would drop off sharply. This equipment enabled the rig to be run

continuously without constant observation until the blade failed or 100 million cycles were reached. Another chart recorder was used to record the air-pressure variations during the fatigue tests. It was found that the maximum variation in air pressure was only 0.5 percent during periods of several days. The use of the air-pressure recorder was therefore discontinued in later tests.

The stress distribution along the span of an undamaged blade was determined with resistance-wire strain gages, and the tip deflection was calibrated against maximum stress with the strain gages.

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The depths of the defects were measured with a toolmaker's microscope.

PROCEDURE

Reason for Fatigue-Strength Testing

Fatigue-strength testing was the basis on which the loss of blade strength due to damage was evaluated, because mechanical fatigue due to rotating stall or stall flutter, particularly at part-speed operation is the principal cause of compressor failure in jet engines.

No tensile component was added to the blade tests, because at the speed at which the maximum vibrations occur in this engine, the centrifugal stress is comparatively small. At rated speed the centrifugal stress in the critical- or maximum-vibratory-stress section of the airfoil is 19,300 psi. A vibration survey of the engine from which these blades were taken showed that at the speed at which the maximum vibration occurs the centrifugal stress is only 43 percent of that at rated speed.

To find the effect of the centrifugal stress on the fatigue strength, a modified Goodman diagram (fig. 4) was constructed. For the steady-state or mean working stress of 8300 psi (43 percent of 19,300 psi), the maximum working stress from figure 4 is 72,000 psi. The allowable vibratory stress is then ±63,700 psi (72,000 psi - 8,300 psi). The fatigue strength of the blade was reduced only 6.4 percent by centrifugal force.

At the speed of the maximum vibrations the gas bending stress is 7100 psi. The total steady-state stresses are therefore 15,400 psi (7100 psi + 8300 psi), and the reduction in the allowable fatigue stress due to the combined gas bending and centrifugal stresses is 10.9 percent. The reason for not imposing a static-stress component on the blades to simulate the gas bending and centrifugal forces was the complexity required to add these loads and still be able to vibrate the blade.

It should also be pointed out that the static tensile and static bending strengths are relatively insensitive to stress raisers in the ductile materials used for most compressor blades. A ductile material, however, under cyclic loading becomes comparable to a brittle material under static loading in its sensitivity to surface discontinuities such as the nicks and dents in these blades. In reference 2 the stress-concentration effects of discontinuities on fatigue of metals are discussed. It is virtually impossible to analytically determine the localized concentration of stress due to damage because stress-concentration factors are functions of variables such as the notch sharpness and depth, specimen size and shape, work hardening, plasticity, and grain size. The smallest radius at the base of the nick or dent is the most sensitive parameter on the stress-concentration effect and this radius is seldom measurable. The blade nicks and dents could only be classified according to depth and span location, which were measured for every defect on every blade before any testing was done.

Vibratory Stress at Critical Section

To find the normal location of failure, several undamaged blades were vibrated at a high stress level to failure. A resistance-wire strain gage was then attached to an undamaged blade at the thickest part of an airfoil section on the suction surface at the normal location of failure. The force of the air blast was increased in small increments, and the tip deflection and the stress at the strain gage were measured for each increment. From these measurements was plotted the calibration curve of tip deflection against the maximum vibratory stress at the critical section of the blade (fig. 5). This did away with the necessity of mounting strain gages on all the blades to be tested; the stresses at the critical section were subsequently estimated by measuring the tip deflection and determining the corresponding stress from figure 5.

The stress distribution along the span of the airfoil was found by mounting strain gages at various span locations on the thickest parts of the suction surface of another undamaged blade.

Fatigue Curve

The stress against blade-life curve for the blade material, type 403 stainless steel, was established from a previous investigation in which blades of the same material from an engine of a different make were fatigue tested. This curve is shown in figure 6 together with some data points from the fatigue tests of the undamaged blades in this investigation. The data points match the stress against blade-life curve reasonably well so that it can be considered applicable to the damaged blades. The endurance limit of the blade material from figure 6 is about 68,000 psi.

Testing and Analysis

Most of the damaged blades were fatigue tested with a nominal stress in the critical section slightly above the endurance limit of the material. This high stress level insured failure of all the blades tested. The blades were vibrated in the first bending mode. From the natural frequency and the time to failure, which was found from the frequency chart recorder, the number of cycles imposed on the blade could be calculated. The number of cycles required to produce failure was correlated with the type of damage (nicks or dents), the span and chordwise location, and the depth of the damage. 3936

To evaluate the effects of different degrees and locations of impact damage and to compare types of damage, a factor to indicate the reduction in strength was devised. Normally, stress-concentration factors would serve this purpose, but experimental determination of stress-concentration factors for each damage point requires an accurate knowledge of the stress at the damage point when the damage was not present. The only point where the vibratory stress is known for all the blades is at the maximum-vibratory-stress location.

Reworking

To learn whether the strength of damaged blades could be restored, a number of these blades were tested with the damage reworked. Nicks were reworked by dressing out the surfaces of the nicks with files and emery cloth until no sharp edges were left, leaving smoothly faired indentations in the metal. Dents were reworked by hammering and bending until the blade surface was straight.

DISCUSSION OF RESULTS

Stress Distribution in Blades

In order to see whether the normal location of failure could be predicted analytically, the vibratory-stress distribution for the compressor blade used in this investigation was calculated. Numerical summations of the moments along the airfoil span due to the forces of inertia were computed and were applied to the elementary flexural formula for a number of airfoil sections. The distribution of the maximum vibratory stress determined in this manner is shown in figure 7. The critical or most highly stressed section on this curve is at about 22.5 percent of the span from the base. At this critical section the points farthest from the neutral axis were at the leading and trailing edges and the thickest part of the suction surface; the distances to the neutral axis were about equal for all three points. The vibratory-stress distribution will vary with the blade shape, and for some blades the maximum stresses may be uniform over a sizeable part of the airfoil span. The stress distribution

obtained from the strain-gage measurements is also shown in figure 7. The critical section on this curve is at about 28.5 percent of the span from the base. Since the analytical curve was determined for the maximum-stress point at every section, which sometimes occurred on one of the edges, the two curves of figure 7 were not expected to agree perfectly. The stresses at the blade edges were not measured because of the difficulty of mounting the gages at these points.

A blade, which except for the tip region was initially undamaged, was fatigue tested to failure to determine the failure location (fig. 8). In this blade the crack started at the thickest part of the section on the suction surface. In other undamaged blades, failure started at the leading edge. The spanwise location of failure, regardless of where the failure started chordwise, was always about 30 percent of the span from the base of the airfoil. Both the analytical and measured stress distributions of figure 7 satisfactorily predict the critical section, the experimental curve giving the closest prediction.

To check on whether this critical section was a function of the way the blade was mounted, one of the blades was welded to a heavy block and vibrated to failure. It failed at the 30-percent-span location, thus showing that the type of mounting had no effect on the location of failure.

Fatigue of Damaged Blades

The damaged blades were fatigue tested at ±70,000 psi in the critical section or slightly above the endurance limit of the blade material, type 403 stainless steel. The reasons for conducting the tests at this stress level were to guarantee failure and to find the location of failure with respect to the critical section. Regardless of how much damage a blade has suffered, if there is no damage present at the critical section and the blade still fails there, the blade fatigue strength has not been adversely affected by the damage. If the damage reduces the blade life at a stress of ±70,000 psi, it will reduce the allowable vibratory stress for any given number of cycles on the stress against blade-life curve.

Fatigue Test Results

The results of the fatigue tests are shown in figure 9 in the form of a distribution of blade failures in various increments of span. The percent of blades that failed because of damage in each increment out of the total number of blades tested is shown by the lengths of the bars. The increment from 25 to 35 percent of the span from the base had the most sensitivity to damage. Over 40 percent of the total number of failures of damaged blades occurred in this small region. This was to be expected since the critical section falls within this span increment. The 35- to 45-percent-span region also showed a great sensitivity to damage.

Neither the randomness nor the amount of blade damage is indicated by figure 9. Almost all of the blades suffered damage at locations other than where failure originated. There were also a few blades that failed at the 30-percent-span critical section at high numbers of cycles even though damage had been suffered at other locations. This can be seen in figure 10 where the solid circles denote damage defects where failure originated, the solid squares indicate where failure started when damage defects were not involved in the failure, and the open circles denote damage which did not cause failure.

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From figure 10 it can be seen that nicks and dents were scattered over the whole span of the airfoil with the tip region having a greater concentration of damage. No failure occurred, however, because of defects located within 20 percent of the span from the base or within 25 percent of the span from the tip (in a total of almost half the airfoil span). Figure 10 also shows that there is a sharp reduction in the blade life whenever failure initiated at a damage defect.

In figure 11 the airfoil span is divided into the same increments as in figure 9, but here the number of blades that failed in each increment is correlated with the number of blades that suffered damage in that increment rather than the total number of blades tested. Figure 11 is probably a fairer basis for evaluating the sensitivity of span location to damage than figure 9. From figure 11 it can be seen that in the 25- to 35-percent-span region nearly 90 percent of the blades damaged in that increment had failure originating at the damage. In the 35- to 45-percent-span region about 70 percent of the blades with damage in this region failed because of that damage.

Correlation of Reduction in Strength

All damage defects are compared through a factor based on the known maximum vibratory stress and its location. An explanation of the strength-reduction factor is illustrated by the following examples. It was experimentally determined that undamaged blades when vibrated at ±70,000 psi would sustain about 10^8 cycles before failure (fig. 6). Assume a blade has a defect exactly at the maximum-vibratory-stress point. Also assume that the blade was vibrated at a nominal maximum stress of ±70,000 psi and that the blade failed in 10^5 cycles. From the stress against blade-life diagram (fig. 6) an undamaged blade would require a vibratory stress of ±114,000 psi to produce failure in 10^5 cycles. The strength-reduction factor for the hypothetical damaged blade would be 114,000 psi/70,000 psi, or 1.63. The stress-concentration factor in this case would also be 1.63, because the apparent stress, 114,000 psi, is compared to the nominal stress for an undamaged blade at the same location.

For another example, assume that another blade suffered sufficient damage at the leading edge at a 50-percent-span location to fail in 10^5 cycles when vibrated at the same maximum stress of ±70,000 psi. The strength-reduction factor would again be 1.63, but would not be equal to the stress-concentration factor. The actual stress-concentration factor in this case would be much higher, because the nominal stress for an undamaged blade would be much less at the 50-percent-span location, as shown in figure 7. A defect must be much more severe when considerably removed from the critical section to have the same detrimental effect as damage at the critical section.

The question arises as to whether the strength-reduction factor remains constant for different vibratory-stress levels. As a check, a damaged blade, which from previous experience with similar damage at the same location and for the same depth would be expected to have a strength-reduction factor from 1.6 to 1.75 at ±70,000 psi, was run at a stress level of ±40,000 psi at the critical section. The blade failed in 6×10^7 cycles or at an effective vibratory stress of 68,000 psi according to figure 6, giving a strength-reduction factor of 1.7 (68,000 psi/40,000 psi). Strength-reduction factors were determined for all the damaged blades tested.

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Analysis of Results

In figure 12(a) the results of the fatigue testing of blades which failed because of damage in the region between 20 and 45 percent of the span from the base are shown as a plot of the strength-reduction-factor parameter against the depth of the damage, which, owing to the jagged nature of some of the nicks, was the only pertinent dimension that could be determined. A band was drawn through the upper and lower limits of the data points for the failures due to edge nicks. In this region even the slightest nick sharply reduced the strength of the blade. Increasing the nick depth over 1/32 inch did not further reduce the blade strength appreciably. There is no difference between the effects of leading-edge and trailing-edge nicks. If the nick is even slightly in from the edge, the strength-reduction factor drops sharply. In no case where a nick was more than 1/8 inch from the edge did it result in premature blade failure. This must be qualified by the fact that no damage normally occurs on the suction surface of the blade. Conceivably, damage on the suction surface near the thickest part of the critical section could cause premature failure, since, for one of the undamaged blades (fig. 8), failure originated in that region. None of the blades investigated, however, showed impact damage on the suction surfaces due to foreign objects.

In figure 12(b) the effects of nicks, outside the 45-percent-span region, and of dents are shown. The strength-reduction factors for edge nicks above the 45-percent-span region either fell below or at the lower

limit of the scatter band replotted from figure 12(a). Dents, even those in the 20- to 45-percent-span region are less serious than nicks of comparable depth.

Reworking

To find what effects, if any, reworking has in improving the strength of damaged blades, a number of fatigue tests were conducted with the nicks and dents reworked. One blade with a dent at 36 percent span on the leading edge, which might have been expected to introduce a strength-reduction factor of 1.6 from figure 12(b), was reworked by hammering the dent until the leading edge was straight. The resulting strength-reduction factor was only 1.09. A second blade with a reworked dent at the critical section on the leading edge was run at the endurance limit of the material for 10^8 cycles without failing. 3936

Efforts to improve the strength of blades with sizeable nicks, while keeping the reworked or filed-out area to a minimum so as not to affect the blade aerodynamically, were unsuccessful. Nicks were filed in two undamaged blades at the critical section on the leading edge to a depth of about 1/32 inch. These nicks were then dressed out with files and emery cloth until no sharp edges were left, only a smoothly faired indentation on the leading edge. The results of fatigue testing these two blades are shown in figure 12(a). There is no discernable improvement in strength due to the reworking of these nicks.

Additional conclusions can be drawn from the data presented in figure 12. First, very small nicks in the leading or trailing edge are extremely detrimental to blade life when located near the maximum-vibratory-stress region. For example, a 0.010-inch-deep nick which is relatively difficult to detect upon inspection without complete disassembly of the engine had an average strength-reduction factor of about 1.5 (fig. 12(a)). A blade normally vibrating at ±70,000 psi would sustain about 10^8 cycles before failure. With a 0.010-inch-deep nick, a blade vibrating at the same nominal stress according to figure 6 would sustain only 2.3×10^5 cycles before failure ($70,000 \times 1.5 = 105,000$ psi effective stress). This constitutes a reduction in blade life of 1000/2.3, or 435 to 1. When a blade with a 0.010-inch-deep nick vibrates at ±47,000 psi (70,000/1.5), it is possible to have a failure in 10^8 cycles while the undamaged blade can vibrate indefinitely near this stress level. The time to failure may be relatively short, because the average inlet-stage blades undergo 10^6 cycles per hour of vibration, and exit stages undergo as many as 5×10^6 cycles per hour.

The highest strength-reduction factor computed for these tests is 1.8 (fig. 6). This fact would indicate that if the vibratory stresses could be kept well below ±38,000 psi (70,000 psi/1.8) for all blades at

all times, there is very little danger of fatigue failure resulting. This conclusion should only be accepted with some reservations. It is conceivable that more extensive damage than existed on the 40 test blades may be encountered and still not produce immediate failure. Also, the safe vibratory-stress limit indicated does not include the reduction caused by addition of other steady-state stresses which at rated speed become rather high, nor does it include stress concentrations which may be present in other blades if the maximum vibratory stress is located near a base fillet or root serration. The data suggest, however, that some safe, practical limit of vibratory stress exists below which damage resulting from small objects passing through the mesh openings of engine-inlet screens will not cause a flight hazard.

Because a limited portion of the blade span is subject to high vibratory stresses and therefore exposed to accelerated fatigue due to foreign-object damage, only part of the blade need be protected to reduce the problem. An approach that has been advocated for greater ruggedness of compressor blades is to fabricate them in a composite structure. The material properties at every point would be designed to protect the blade against likely causes of failure at that point. Thus in order to protect a blade against foreign-object damage those parts of the blades where the effects of damage would be the most serious would be composed of material either more resistant to impact damage or less notch sensitive.

This investigation was limited by the number of damaged blades available. To observe trends the results had to be compiled in large increments of span and degrees of damage. Large numbers of damaged blades from different engines should be fatigue tested at various stress levels to give a better understanding of the problems. Overhaul bases having a continual supply of such blades could easily and inexpensively assemble a battery of pneumatic exciters and thus obtain valuable data.

SUMMARY OF RESULTS

The results of the fatigue testing of a particular compressor blade shape with typical impact damage may be summarized as follows:

1. The critical or most highly stressed section of an airfoil was the most sensitive to damage. The detrimental effect of damage decreased the farther the damage was from the critical region. The critical section or region can be determined experimentally by vibrating a blade to failure or measuring the vibratory-stress distribution along the blade span with strain gages.

2. Impact damage was the most damaging at the blade edges. Nicks more than 1/8 inch from the edge on the pressure surfaces did not cause premature fatigue failure. None of the blades suffered impact damage on the suction surface. For the blade used in these tests there was no difference between the effects of damage at the leading and trailing edges.

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3. Nicks were much more serious than dents. In the vicinity of the critical section even minute edge nicks sharply reduced the blade strength.

4. The original strength of dented blades could be almost wholly restored by reworking the dents. Attempts to restore the strength of blades with sizeable nicks by reworking were unsuccessful.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 20, 1956

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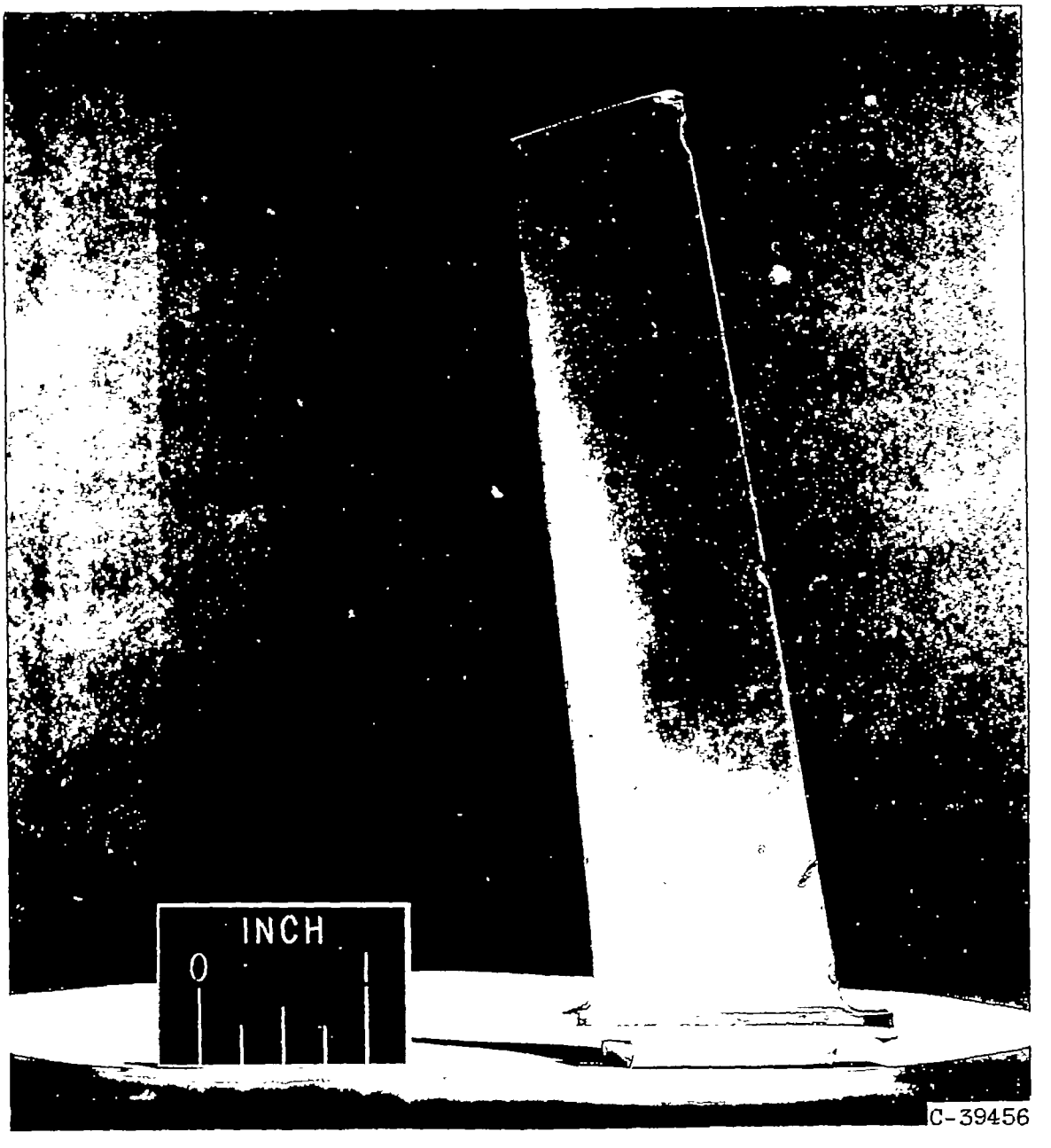

Figure 1. - Typical damaged blade.

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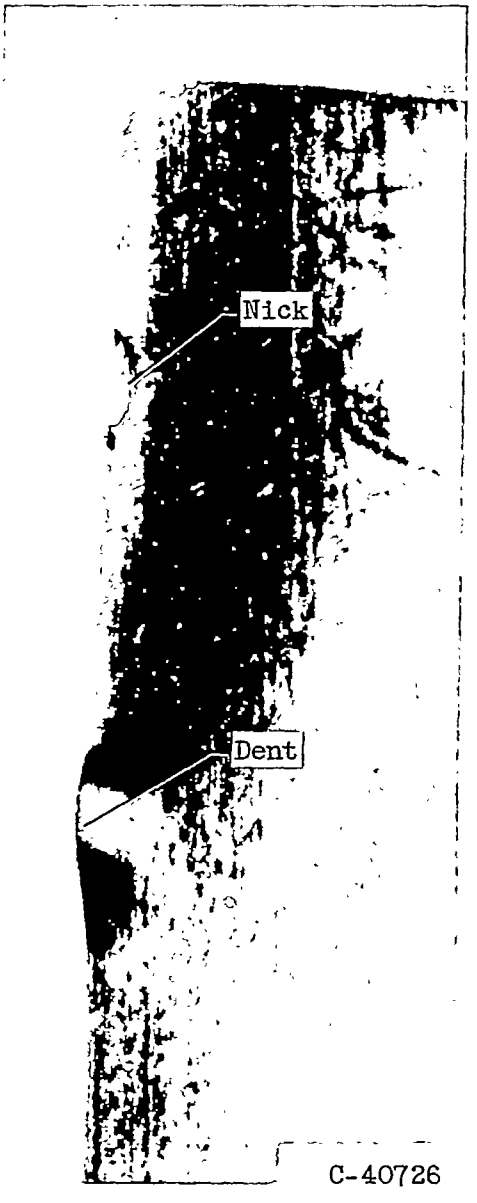

Figure 2. - Types of blade damage.

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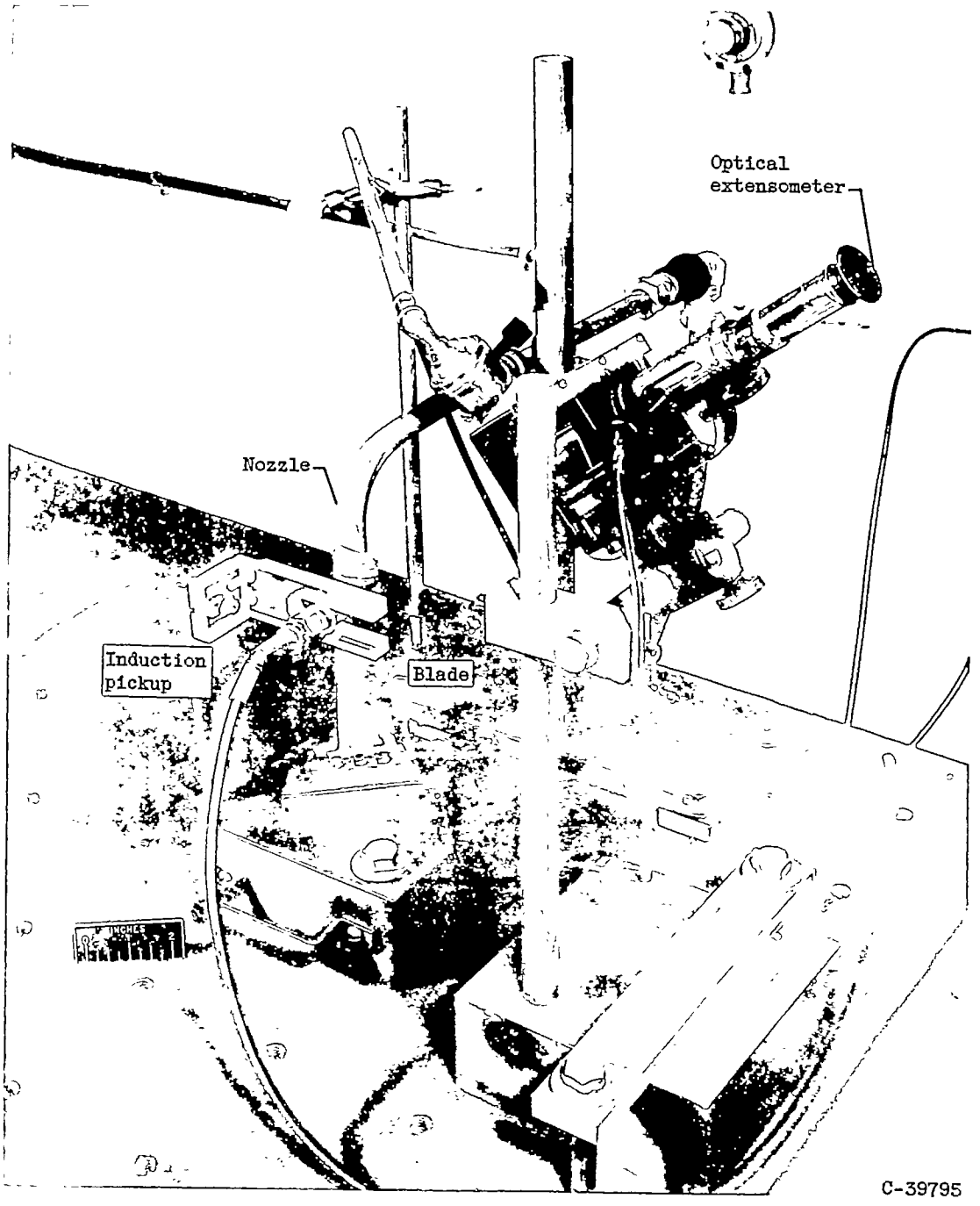

Figure 3. - Apparatus for fatiguing blades.

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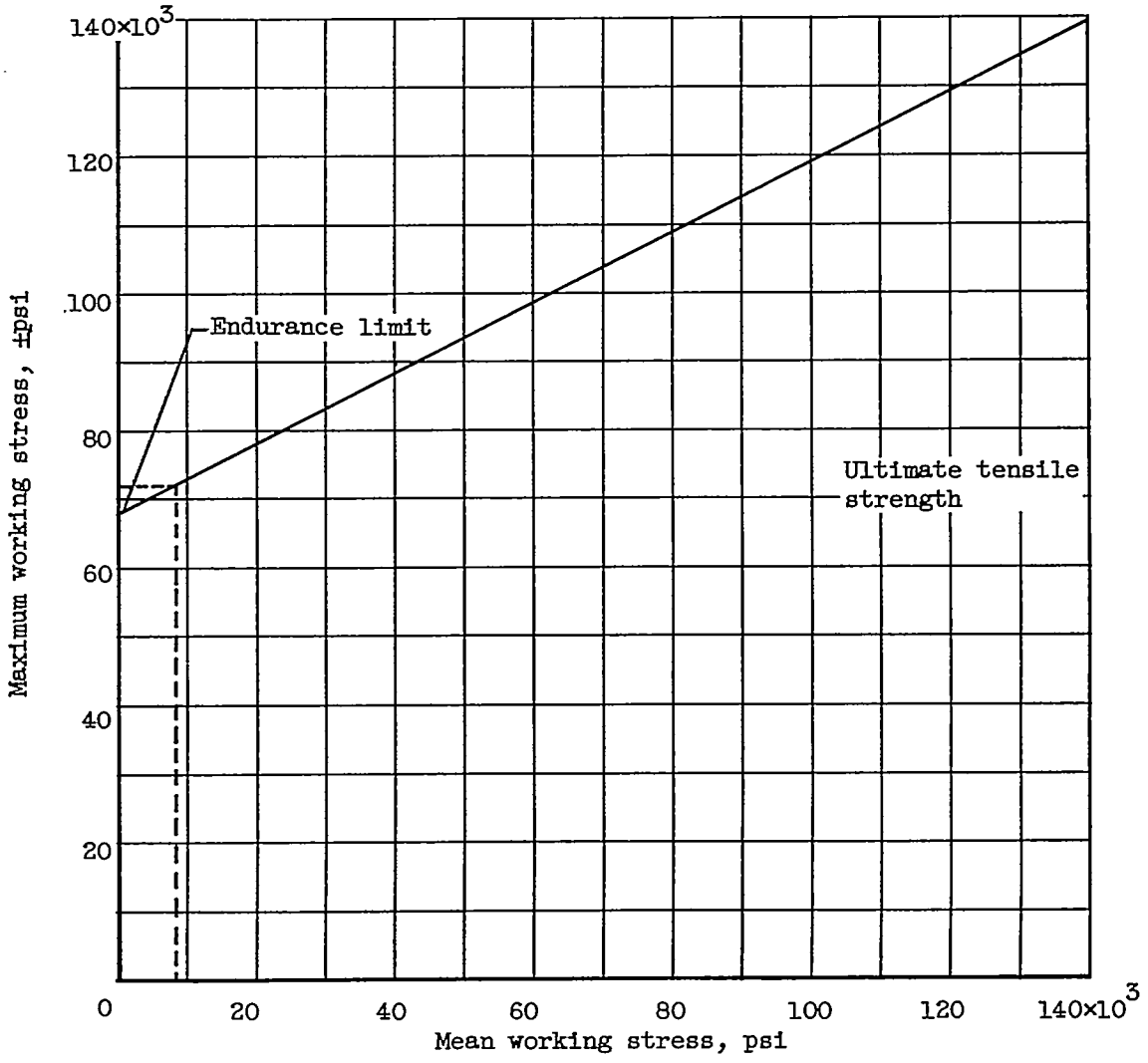

Figure 4. - Modified Goodman diagram for 403 stainless steel blade material.

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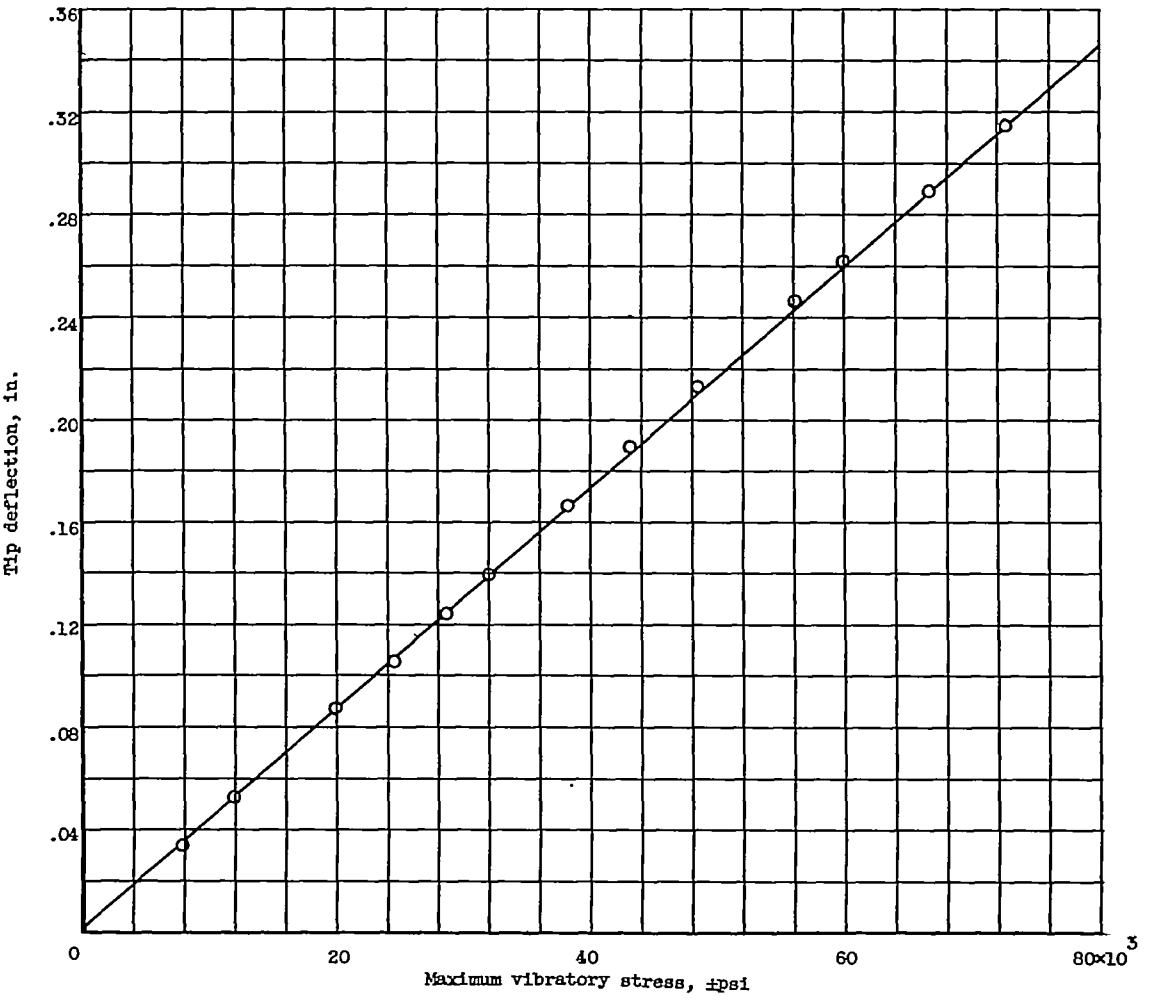

Figure 5. - Blade tip deflection as function of maximum vibratory stress.

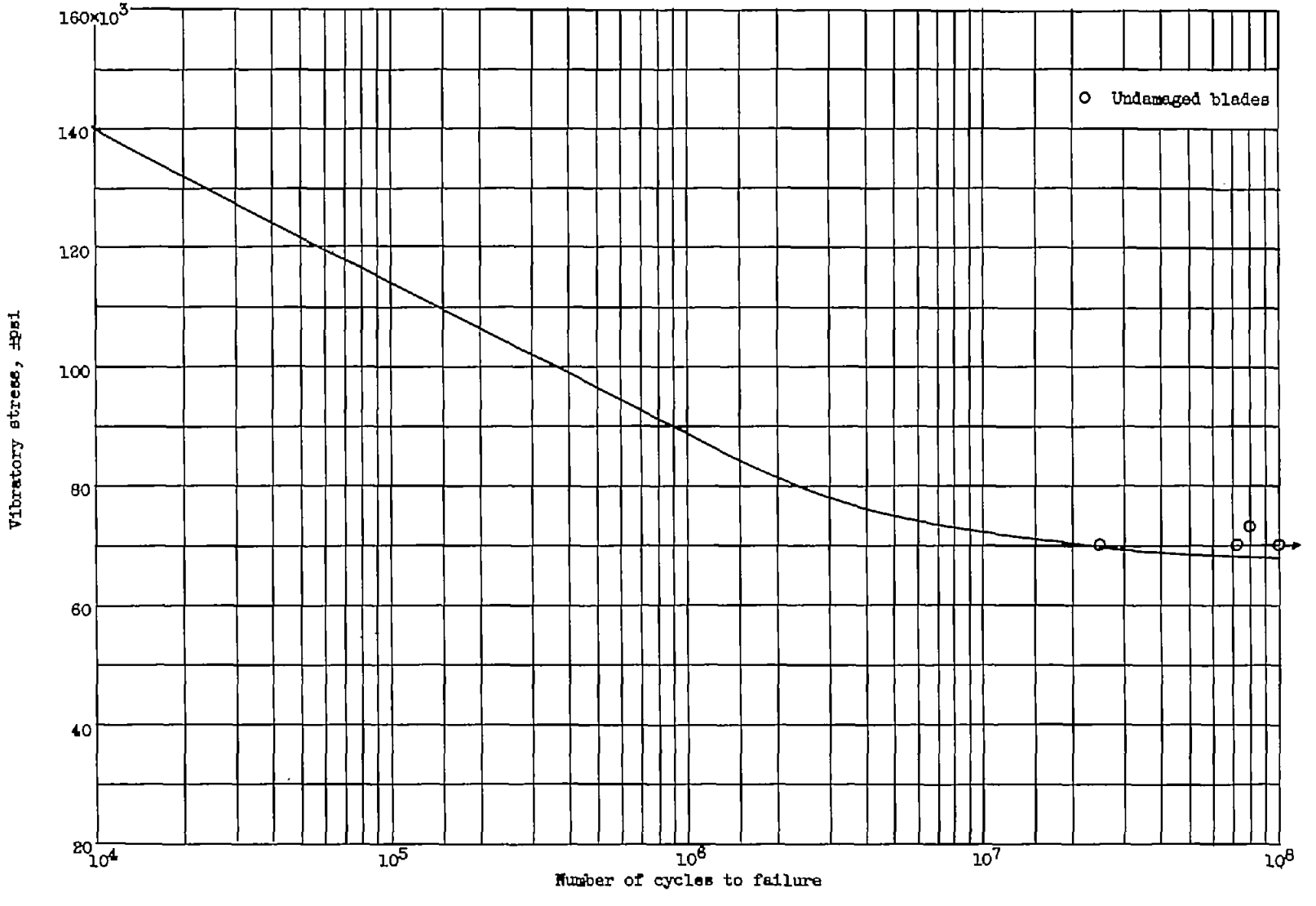

Figure 6. - Blade life as a function of vibratory stress.

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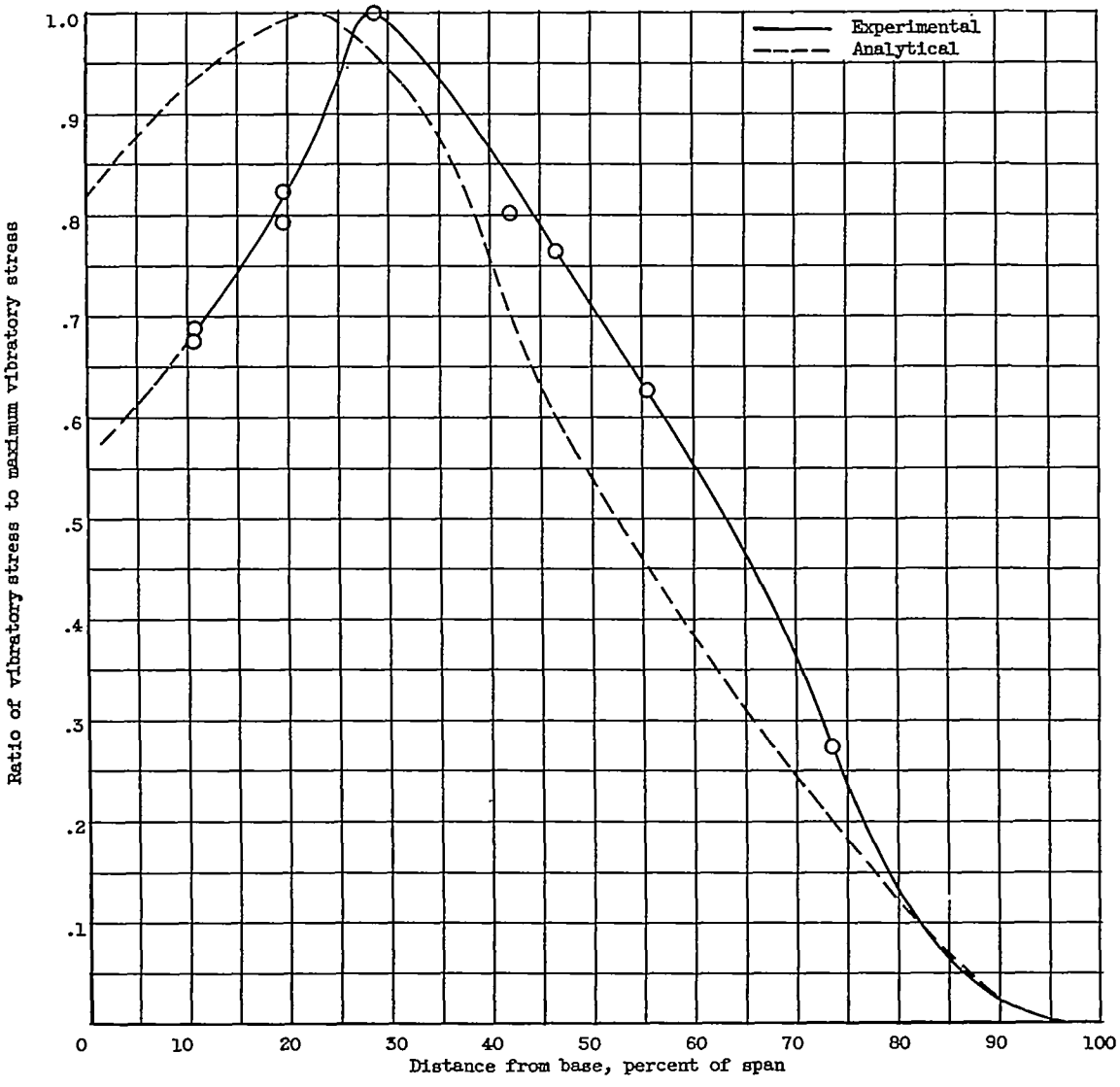

Figure 7. - Airfoil vibratory-stress distribution.

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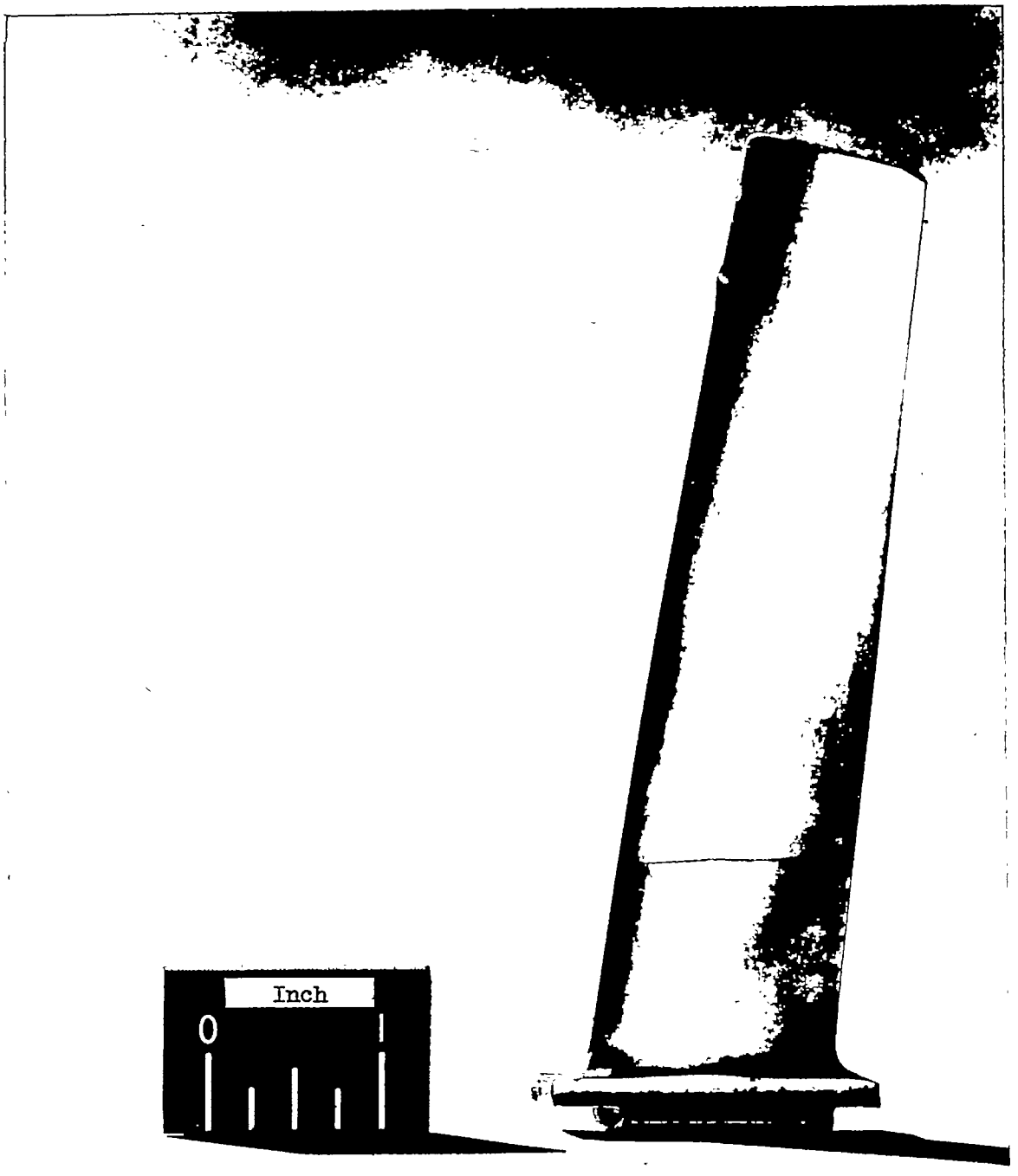

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Figure 8. - Blade with failure in normal location.

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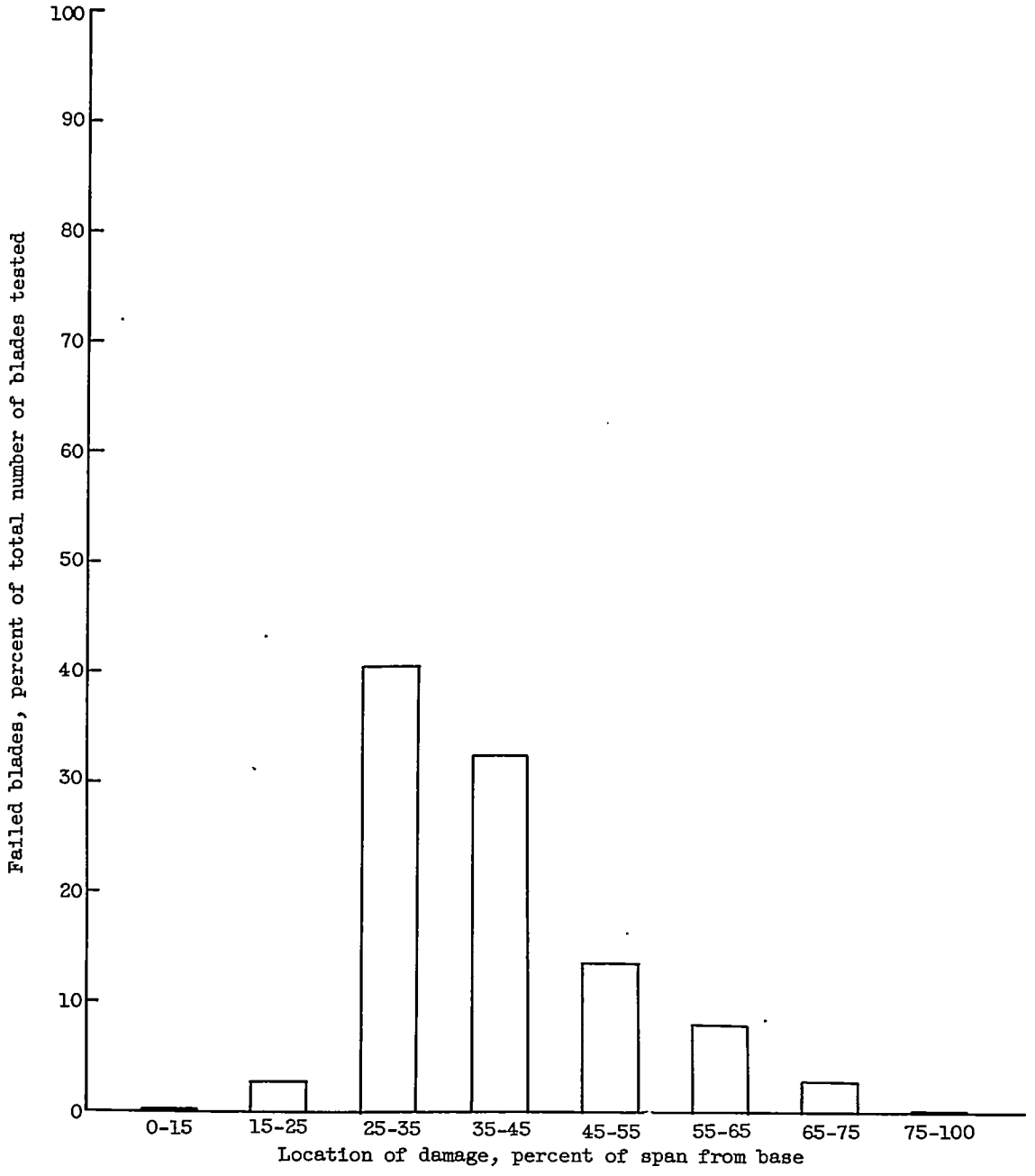

Figure 9. - Percent of blades that failed out of total number of blades tested as function of failure location.

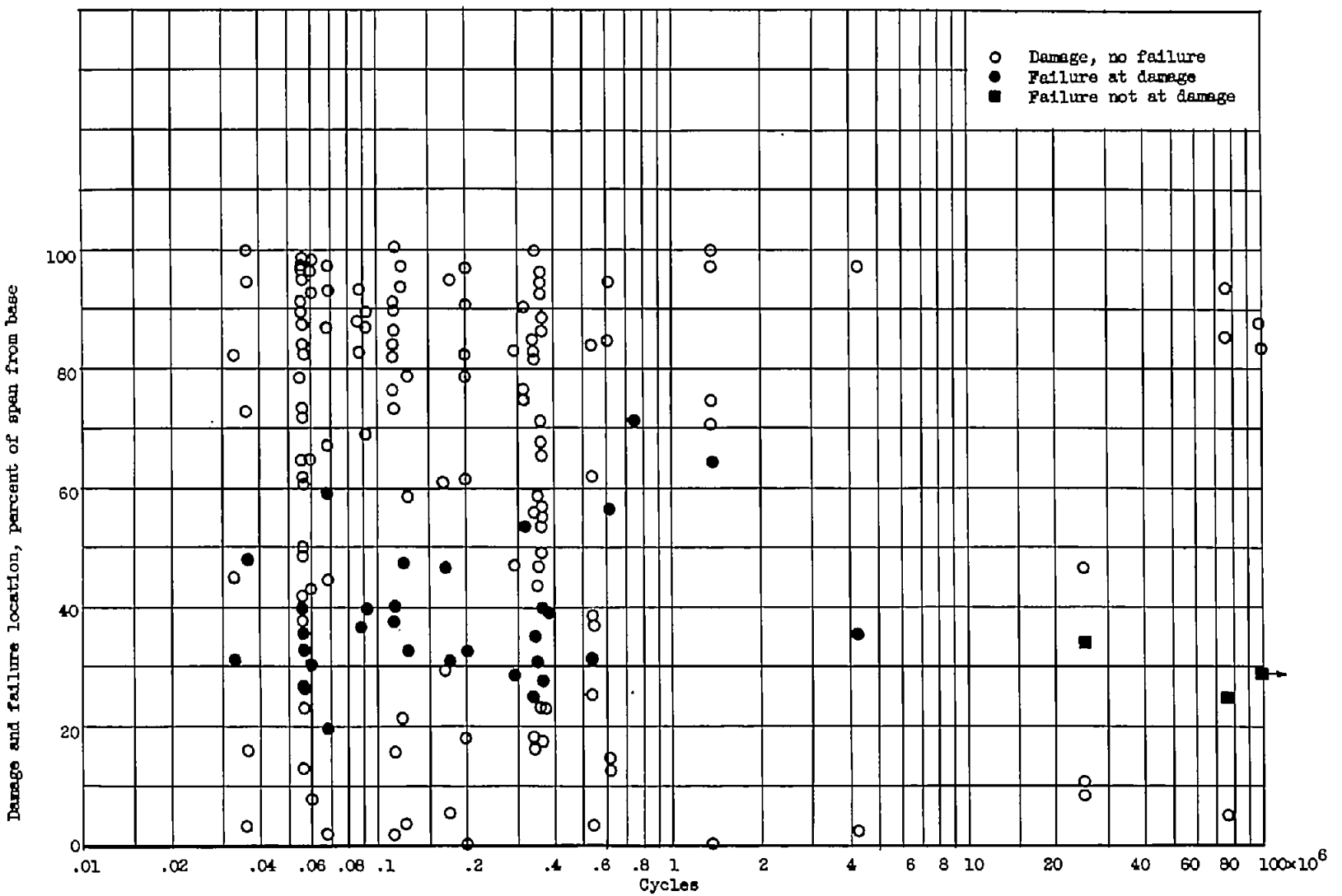

Figure 10. - Fatigue testing results at stress level of ±70,000 psi.

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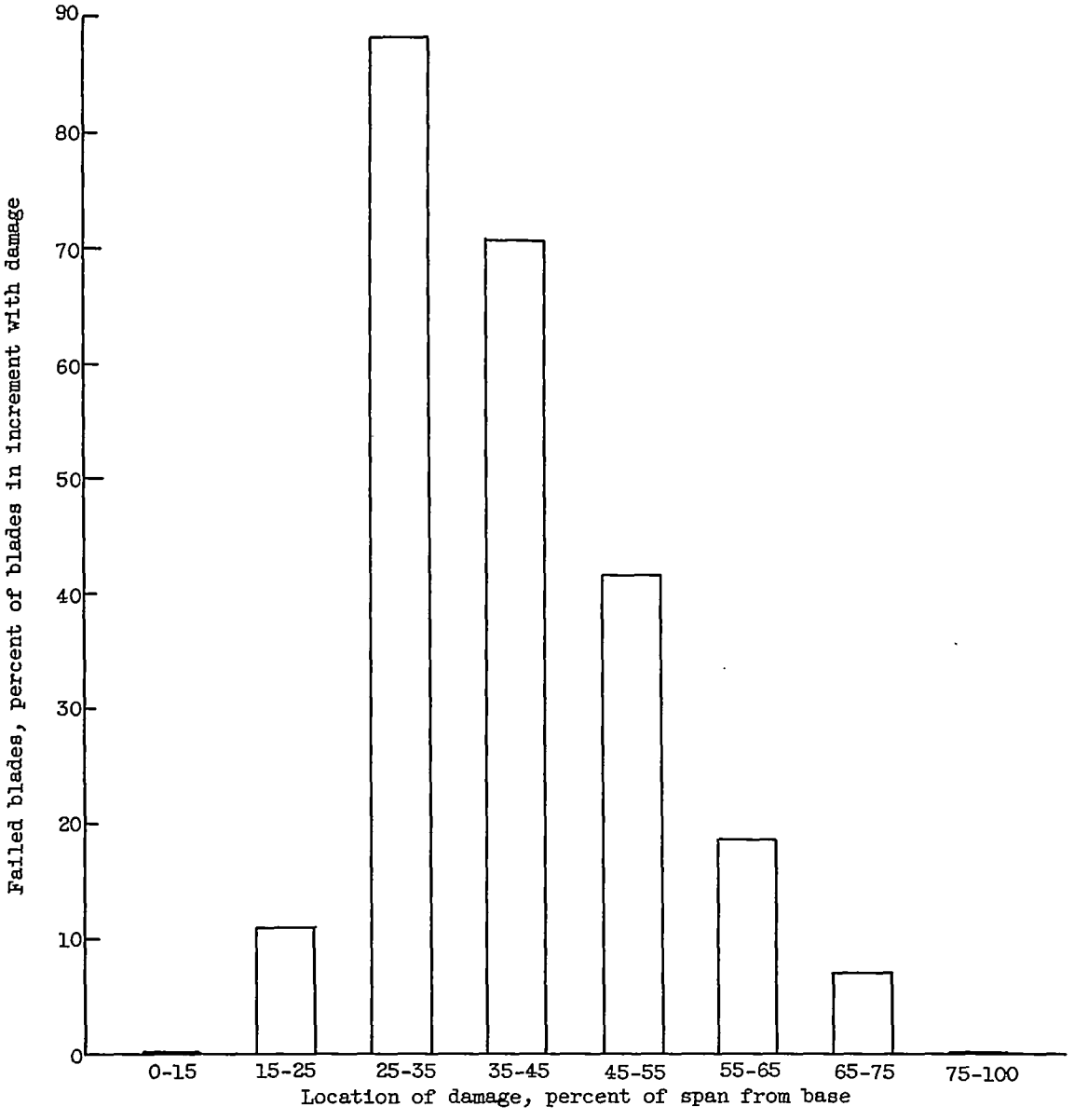
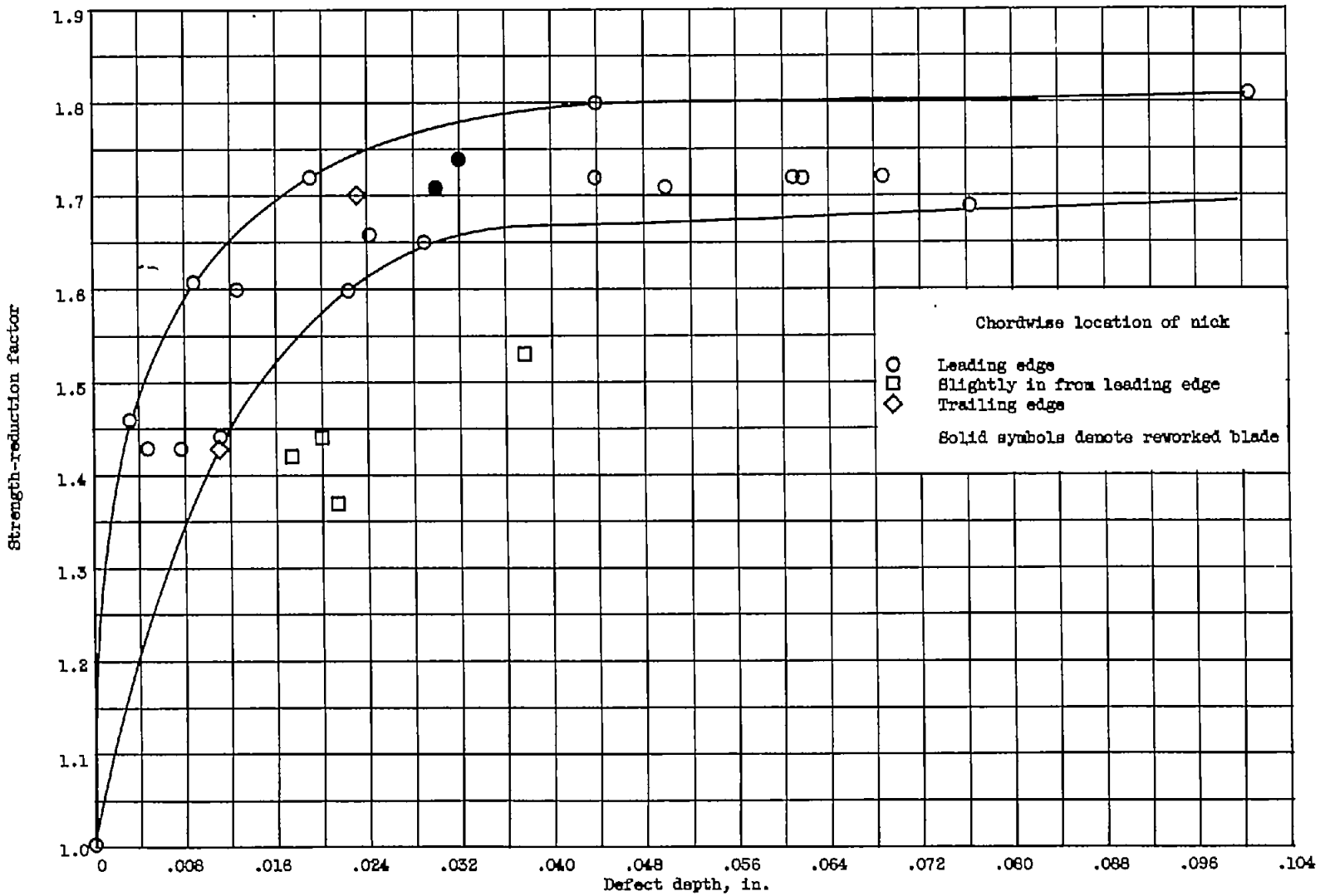
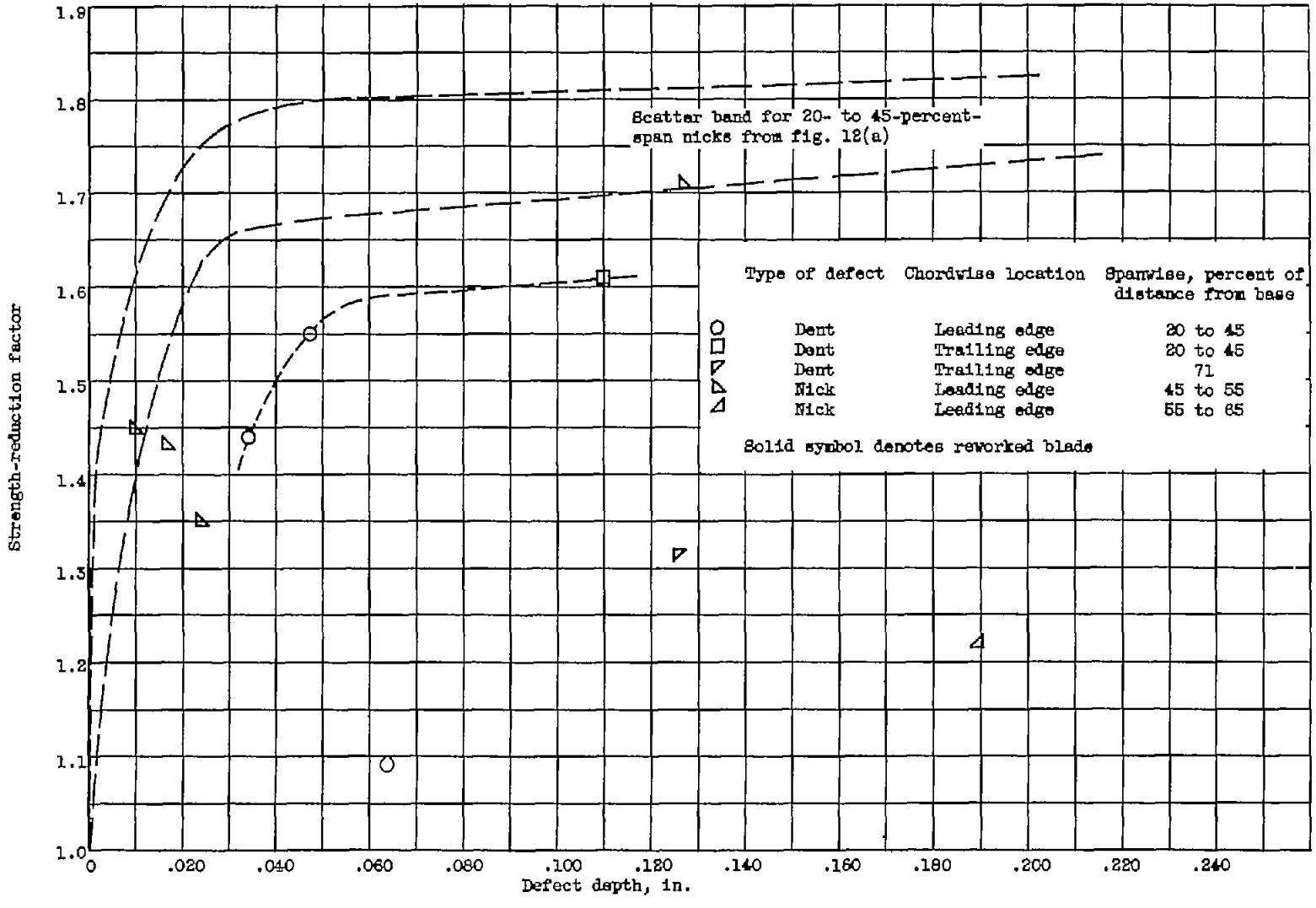


Figure 11. - Percent of blades that failed out of number of blades in increment with damage as function of failure location.



(a) Nicks in 20- to 45-percent-span region.

Figure 12. - Effect of defect depth and location on strength reduction.



(b) Nicks outside 20- to 45-percent-span region and dents.

Figure 12. - Concluded. Effect of defect depth and location on strength reduction.

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