STRESS WAVE RIVETING

by

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Introduction

Whenever a metal joint undergoes cyclic loads of constant or variable amplitude, the problem of fatigue becomes prominent in aircraft design considerations. Optimization of aircraft designs for long fatigue life is the goal of every design engineer in the aircraft industry. Despite the recognition of this goal, fatigue failures are still the most unpredictable and feared failures in aircraft structures. We can all appreciate, therefore, the continuous efforts of government and industry to understand fatigue and to improve the fatigue life of metal joints.

There are many possible combinations of material defects and applied loads that can cause fatigue failures. It is not the purpose of this paper to analyze details of such failures. To understand the motivation for our work, however, we state three conditions that must coexist in fatigue failures:[1]

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[1] Madayago, Angel F., Metal Fatigue Theory and Design, John Wiley & Sons, New York, 1969.

1) Cyclic stress,

2) Tensile stress, and

3) Plastic strain.

In our efforts to improve fatigue life, therefore, we must prevent tensile stress or plastic strain or both of these conditions.

The Grumman Stress Wave Riveter (SWR) is a semiportable tool that can improve fatigue life in aluminum, steel, and titanium joints in aircraft structures, because it can eliminate one or two of the above conditions.

In addition, instead of the precisely machined holes and fasteners that are usually required with existing fastener systems, the SWR can be used with inexpensive rivets (8¢ per rivet) in holes with clearances varying from 0.002" to 0.020" in aluminum, and from 0.002 to 0.012 in titanium structures.

Description of the Stress Wave Riveter

Unlike the conventional concept of metal deformation under static forces that exceed the elastic limit, deformation may also take place under large rates of energy change that occur in high amplitude stress waves. The difference between the two types of deformation is the time duration of the applied force. In the static load, the duration is long as the force builds up from zero. In the stress wave, it can be very short (400-800 millionths of a second).

310<

In static loads the supporting structures must withstand the large forces applied to the rivet. When a stress wave is used, its wavelength, or time duration, is so short that the supporting structures do not have enough time to react. The result is a smaller device that can upset a rivet in a very short time. The other advantages of the stress wave type deformation of the rivet will be discussed later.

Once we establish the feasibility of deforming rivets with a powerful stress wave, we need a convenient method to generate the wave. We use electromagnetic repulsion. Figure 1 shows the main aspects of the tool. Although electromagnetic repulsion has been used for metal forming in many applications, it has not been used to deform metal directly by generating a stress wave. The amplitude of the stress wave generation by electromagnetic repulsion is not high enough to deform the rivet without an amplifier that changes both the wave's amplitude and its shape.

The stress wave propagates through the rivet at the speed of sound in steels (i.e., 2×10^5 in./sec). If its energy density (ft - lb/in.^{3}) is high enough, it will bring the rivet material to its plastic state. When the rivet becomes plastic, however, the speed of sound drops drastically because the modulus of elasticity is small. (Speed of sound $C = \sqrt{E/\rho}$, where E = modulus of elasticity, ρ = density.) The elastic stress wave then becomes

311<

a plastic stress wave trapped between two elastic-plastic interfaces, deforming the rivet in about 800×10^{-6} seconds.

Interference Fasteners

Holes drilled in structures that undergo cyclic loadings weaken the structure and reduce its fatigue life. This effect is shown in Fig. 2 where the similar fatigue specimens with and without holes were tested. The best fatigue life is for a specimen without holes ($K_T = 1$ where K_T = stress concentration factor). A good joint, therefore, will approach the curve $K_T = 1$. Of course, no joint can achieve this monolithic state. Figure 3 shows the fatigue life of various joints.[2] It is apparent that most of the methods give a joint with life considerably below the $K_T = 1$ curve. This is especially true in the low stress region.

Two methods have been used successfully during the last several years to improve fatigue life: a) interference fasteners; and b) plastic deformation of the surface of the hole. With interference fasteners, the hole is prepared several thousands smaller than the fastener. The fastener, either tapered or straight, is then driven through the hole and a nut is normally attached on the other side and tightened. With this method an interface pressure

[2] Speakman, E. R., Fatigue Life Improvement Through Stress Coining Methods, 12th Annual Meeting ASTM, June 1969.

312<

between the fastener and the hole wall leaves a radial compressive and a hoop tensile stress around the hole that reduce the stress concentration factor and improve fatigue life (see Fig. 4 — this is called propping). Since everything depends on the difference in size between the hole and the fastener, this method requires both precision-made fasteners and holes. The finish of the hole surface must be good enough to avoid surface cracks and to provide uniform interference. The result is shown in the increase in cost per hole.

In the second method, the hole surface is plastically deformed so that a relatively large compression residual hoop stress will remain after the operation (see Fig. 5). It can be achieved by passing an oversized hard ball or an oversized hard pin through the hole.

Deforming the hole surface is especially attractive because it could partially remove two of the three conditions that cause fatigue failure: a) tensile stress; and b) plastic strain.

In general, it is axiomatic that cracks will not propagate in a compressive stress field. In addition to the compressive residual stresses, this method also conditions the surface and eliminates surface defects that can cause cracks. Since most fatigue failures are caused by crack propagation, plastic deformation of the hole is a very effective way to increase fatigue life.

We conclude, therefore, that while interference fasteners in general can improve fatigue life, they are expensive and in many aircraft applications inadequate. Deforming the surface of the hole plastically on the other hand gives greater improvement in fatigue life, with less expensive slug type rivets. A good example of the residual stresses is given[3] in Fig. 6.

Interference Rivet Joints

The same reasons that were discussed above for interference fasteners apply to rivets. To establish interference, however, the rivet must be "oversqueezed" or deformed with high force to set up the interference. The force to oversqueeze a ¼-inch rivet is approximately 30,000 pounds. Such high force can only be applied by large hydraulic squeezers. Ordinary pneumatic portable riveting tools cannot set up interference rivets without cracking the tails.

The large forces, however, start forming the tail at the same time they squeeze the rivet shank. The result is large interferences (expansion of the hole) near the tail (0.006" - 0.008") while the shank near the head is hardly expanded (0.000 to 0.001"). This nonuniformity of interference causes distortion in the skins. The nonuniformity in interference is even greater in aluminum skins. Furthermore, oversqueezed rivets can only be used in new aircraft because existing aircraft cannot be put under a squeezer to replace

[3] H. Armen, Grumman Research Department, Private Communication.

314<

a bad rivet, or to do any repairs that require the replacement of a large number of rivets. Oversqueezed rivets can be used effectively to improve fatigue life in aircraft using titanium skins. It is not acceptable, however, to use oversqueezed rivets in aluminum skins, because of the large uneven deformation near the tail of the rivet.

Stress Wave Riveting

The Stress Wave Riveter deforms the rivet material by a high amplitude stress wave. Thus, the entire rivet is set in motion radially. The rivet expands rapidly and impacts the hole surface before the rivet tail begins to form. Unlike the oversqueezed rivets, therefore, it sets up uniform interference without distortion in the skins (see Fig. 7).

Furthermore, the radial velocity is so high (over 200 in./sec) that upon impact with the hole surface it deforms the surface plastically. This is especially effective in aluminum skins using A-286 type rivets.

Thus the SWR combines the advantages of plastically deforming the hole and the economic advantage of a relatively nonprecision hole and inexpensive rivets like those used in oversqueezing. The additional advantage SWR offers is that it is a portable tool.

The fatigue life of joints riveted with the SWR is shown in Fig. 2. These results were established with 7076-T6 specimens, A-286 rivets and 0.006-inch interference.

An additional advantage is the large initial clearances between the rivet and the hole. In one typical example, $\frac{1}{4}$-inch rivets were upset in 7076-T6 skins. The holes were larger than the rivet by 0.020-inch. The interference achieved was 0.002-inch.

The advantages of the SWR can be summarized as follows:

1) Portability. The tool weights 55 pounds (smaller tools are also available). It can be used with counterbalances. It can also rivet in any direction without precise line-up or initial pressure.

2) Uniform Interference. It provides uniform interference for better fatigue life.

3) Compressive Residual Stress Near the Hole Surface as in Shot Peening. The hole eliminates any surface defects in aluminum skins and provides compressive residual stresses that can arrest the propagation of small cracks.

4) Inexpensive. Standard rivets are utilized in holes drilled to relatively open tolerances.

316<

CAPTIONS

Fig. 1 Stress Wave Riveter Schematic

Fig. 2 Constant Amplitude Fatigue of 7075-76 Specimens

Fig. 3 Constant Amplitude Fatigue of Various Types Joints

Fig. 4 Cyclic Stress in Riveted Joints with Propping

Fig. 5 Cyclic Stress in Riveted Joints with Plastic Deformations

Fig. 6 Radial and Circumferential Residual Stresses in Sheet with Rigid Oversize Fasteners ($z = \pm b$)

Fig. 7 Comparison of Riveted Specimens. a) Oversqueezed; b) Stress Wave Riveted

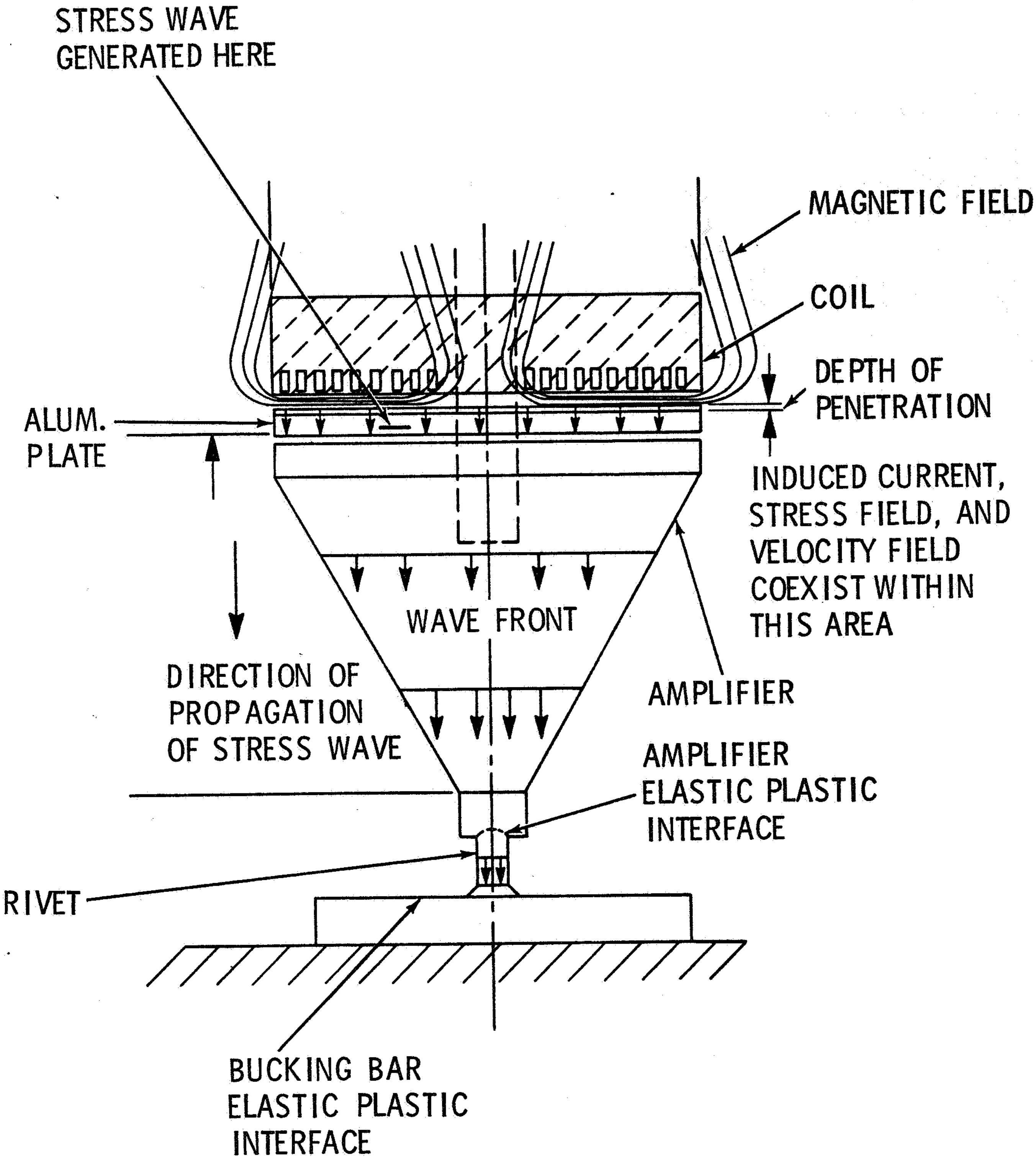
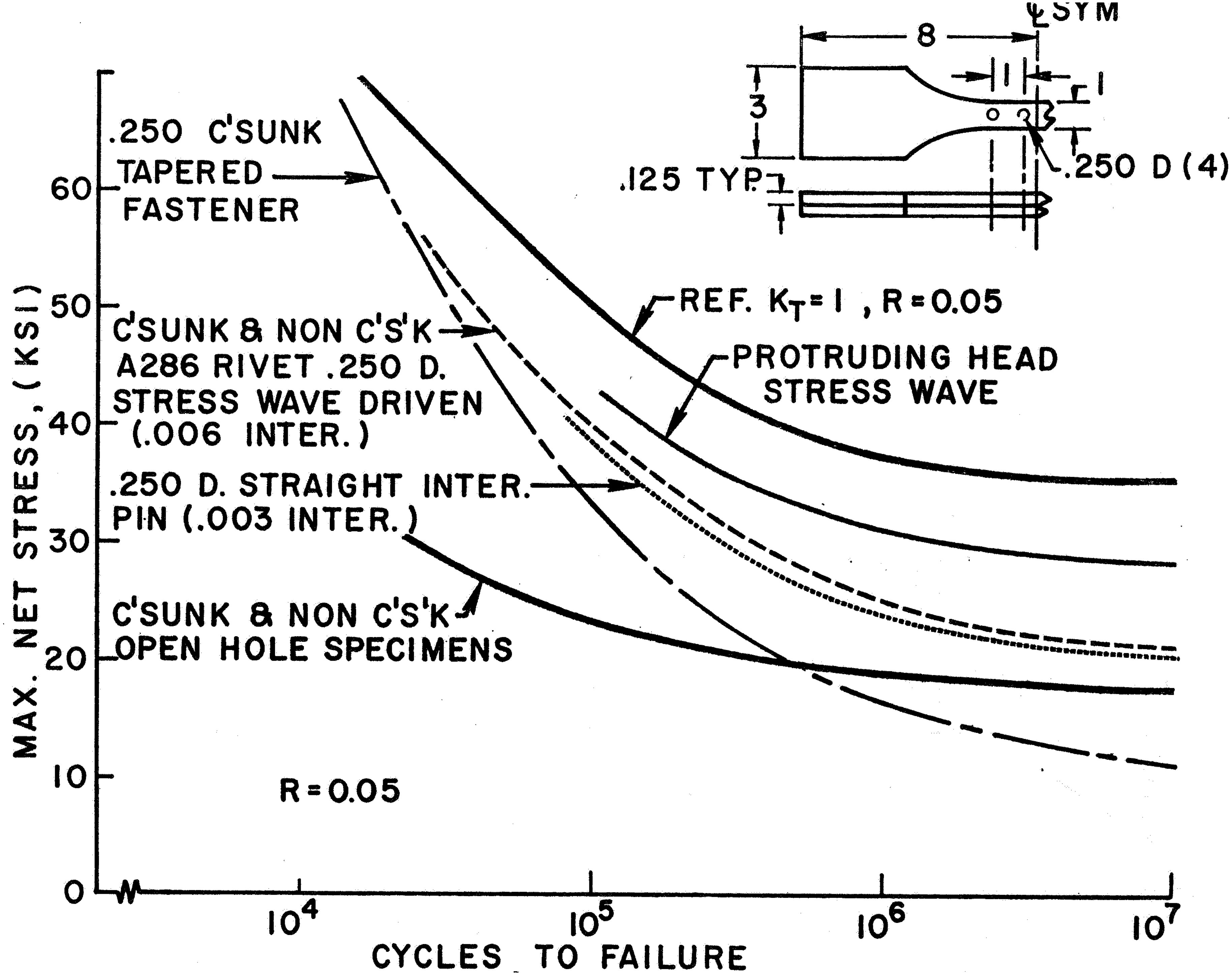


Figure 1. - Schematic diagram of basic shock wave riveter.



MAX. NET STRESS, (KSI)
0
10
20
30
40
50
60
10^4
10^5
10^6
10^7
CYCLES TO FAILURE
.250 C'SUNK
TAPERED
FASTENER
C'SUNK & NON C'S'K
A286 RIVET .250 D.
STRESS WAVE DRIVEN
(.006 INTER.)
.250 D. STRAIGHT INTER.
PIN (.003 INTER.)
C'SUNK & NON C'S'K
OPEN HOLE SPECIMENS
R = 0.05
REF. K_T = 1 , R = 0.05
PROTRUDING HEAD
STRESS WAVE
8
3
1
1
SYM
.250 D (4)
.125 TYP.

Figure 2

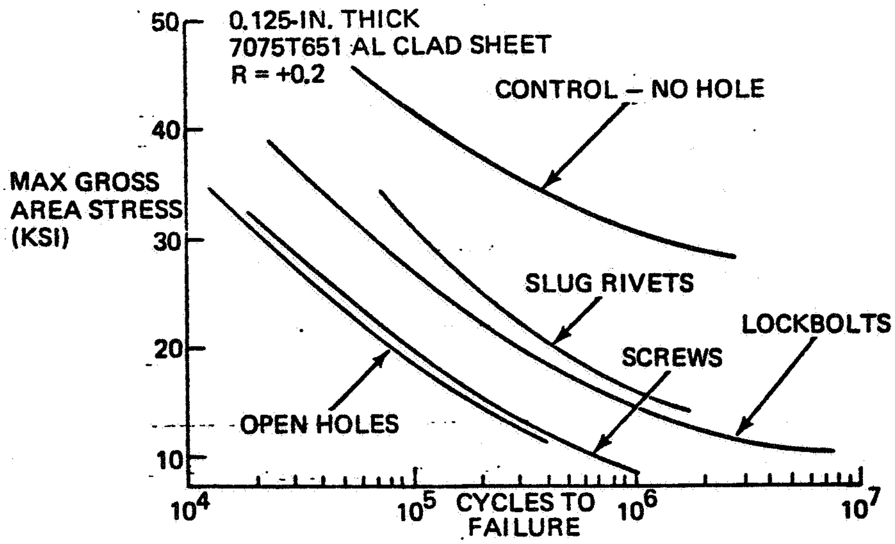


Figure 3

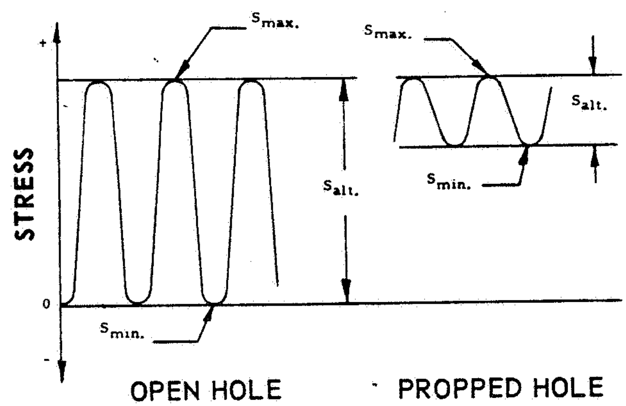


Figure 4

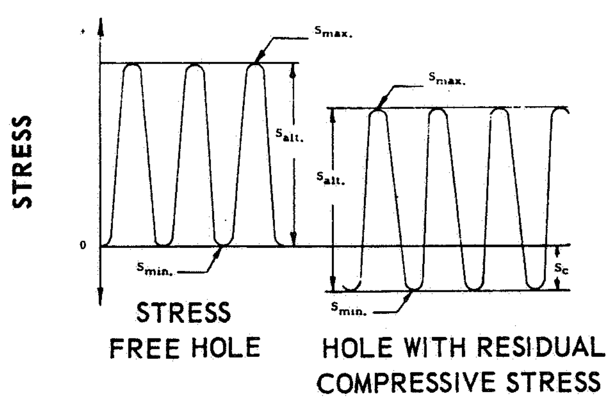


Figure 5

FIGS. 3, 4, 5 LEFTHERE

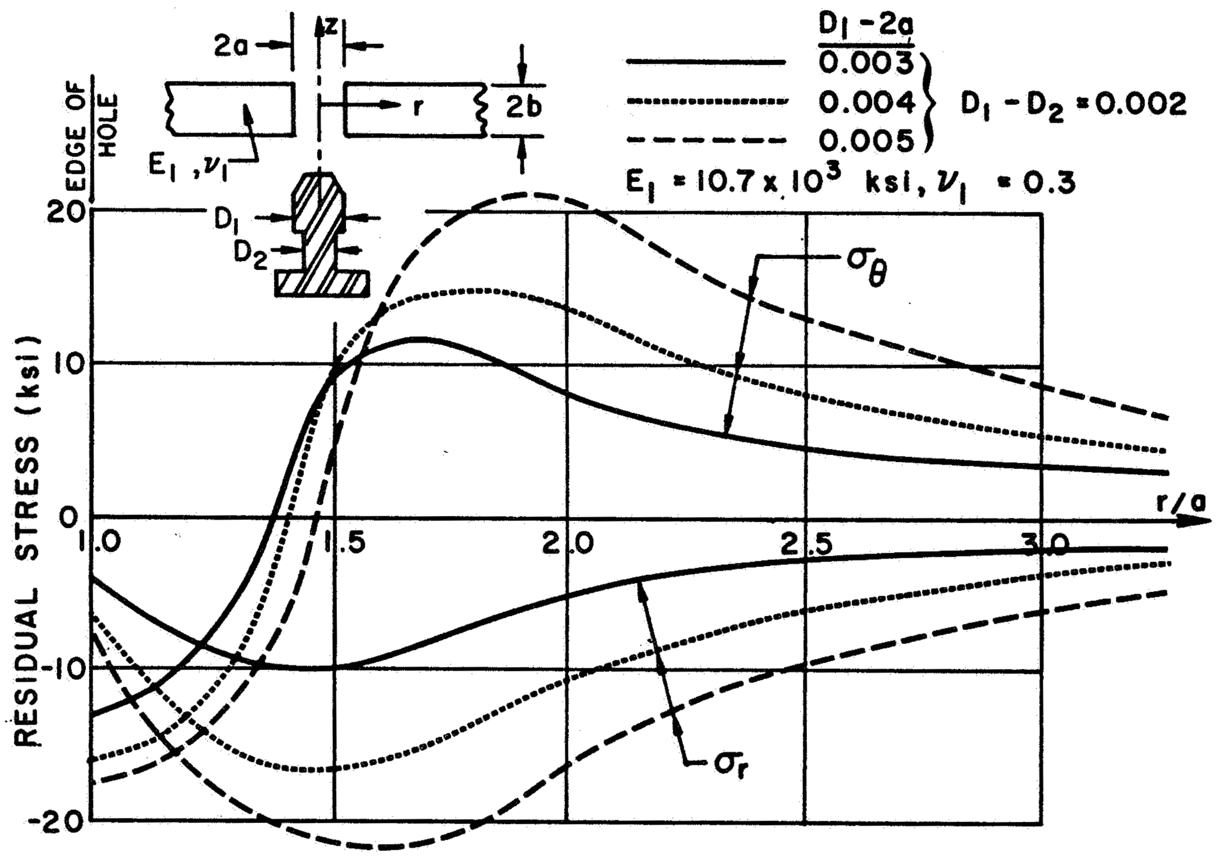
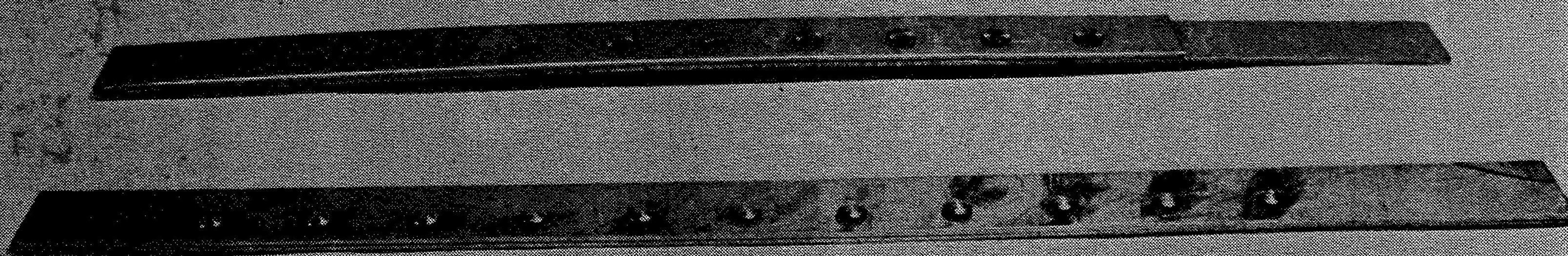


Figure 6

FIG 6 LEFTHERIS

a) Oversqueezed



b) Stress Wave Riveted

Figure 7