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PRACTICAL ASPECTS OF DESIGNING FOR AND EVALUATING STRUCTURAL INTEGRITY

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INTRODUCTION

The objective of this paper is not to show the results of very scientific studies, but only to put forward some points which can be of practical use to the designer. The following procedures apply generally in the tests discussed:

(1) Skins are machined, either chemically or mechanically

(2) Their surfaces are blasted with glass beads and wet sand

(3) They are given a surface protection and painted

(4) No bonding is used.

FATIGUE PERFORMANCE IMPROVEMENT

It is well known that bolts with tight fit give a definite increase in fatigue life. However, this increase is guaranteed only if every bolt is mounted with the right fit and if no undetectable fault may change the assumed condition.

Conical Fasteners

For a long time we have been using bolts or fasteners with tight fits of 5 to 30 microns, with very satisfactory results. But it is quite a problem to achieve a guaranteed fatigue life of 40 000 hours while saving much weight, especially in the joints or in the lower skin of the wing. The search for a higher admissible stress is then a constant undertaking.

Conical bolts had at first sight appeared most interesting. There was indeed the danger of stress corrosion when a tight fit of 90 microns was used with alloys such as 2024-T3 and 2014-T6, but riveting on short transverse components is infrequent, and less sensitive alloys may be used. A test program was started with two types of test specimens, a "dog bone" type and a lap joint. (See fig. 1.)

The first test results (fig. 2) were most encouraging, until a test specimen broke after a disappointingly low number of cycles. A more thorough inspection of the test piece (which had been inspected prior to testing) showed a reaming fault as in figure 3. The bolt bears only on four regions.

It was necessary to determine why this fault existed and why it had escaped inspection. The first problem was easy to resolve. It took many years to learn how to drill a perfectly circular cylindrical hole. Conical holes, because of their high drilling torques, will surely require still more development and tooling for reliable results. With limited tooling, we succeeded in drilling correct holes up to 6 mm in diameter and 8 mm deep. But for larger diameters, very rigid jigs and expensive tooling were needed. Both the cost of tooling and the drilling time were found to be prohibitive for an extensive conical fastening.

Furthermore, inspection was most difficult, with the necessity of blueing checks at every hole, which increased the cost of the total operation. Finally, a subsequent test with holes purposely drilled incorrectly showed a dramatic decrease in fatigue life. (See fig. 4.) These results, added to the danger of stress corrosion, led to the decision not to use conical fasteners in the Mercure.

Hole Preparation

In an attempt to increase the fatigue life of structures, the following processes were examined:

(1) The way in which the hole is made:
  (a) Normal reaming
  (b) Heli-Armor reaming
  (c) Broaching

(2) The finish given after reaming:
  (a) Deburring
  (b) Roll over

Significant differences were found between treated and untreated holes without rivets (fig. 5). On the other hand, once the bolt is set, these differences decrease and even disappear (fig. 6).

Interference Fit

On one hand, interference fit has a positive influence on fatigue life, but on the other hand, beyond a certain level of interference (30 microns), fretting under the fastener becomes too important unless special care is taken. Figure 7 shows the type of failure in each case. With the free bolt, the crack started in the cylindrical part of the hole, but with the interference-fit bolts, the cracks started by fretting in the countersink.

Antifretting Protection

In all previously described tests standard sealing and surface protection treatments were used; that is, rivets were wet mounted with PR 1422 or Blendexite and the test specimens were painted with PR 1460 or Cellolac 78-28. Figure 8 shows the effect on fatigue life when one of these two protections is omitted. The fatigue life was reduced by fretting underneath the fastener collar when the specimen was not painted, and in the countersink when the rivet was dry mounted.

Selecting Parameters for Mounting a Fastener

The results of these experiments led to the selection of the following procedures:

(1) Use of a moderate amount of interference (bearing in mind the problem of stress corrosion)

(2) Painting and wet mounting

The influence of the way in which the hole is obtained is not so obvious. Broaching and Heli-Armor give comparable results, but broaching is an extremely reliable method of obtaining holes of a high standard, while Heli-Armor may be less reliable. The "miracle" alloy for the best life has appeared to be 2024-T3. (We have not tested 7075-T73.)

FAIL-SAFE DESIGNS

General Considerations

The greatest risk of crack initiation is surely incurred in joints. Multiplying stress concentrations by using, for example, riveted reinforcements around door openings should be avoided as much as possible. Integral structures mechanically or chemically milled might seem a good solution, but then the difficult problem of fail-safe design enters the picture.

We have already made some remarks about this problem at Melbourne, having been unfavorably impressed by some examples of so-called fail-safe design, the most classic being a structure cut in two pieces and bolted back together. Since then the situation has apparently worsened, judging by the design of some recent tail-unit hinges and control-surface bearings.

Are the regulations responsible? It is certain that FAR 25-573 encourages a designer who does not want to put questions to himself to demonstrate that a structure can sustain the required static load when one of the elements has failed. This test allows him to claim that his structure is fail-safe. Moreover, the same paragraph allows a failure to be considered only partial if it is obvious.

As far as fatigue is concerned, the basic idea, in itself quite legitimate, of assuring security by means of residual strength has been put in a wrong way.

Fatigue and Fail-Safe

Of course a fatigue test is not a fail-safe demonstration by itself, but it is not negligible in assessing structural fail-safe designs. Also, fatigue testing is a good method for determining inspection schedules for the various parts of the airplane.

We do not believe that an element cut in two, but in which cracks appear and grow rapidly, is sufficiently fail-safe. What happens to the half of this element carrying the whole load when the other half has broken?

Some recent mishaps with elements working in parallel should prove of interest. One instance was the F-14 prototype, in which two hydraulic tubes used on separate circuits, but subjected to the same fatigue duty, gave up in a 5-minute interval.

Another example of a more structural nature was found during a fatigue test on a military aircraft. The main frame supporting the bending moment of the wing was made of two rings working in parallel. (See fig. 9.) Cracks appeared and grew almost identically in the two rings, and a rupture occurred in each, the load being then supported by the remaining structure outside.

Another example concerns a wing attachment (fig. 10). Cracks grew at the same time from five holes and, what is more, on both wings. To have separated the attachment into halves would only have given a formal fail-safe structure without increasing enough the safety of the design.

These problems occurred because the fatigue life was short enough for all the pieces involved to be damaged. A quite different case appeared in the test of the Mercure main frame. An artificial crack in the flange of the frame grew only on one half of the flange, not passing the "wall" of the web, and at a rate low enough to be found in inspections.

Here the stress was lower, and this explains most of the difference. Thus a fatigue test may give important indications for fail-safe designs.

There is a still worse method for obtaining fail-safe. Take a beam with an I-section, the tensioned flange of this beam being perfectly smooth, without any hole. Then replace the integral tension flange by riveted flanges, the tensioned area being the same. Fail-safe is not definitely guaranteed and fatigue life is severely decreased.

If you feel unable to insure safety with such a monopiece structure, you can design a double load path while avoiding putting rivets in the tensioned zone. You will keep good fatigue life and get a double load path at the same time, but perhaps you will have some trouble with fretting or corrosion.

Fail-Safe and Unexpected Cracks

The double load path finds its soundest justification in unexpected cracks. However, this should not deter the designer from looking at the types of remaining risks and finding a solution to them. These risks can be defined as flaws in the material, fretting, and stress corrosion. With correct designs, care, and inspection these difficulties can be overcome, and we have to work for that in any possible way.

Important Conclusions Regarding Fail-Safe

Certainly a low stress level is an important factor for fail-safe guarantee. For less important elements where weight loss is small, no regrets should be had in designing with important margins for a theoretically infinite life. But this is not enough. During the fatigue tests and after, it is necessary to monitor the crack propagation rates at every point which may be critical. The results should be linked with the inspection schedule of these particular points.

Double load path must not be neglected. But its reliability must be assured with regard to fatigue considerations as well as corrosion and fretting, and the structure must not be weakened by a bad design.

OUR FAIL-SAFE APPROACH

It must be admitted that we have often used the classic fail-safe methods described here. However, even in these cases we applied the procedures described in the following paragraphs to investigate crack propagation.

Photoelastic Tests

For the Mercure design, we had previously developed tests on photoelastic models and on metal parts coated with photostress material (figs. 11 to 13). Thus, we were able to study stress concentrations on a particular component, and even on an entire element of the fuselage. Also, we were able to determine critical areas where we could provoke cracks.

Partial Fatigue Test

Usually the area where we want fail-safe capability of a one-piece structure is greatly overdimensioned for fatigue. So we perform tests with normal fatigue loads, followed by cycles at higher loads. During these tests, cracks must not originate.

Crack Propagation

Next we artificially provoke cracks in critical areas – that is, areas where calculations and photostress investigations show stress concentrations. (See fig. 14.) The crack growth rate is plotted against time in order to define a schedule of inspections that will provide detection in service before the risk of dangerous failure is encountered. This implies that the tests are based on particular conditions.

It is best to have two types of cycles. The first, with only normal fatigue loads, is applied on specimens to monitor the crack growth rate. The second, including the same normal fatigue loads, also includes "fail-safe" loads, and is applied on other specimens to evaluate the critical length of crack beyond which a static failure may occur.

Another possible application for fail-safe design is found in secondary effects (fuel leakage, for instance).

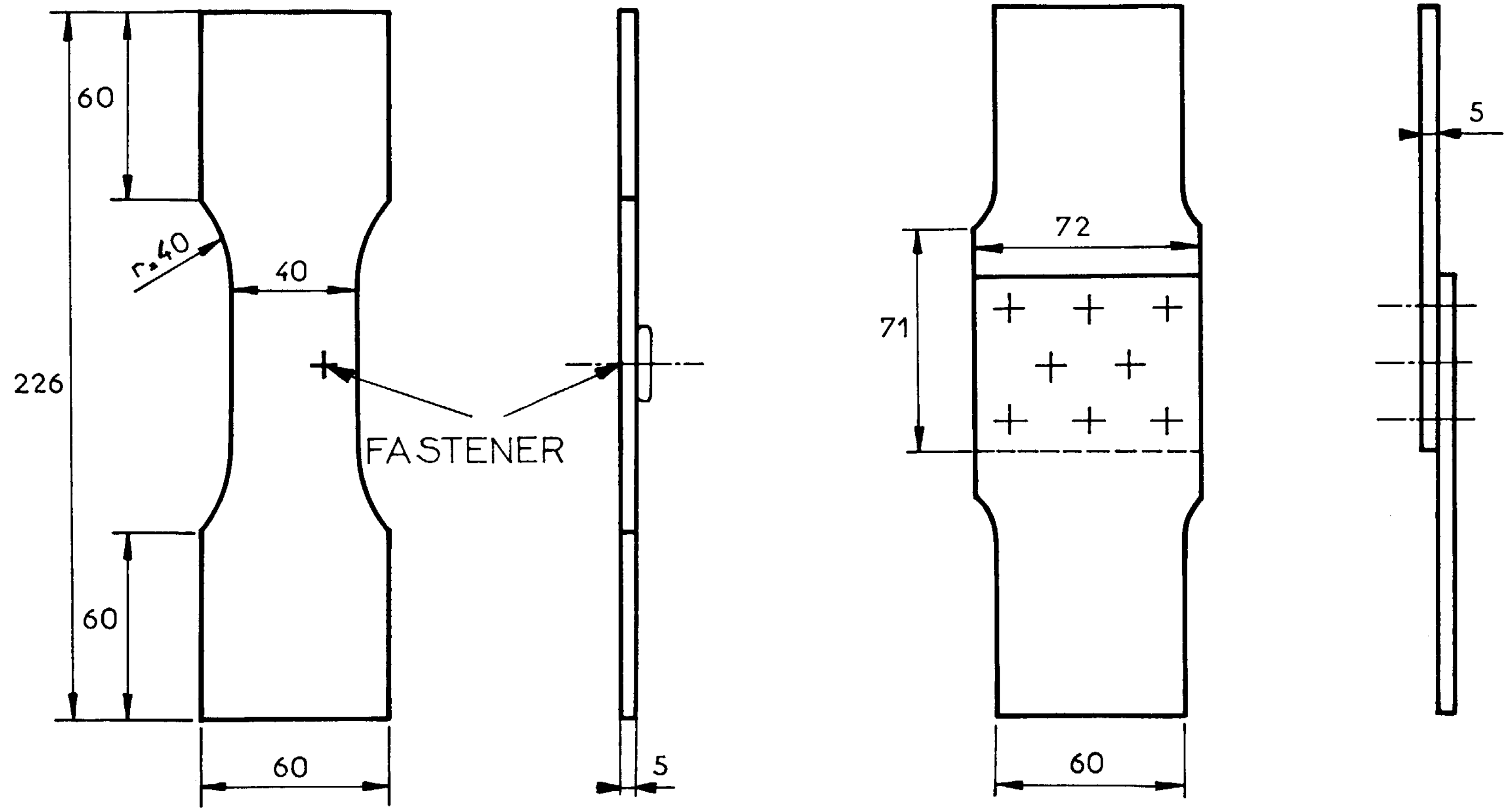
CONCLUSIONS

The double load path, although a good fail-safe concept in many cases, is not entirely satisfactory. It may be insufficient when fatigue life is too short, and superfluous when the stress is low, detection is easy, or fail-safe capability is achieved by other means.

The best procedure is to rely on crack growth-rate studies and guaranteed crack detection by inspection in service.

The use of double load path to cope with unexpected phenomena such as stress corrosion or flaws seems rather makeshift, and it is better to seek specific action (improved forgings, inspection, protection) in each case.

The easier the inspection, the better for fail-safe.



"DOG BONE"

LAP JOINT

Figure 1.- Test specimens.

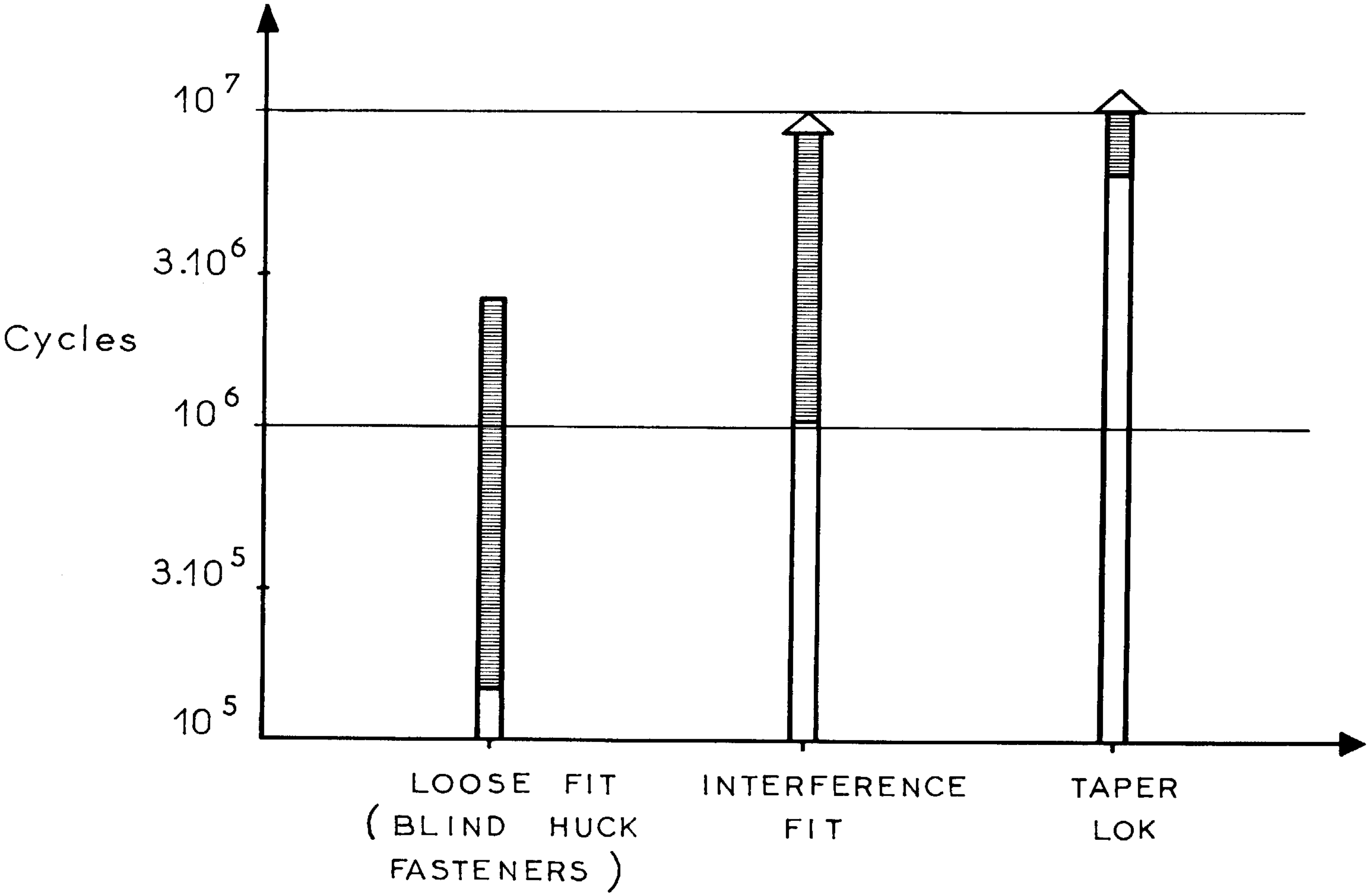
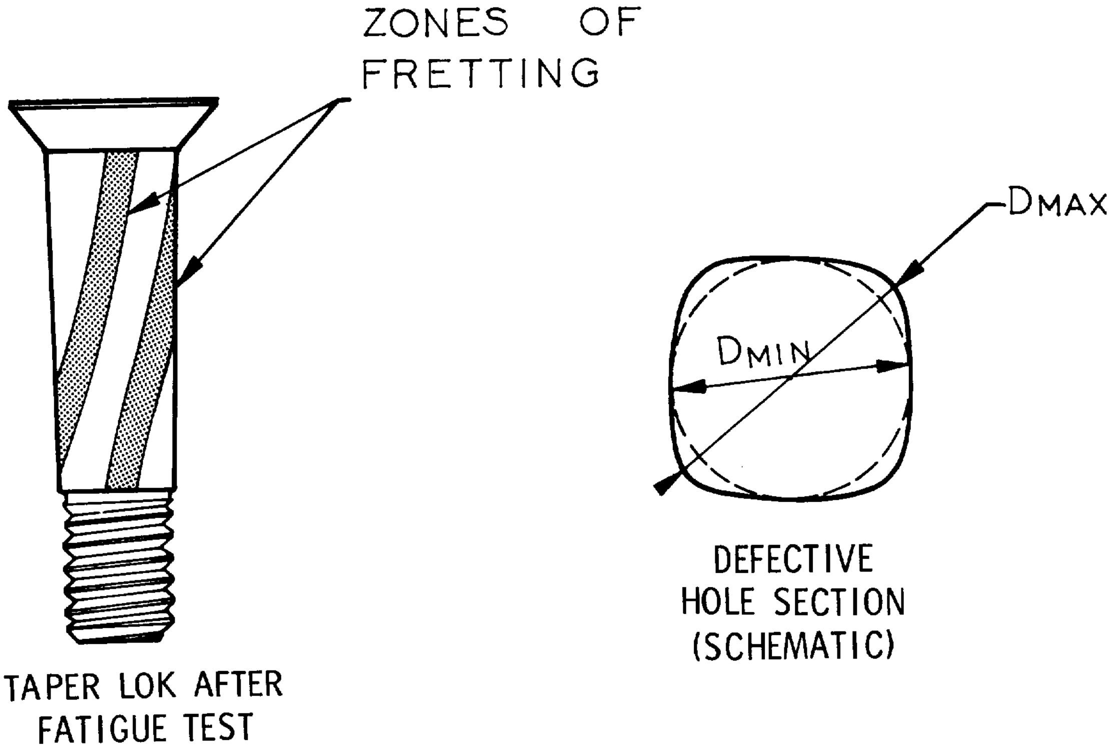


Figure 2.- Early results with Taper Lok and classic fasteners in "dog bone" sample of 2014 or 2024-T6 aluminum alloy. Test cycle σ = 10.8 hectobars (15.7 ksi), R = 0.1.



TAPER LOK AFTER FATIGUE TEST

DEFECTIVE HOLE SECTION (SCHEMATIC)

Figure 3.- Defective installation of Taper Lok.

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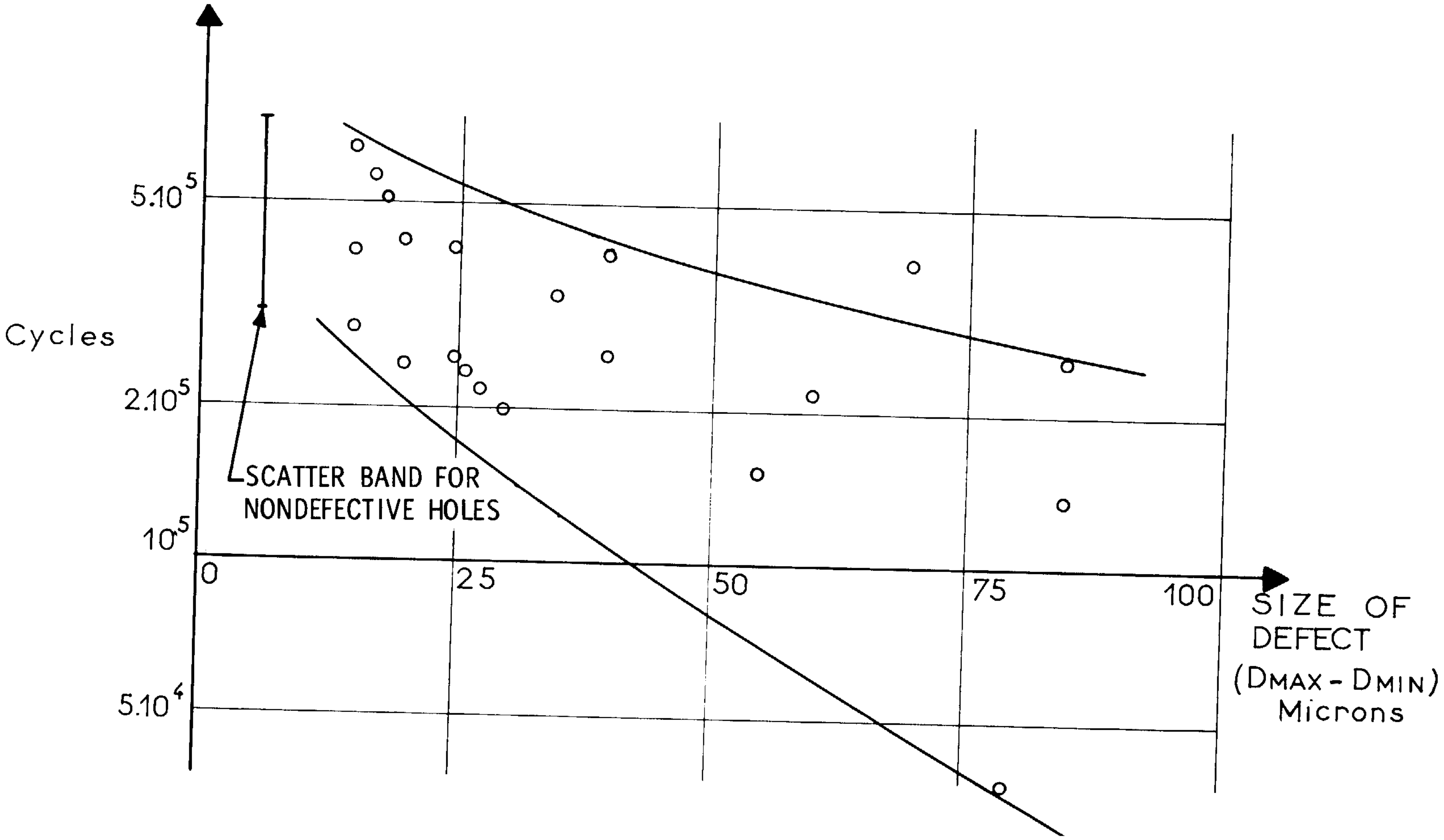


Figure 4.- Fatigue life as a function of size of defect in holes for Taper Lok. "Dog bone" sample of 2024-T6; test cycle σ = 17.2 hectobars (25 ksi), R = 0.1; fastener, 1/4-inch-diameter TL 100.

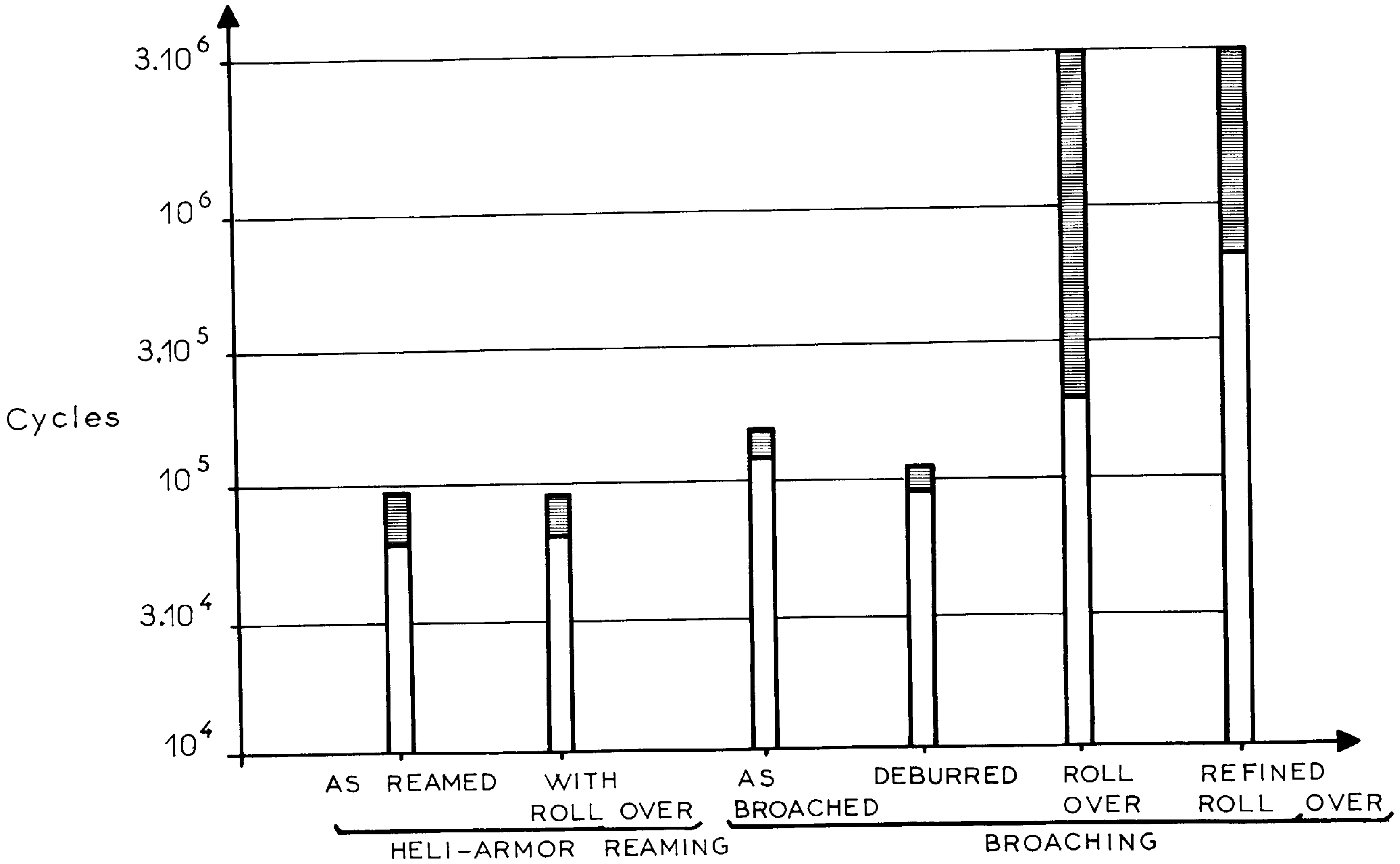


Figure 5.- Effect of finish of empty holes on fatigue life of "dog bone" sample of 2014-T6. Test cycle σ = 13 hectobars (18.8 ksi), R = 0.1.

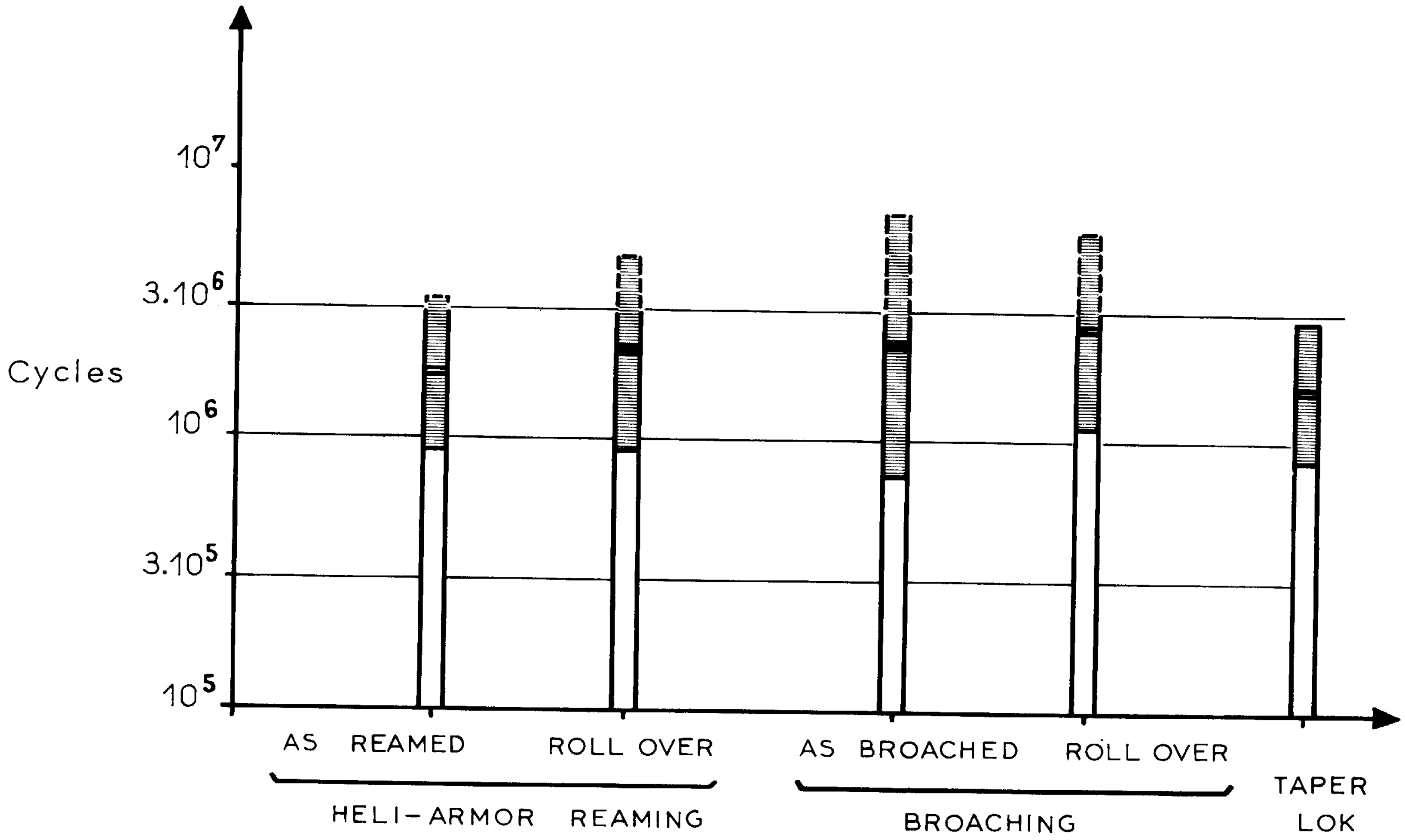


Figure 6.- Effect of finish of holes with fasteners on fatigue life of "dog bone" samples of 2014-T6. Fastener, 6-mm-diameter "SLF" titanium, interference approximately 30 microns; test cycle σ = 15 hectobars (21.8 ksi), R = 0.1.

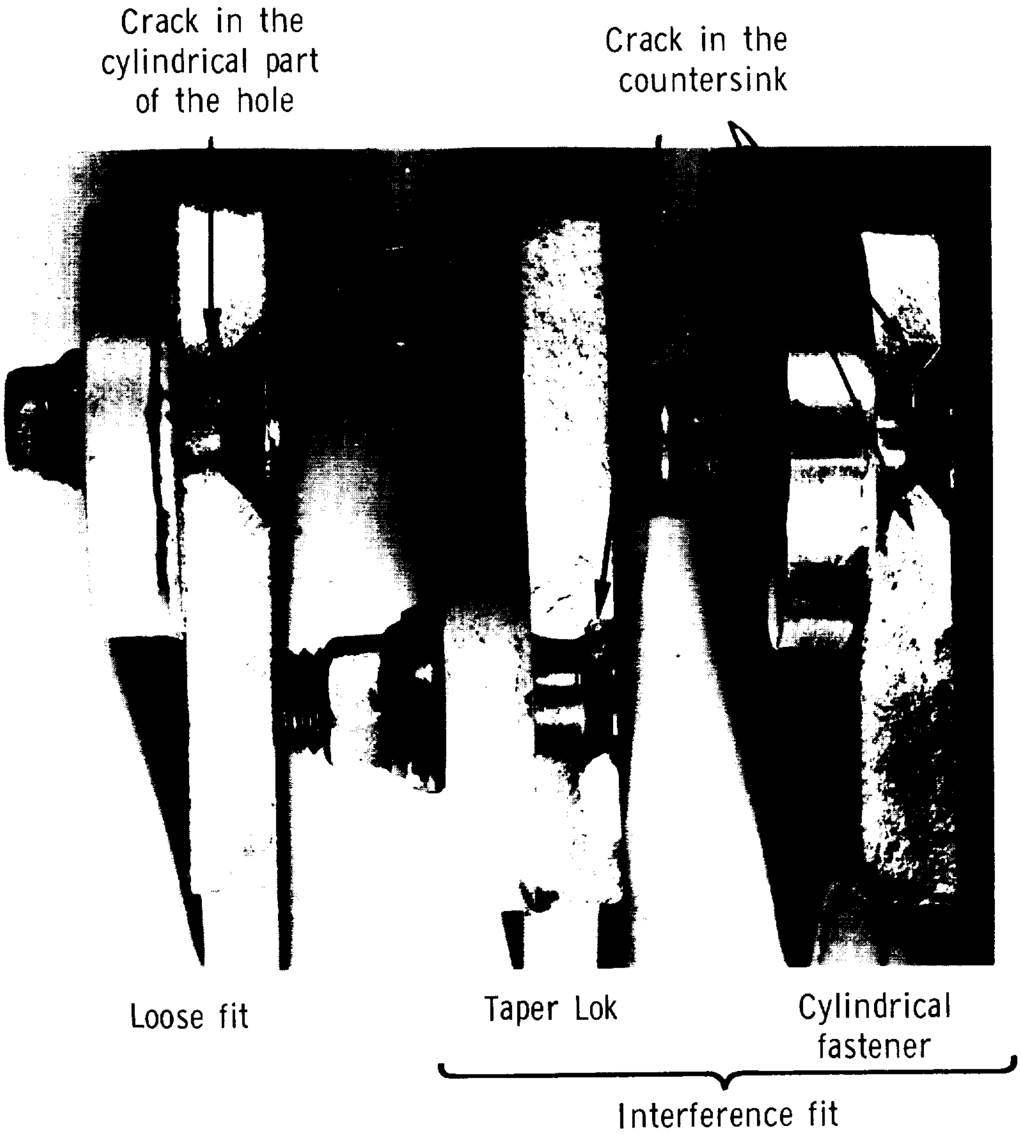


Figure 7.- Effect of interference on fracture mode.

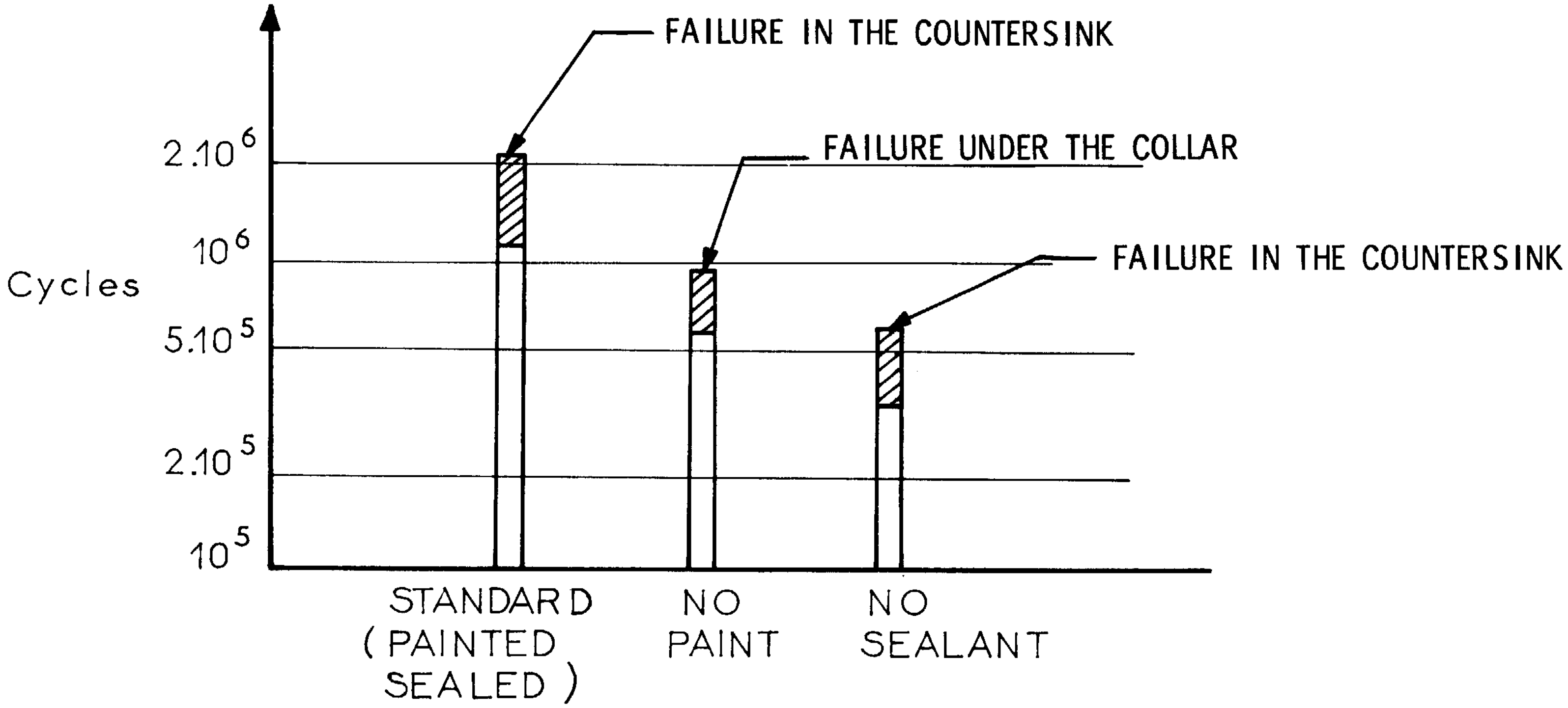


Figure 8.- Effect of paint and sealant on fatigue life of "dog bone" samples of 2024-T3. Fastener, 6-mm-diameter SL titanium, interference fit; test cycle σ = 17.2 hectobars (25 ksi), R = 0.1.

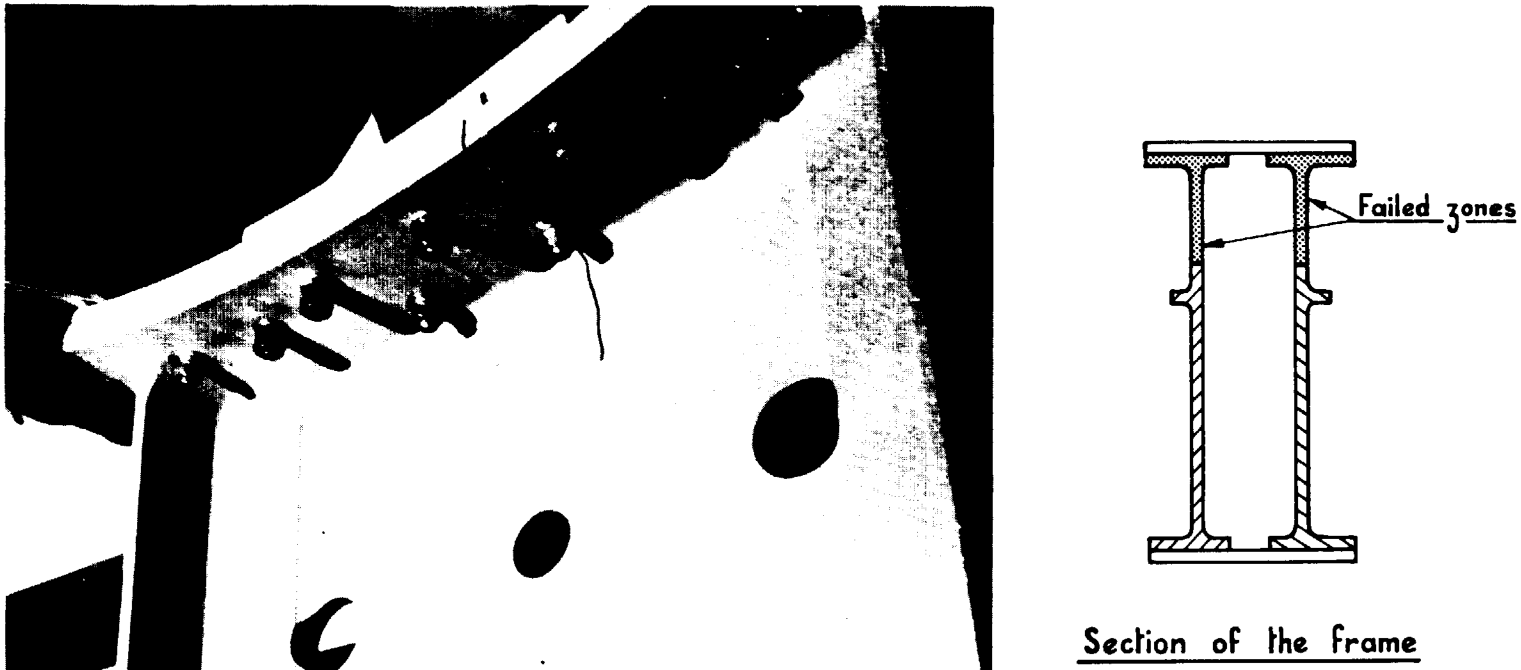


Figure 9.- Failure of a two-part main frame.

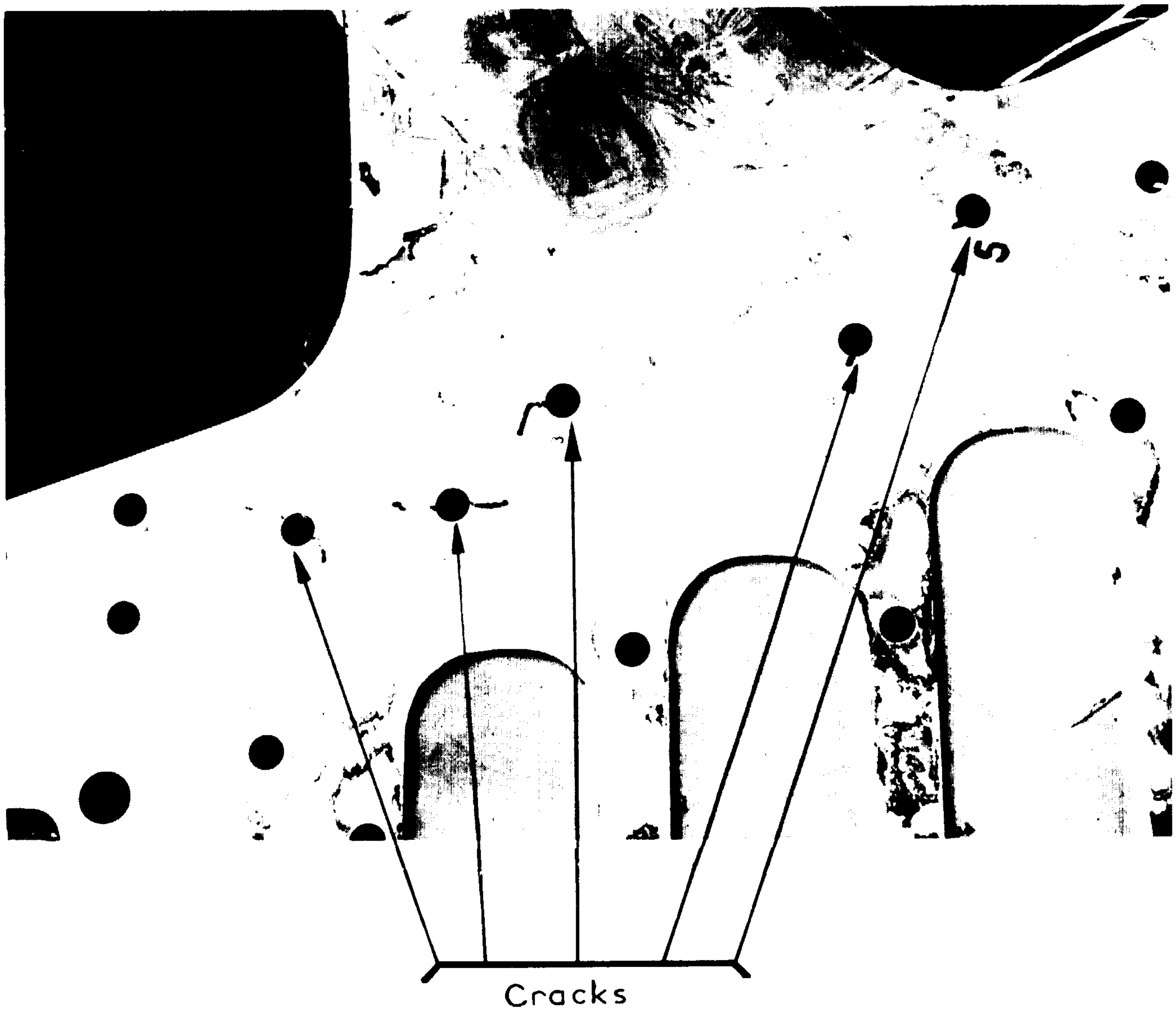
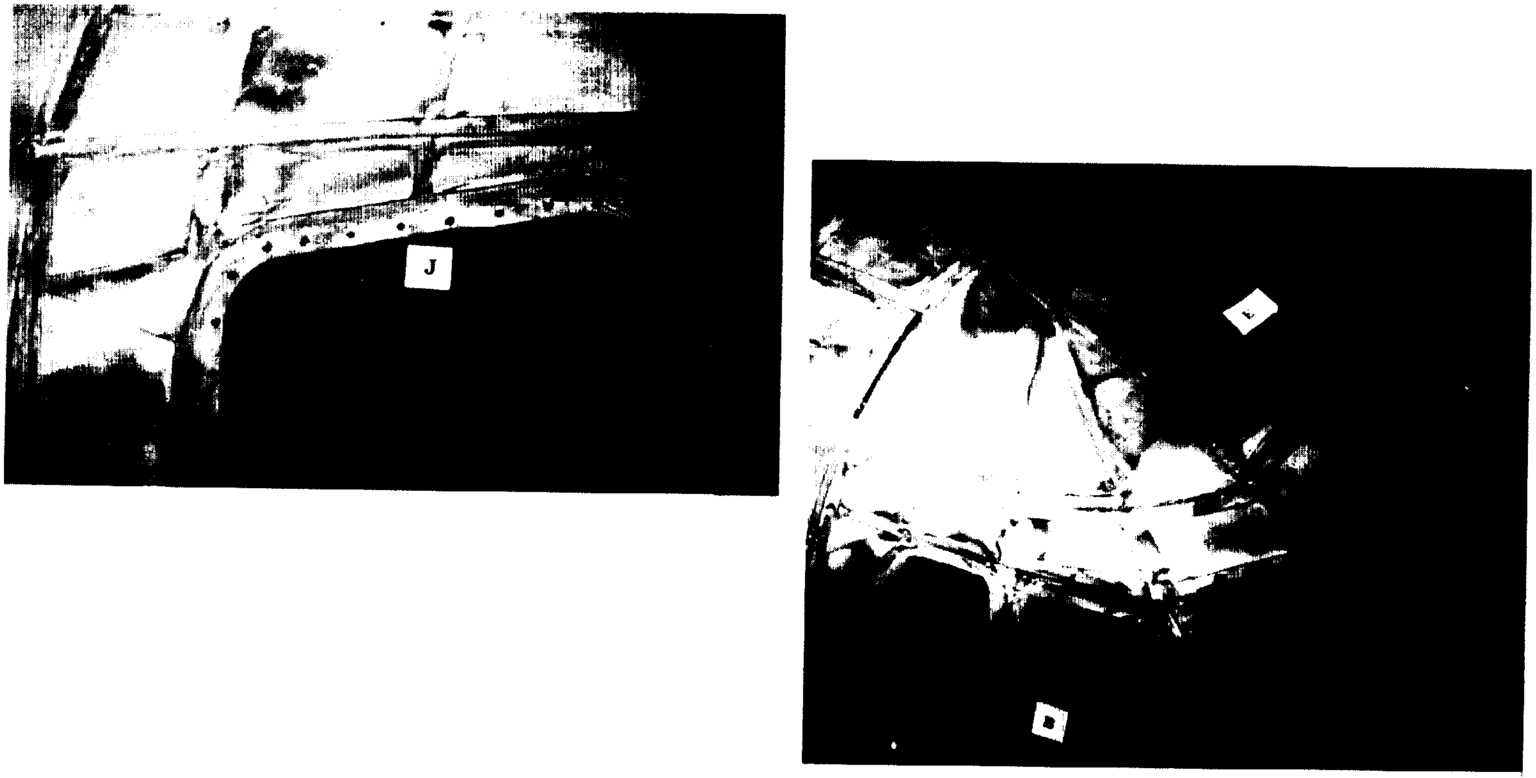


Figure 10.- Wing attachment fitting in which cracks grew at the same time from five holes.

Overall view

Emergency exit zone

Figure 11.- Study of photoelastic model of central part of fuselage.



Top part of passenger entrance

Cockpit

Figure 12.- Photoelastic model of front part of fuselage submitted to interior pressure.

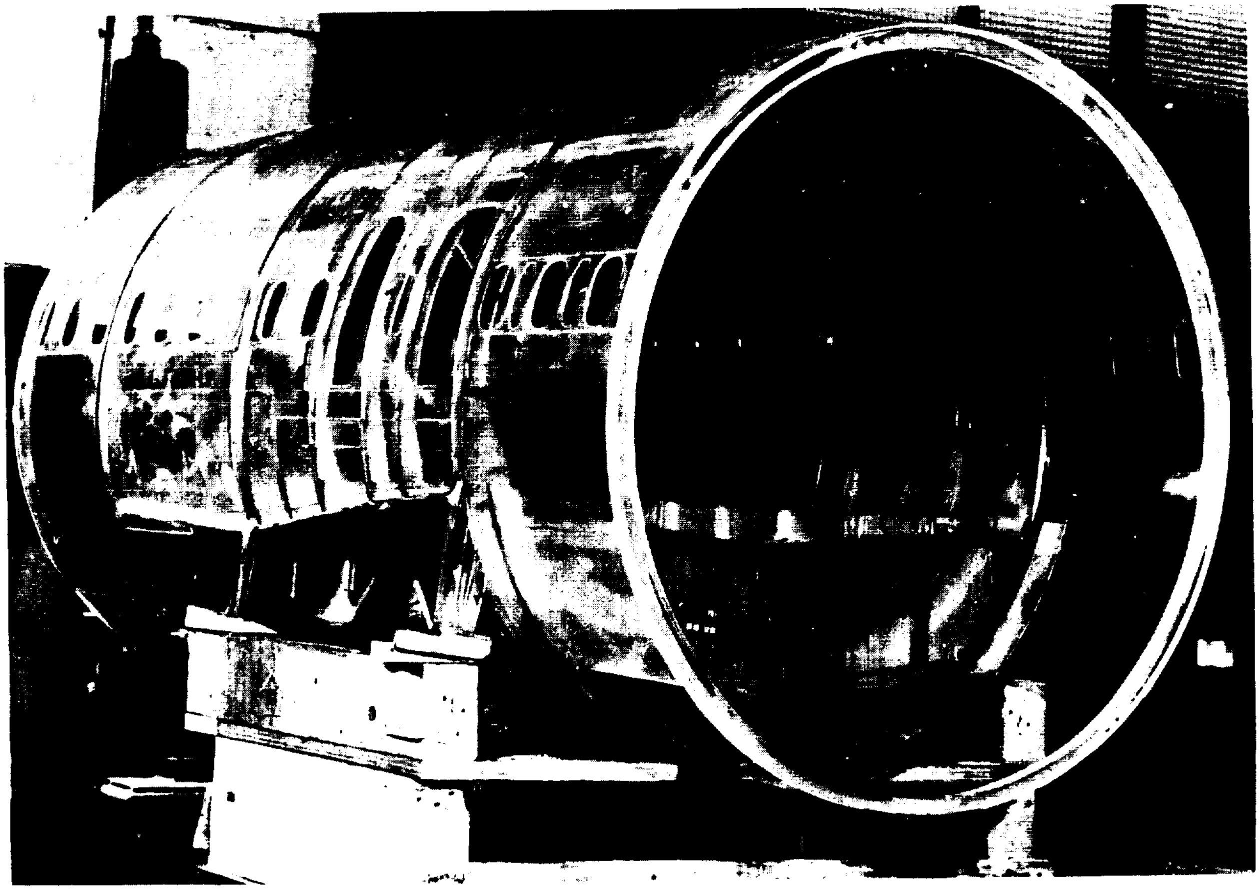
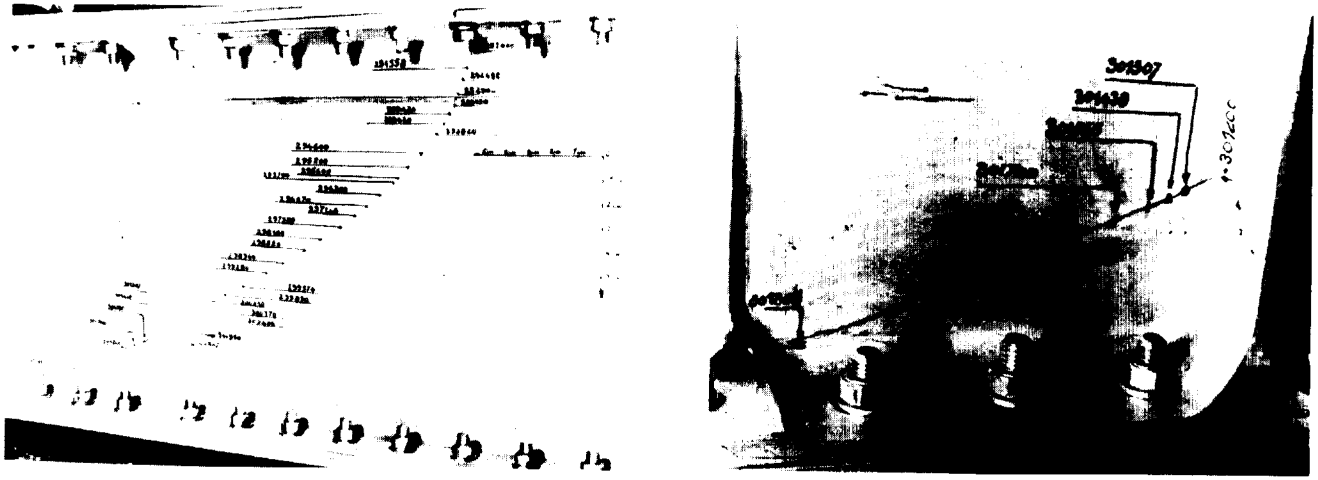
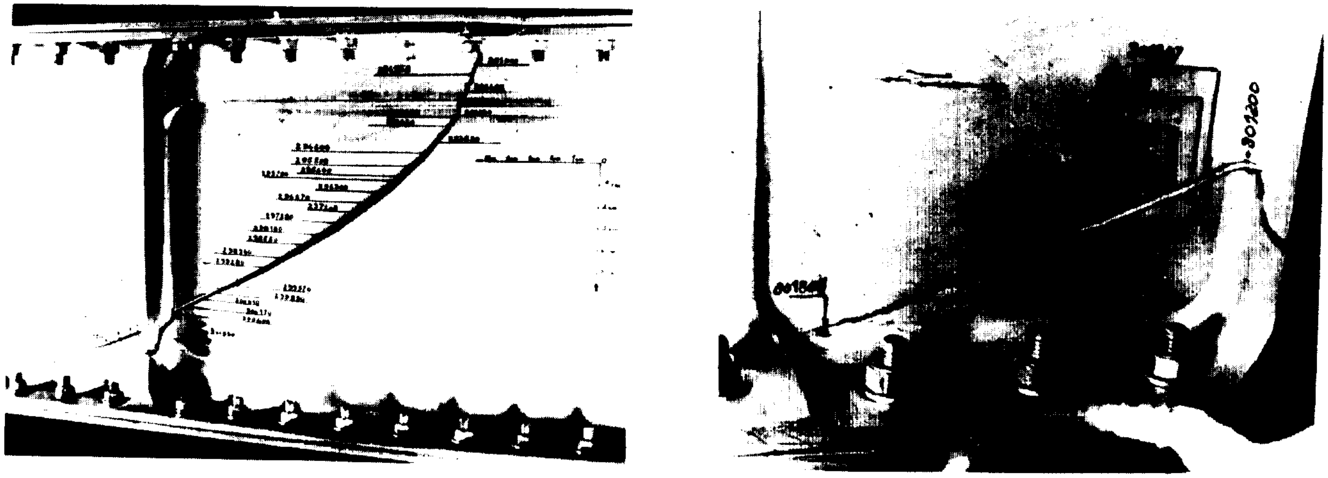


Figure 13.- Photoelastic model of central part of fuselage (1/5 scale).



Overall view without load.

Closeup view without load.



Overall view under load.

Closeup view under load.

Figure 14.- Test of development of a crack in longeron no. 2.